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Comparison of Marcellus Fracturing Using Azimuthal Seismic Attributes Versus Published Data from Outcrop Studies

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Summary

Fracture analysis using seismic velocity volumes has been pushed from qualitative to quantitative analysis using rose diagrams and comparison to calculated decline EURs for a northern PA Marcellus prospect. Comparisons to published data from Appalachian black shale outcrops and to subsurface fracture models proposed in various papers are used to validate the results from subsurface data. While it has long been understood that natural fracture systems are essential for achieving the best production in Marcellus Shale gas wells, methodologies for understanding the heterogeneities in these fracture systems, in the subsurface, are less well understood. Analysis of wide-azimuth p-wave seismic velocity attributes at the reservoir level, and for specific laterals or proposed laterals, can provide this insight. Although anisotropy, measured as azimuthal variations in velocity, can be a result of joints or fractures, fabric or stress, we can show evidence to highlight the likely source of these anisotropies to be a result of joints or fracturing.

Published data and azimuthal seismic attributes show two primary joint sets, the J1 set, and a J2 set, as well as neo-tectonic J3 joints that affect the Marcellus and other Devonian shales in the Appalachian basin. Engelder (2008) contends that in organic-rich Devonian black shale intervals, including the Marcellus, the J1 and J2 joint sets formed in sediments at or near peak burial depth as a result of anomalous pressures during thermal maturation of organic matter. While authors indicate that the ENE to WSW J1 is generally restricted to the black shales, the younger NNW to SSE J2 joint set is described as being more likely to extend out of the black shales into overlying rock relative to the extent of overpressure, varying with the gas volume generated. Joint analyses by Lash et al (2004), for black shales in outcrops within the Finger Lakes area of New York, show J1 and J2 orientations approximately parallel and perpendicular to the Alleghenian fold axes exposed there. Similar orientations can be seen in seismic analysis for the Marcellus Analog survey and a second survey in Clearfield County.

Rose diagrams from azimuthal attributes are similar to outcrop, with the J2 azimuths dominant in areas with higher EUR wells, which may be attributed to higher gas generation and longer joint length. High EUR areas also show generally lower "Interval Vfast velocities" and show J2 joints well above the top Marcellus in Hamilton Group grey shales. Areas with low EUR wells show a more dominant J1 trend or no dominant trend, along with higher anisotropy, and more heterogeneity. The seismic velocity attributes show evidence of velocity anisotropy which could be attributed to fractures. Calculated velocities can be used to identify areas that may be more fractured. Azimuthal gradients can be used to show reservoir compartmentalization and heterogeneities that could impact production. These attributes offer a tool to high grade drilling opportunities and improve production estimates for Marcellus wells.

Introduction

The Middle Devonian Marcellus black shale was deposited on continental crust in an interior seaway of relatively shallow water (< 200 m), perhaps because sea level was unusually high at this time. During the Middle Devonian, a micro-continent called Avalonia depressed the edge of the Laurentia continental margin (now the Appalachian Basin) as a consequence of thrust loading in a highland at the edge of the continent. This created the accommodation space in which the Marcellus and subsequent black shales were deposited. The seabed was depressed below a pycnocline which is a boundary below which oxygenated sea water does not circulate. Organic material, mainly from marine algae, was preserved in this oxygen-starved environment to be buried to depth favorable for generation of oil and gas. The Marcellus consists of two major cycles of organic-rich shale accumulation, with the basal portion being particularly rich. Because Middle Devonian black shale is local rather than being distributed globally, tectonism is believed to have contributed to relative sea level change. One model for the development of the richest black shale is that thrust loading disrupted river systems so that, for a period, sediment flux into the basin was low, favoring the accumulation of rock with a high total organic carbon (TOC) content. Eventually, river channels organized to deliver clastic sediments at a higher rate so the gray shale covered the black shale. Each of the two cycles of black shale, the Union Springs and the Oatka Creek Members of the Marcellus Formation, is bounded above and below by a carbonate, characteristic of a low stand systems tract.

Regional faulting in the study area is dominantly ENE to WSW, primarily as a result of salt tectonism below the Marcellus, and younger or reactivated NNE to SSW faults. Both fault trends may affect production from the Marcellus. They may be significant when they are connected to fractures near the borehole, and may act to rob the stimulation by carrying fluids away from the borehole. Additionally, younger faults, especially NNE to SSW faults that appear to cut section above the Tully, may allow gas to leak from the Marcellus reservoir. For this reason most wells are drilled to avoid the larger faults. In the survey area, wells have been drilled NNW or SSE to be perpendicular to the contemporary stress field, and have terminated before reaching regional ENE to WSW trending regional fault cuts, however, some wells appear to have been cut by the younger faults.

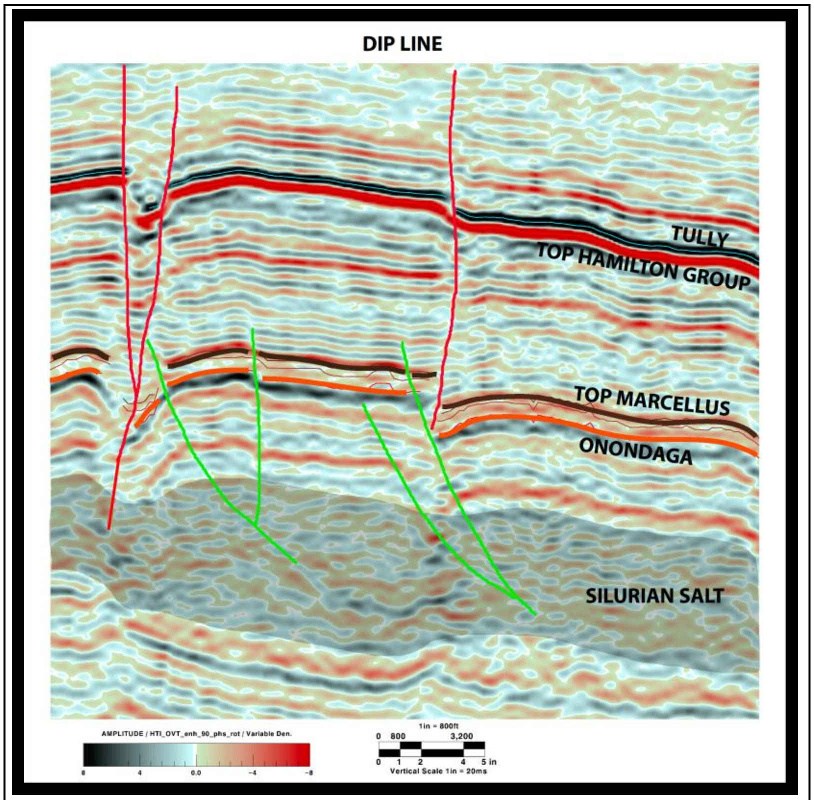
A dip section, vertical seismic profile is shown in Figure 1, which display the structural style of the project area within the Hamilton Group and adjacent formations. This line, which is nearly parallel to most horizontal well trajectories, shows the variable thickness of the Silurian Salt, below the Marcellus, which controls much of the larger structuring in this part of the Appalachian Basin. Large faults, similar to the red faults, parallel to large folds related to salt deformation are avoided when Marcellus wells are drilled. Young faults, that have likely reactivated pre-existing zones of weakness, have variable offset at the Onondaga and Marcellus, but have offset at and above the Tully. These larger structural features are well understood and well documented in the literature. The focus of this paper, however, is a study of reservoir level joints and fracturing using seismic attributes.

Even though this play is a “resource play”, this study shows that the reservoir fracturing is heterogeneous and that not all well locations are likely to be economic. The Marcellus play in Northern Pennsylvania and Southern New York is a “shale gas” unconventional resource play, commonly described as having no obvious trap or seal and no water contact. The Devonian reservoir section in the case study area is the basal unit of four units within the Hamilton Group. Unlike the younger units, the Upper and Lower Marcellus shale contain high Gamma, high TOC facies which have generated gas just prior to and during the Alleghenian. These shale plays depend on fracturing to allow mobilization of the gas during stimulation, as they have low matrix porosity. Using a good quality northern Pennsylvania 3D survey, available well data, published outcrop data and subsurface information as well as production data available from the state, we are able to show how wide-azimuth seismic shows variations in fracturing at the scale of individual pads or even individual wells. This variation begins to explain why production varies significantly, even locally, within the play

Figure 1: Dip line showing the structural style of the Marcellus Analog survey.

Azimuthal Anisotropy

Seismic anisotropy refers to variation in elastic wave propagation velocity that is directionally dependent. The conventional P-wave processing algorithms of the past ignore azimuthally dependent normal move-out by assuming heterogeneous media, resulting in a single, isotropic velocity applied to all traces in a CMP gather. As described by



Tsvankin and Grechka, applying a single value of NMO velocity to the whole gather in a wide azimuth 3D survey causes under-estimation of velocity in the “Vfast” direction and over-estimation of the velocity in the “Vslow” direction for horizontally anisotropic media. In addition to improving the overall stack, azimuthally dependent velocity attributes can provide insight into the anisotropy of these data, including analysis of potential fracture trends, and reservoir heterogeneity. For the Marcellus Analog project, Interval Vfast, Interval Vfast-Vslow Percent, and Interval Vfast Azimuth volumes were used extensively.

Interval Velocities are calculated from the RMS Velocities using a Modified form of Dix Equation. This process effectively strips off shallow layers (near surface anisotropy is removed.) The process looks at the difference between the top and the base of an interval. Because low dip is assumed in the calculation of the interval velocities, areas with higher time dip gradient were eliminated from any analyses of the data. Interval velocity calculations are based on a window cross correlation calculating the time shift required for a least squares fit. This is calculated at every sample in a sliding window of a size that is determined by the processor. The result may be noisy, so smoothing is often applied. Smoothed data may cause artifacts in the result, especially for azimuth calculations, so interpreters may consider using unsmoothed volumes for calculations, keeping in mind that some data values will be anomalous due to noise. It appears that the anomalous anisotropy values mostly occur on the edges of the survey and in low fold areas where the azimuthal contribution to the bins are not ideal. They also appear to occur in fault zones where imaging may be poor. Because of this organization and predictability, it was determined that unsmoothed volumes could still be used for analysis around the production, where these anomalies can be avoided.

HTI processing corrects the time shifts remaining in gathers initially moved out with the best isotropic velocity, after any VTI correction. These residual time shifts that are not corrected by the isotropic velocity, are inverted to create RMS velocity volumes, RMS Vfast and RMS Vslow. More delayed traces are those that traveled in the slow velocity direction, and less delayed traces are the “fast” direction. The azimuthal position of the maximum and minimum (“fast”and “slow”) show the direction of aligned geologic fabric (in this case fracturing) as “fast”, if it is primarily aligned in a single direction. RMS Vfast and RMS Vslow are defined by the maximum excursions from the least squares fit curve for azimuthally varying velocity. RMS calculations are something like an average value, as they represent the sum of anisotropies from the surface. Azimuthal variations are now commonly corrected in gathers where anisotropy is present in order to improve the stack, however these data can also be used to identify anisotropies in the geology.

Figure 2 represents an example subsurface point, with high RMS anisotropy. Consider aligned fracture systems or other aligned changes in sedimentary fabric to be "speed bumps" for a wave travelling perpendicular to the aligned system in an anistropic medium. If fractures or stresses are aligned uni-directionally, the travel time is slower for a direction that crosses the "speed bumps", and would give a Vslow direction perpendicular to the fractures or alignments. Conversely, Vfast is parallel to these "speed bumps". The difference between the calculated Vfast and Vslow as a percentage, is a proxy for percent anisotropy. If there is low anisotropy relative to the scatter of velocity, the difference between Vfast and Vslow is small, such that the Azimuth of Vfast cannot be computed accurately. As with sonic scanner data, these azimuth values are not useful if the percent anisotropy is calculated to be, as a rule of thumb, less than 2-3%. When anisotropy is less than 3%, the azimuthal values from these data should not be used.When the difference between Vfast and Vslow is large, the "sinusoid" representing velocity variation with azimuth can be calculated with confidence. As a proxy for anisotropy, defined by Vfast – Vslow Percent, greater than 3%, the azimuth of Vfast can be shown easily, and with minimal error.

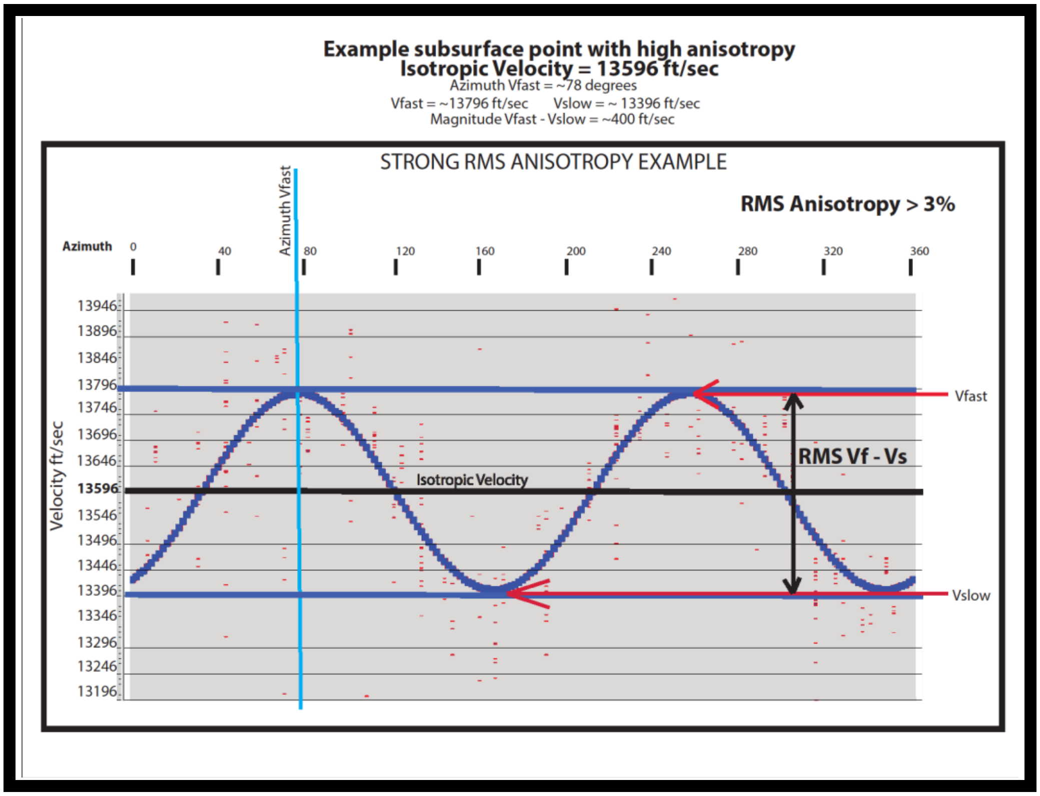


Figure 2: Example scatter of velocities for all traces within a wide-azimuth 3D subsurface bin. The velocity variation indicates a large anisotropy, where RMS Vf-Vs percent is a proxy for anisotropy. The azimuth of Vfast, in this case, is parallel to joints that cause anistropy in the Marcellus.

Natural Hydraulic Fracturing and the Marcellus Play

While it has long been understood that natural fracture systems are essential for achieving the best production in Marcellus Shale gas wells, methodologies for understanding the heterogeneities in these fracture systems, in the subsurface, are less well understood. Analysis of wide-azimuth p-wave seismic velocity attributes at the reservoir level, and for specific laterals or proposed laterals, can provide this insight. Published outcrop and core data and azimuthal seismic attributes show two primary joint sets, the J1 set, and a J2 set, as well as neo-tectonic J3 fractures that affect the Marcellus and other Devonian shales in the Appalachian basin.

For the Devonian black shale intervals, Engelder contends that J1 and J2 joint sets formed in sediments when they were at or near peak burial depth as a result of anomalous pressures during thermal maturation of organic matter. Field observations by Lash et al confirm that the ENE J1 joints are more closely spaced, and best developed in the more organic-rich black shale units. He also states that “While ENE joints are less well developed outside the black shale intervals, joints that formed during the Alleghanian orogeny (NW trending, J2 joints) are found throughout the Upper Devonian shale sequence.” The two fracture sets are cross-cutting within the shales, which is important in the optimization of well placement and fracking of horizontal wells. The earlier J1 fracture set (east-northeast-trending), that resulted from initial gas generation, is nearly parallel to the maximum compressive normal stress of the contemporary tectonic stress field, although Engelder contends that this is a coincidence. In an interview with Engelder, 2011 AAPG Explorer article by L. Douglas, the two major joint sets in the Marcellus are succinctly described:

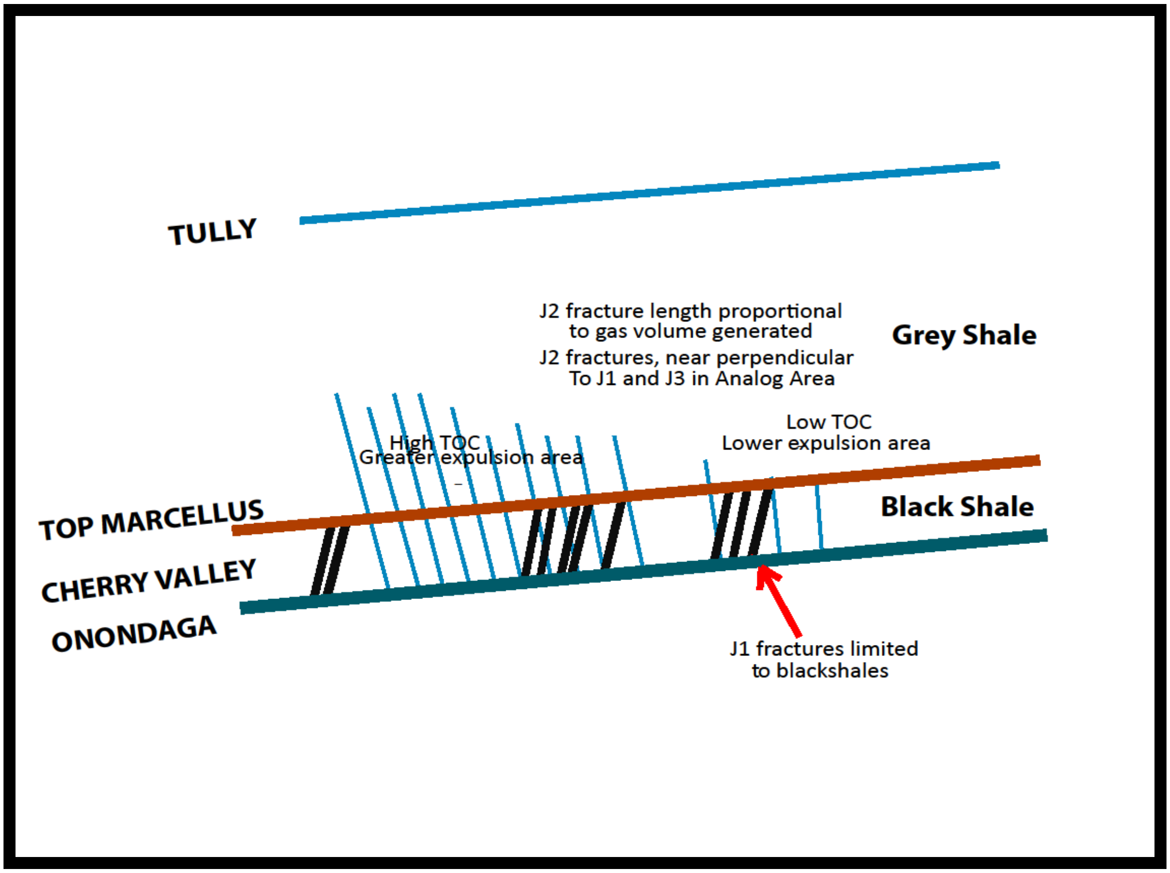
“The J1 joint set appears to be unique to gas shales. The J2 set appears to break out of the gas shales and populate the rock above those gas shales. The second joint set may appear about 1000 ft. or even as much as 4000 ft above the gas shale. We interpret this to mean that a large enough volume of gas was generated so the section above the gas shale became over-pressured to the extent it also was hydraulically fractured. So the section above the gas shale became charged with high-pressure gas as well.”

It is hypothesized that the variable length of J2 joints and fractures that extend into the grey shales above the Marcellus, could be related to TOC. Because the J2 joints are related to the volume of gas generation, we should see changes in the length and presence of J2 joints across the survey area if TOC is changing and the amount of gas produced was variable across the survey. Figure 3 shows, diagrammatically, the relationship between J1 and J2 fractures. The J2 joints, which are Alleghenian in age and perpendicular to Alleghenian folds, grew episodically during the time of maximum gas generation. Although the J1 joint set is described as being more closely spaced within the black shale interval, the J2 joint set, which may occur over a much larger vertical section, may be more “visible” to the seismic tool. This is described in more detail in the analysis of rose diagrams from the azimuthal velocity volumes that follow. Virtually all horizontal wells within the Marcellus Analog 3D survey area to-date have been drilled in the north-northwest to south-southeast direction. In the ideal case, this allows horizontal wells to cross and drain J1 joints where they are present. Subsequent staged hydraulic fracture stimulations run east-northeast, parallel to J1, thus crosscutting and draining J2 joints. XXXX et al, showed a poster session at the April 2014 AAPG that showed that in spite of being perpendicular to present day ShMax, the J2 fractures are partially mineralized, which props open the fractures and allows them to contribute significantly to drainage of the Marcellus gas.

Figure 3: Diagrammatic Model showing natural hydraulic fracturing associated with shales of the Hamilton Group.

Joint analyses by Lash et al, for black shales in outcrops within the Finger Lakes area of New York, show ENE J1 joints, and J2 joints approximately perpendicular to the Alleghenian fold axes exposed there. Analyses for a second seismic survey, in Clearfield County, show that J2 azimuths from subsurface seismic rotate from NNW to WNW remaining perpendicular to the oroclinal fold. J1 azimuths in the Clearfield survey are similar to those in the study area with a ENE trend similar but perhaps slightly more E-W than the present day stress direction ShMax. The rotation of J2 shows that the azimuthal variations are not related to stress. Present day stress has been shown to remain consistent across Northern Pennsylvania. Unless the rock fabric shows linear variation, the small scale of the rock fabric would not be detectable at seismic scales. This leaves the joints and fractures as the source of anisotropy measured by seismic azimuthal anisotropy.

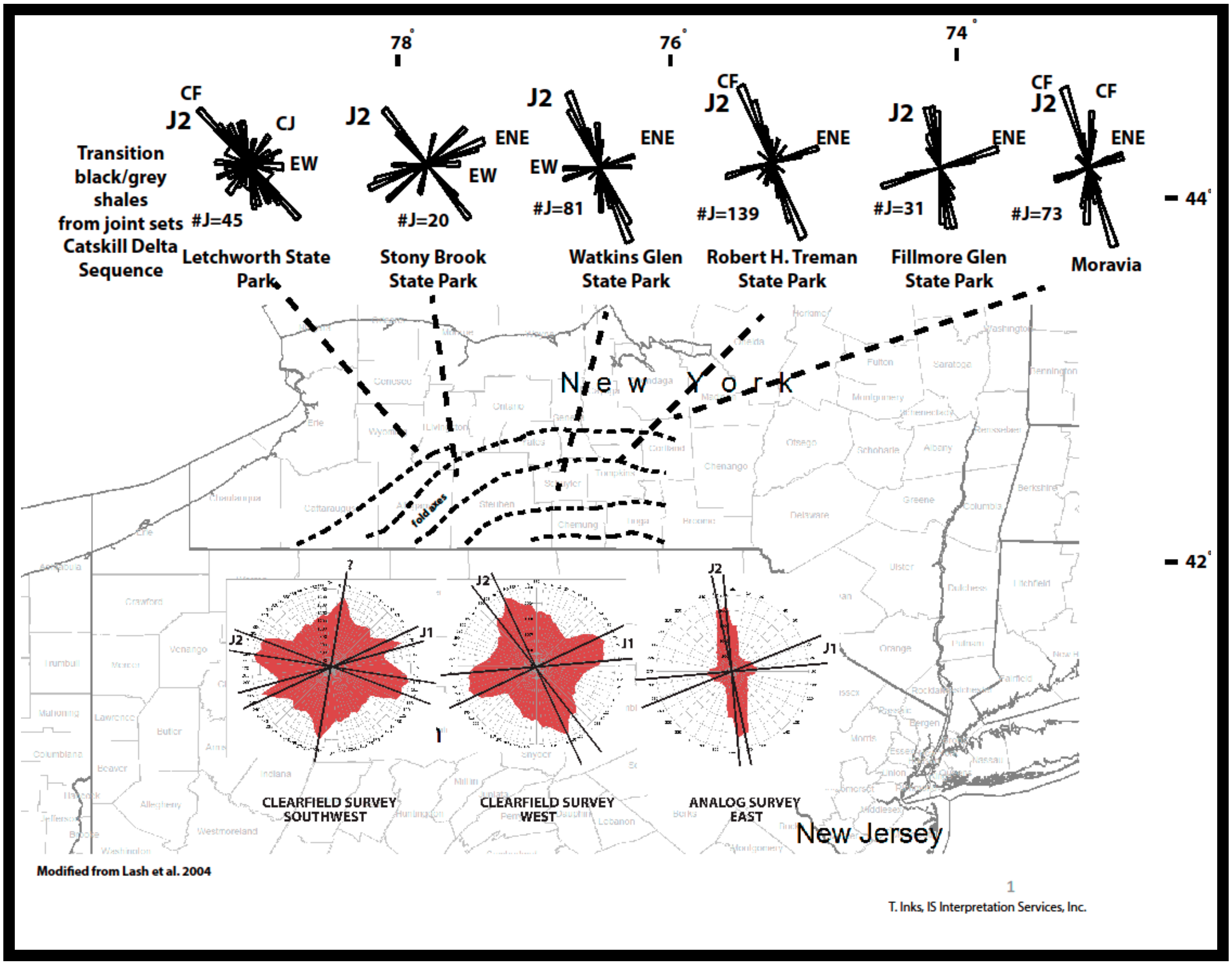
Anisotropy and Productivity from Marcellus wells



The primary goal of this project is to understand the prospectivity of the Marcellus in the Marcellus Analog 3D survey. 3D azimuthal analysis gives us the subsurface information that we need to understand the potential fracture systems within the Marcellus, as well as within zones adjacent to the Marcellus. The results of these analyses show how azimuthal seismic velocity attributes support and compare to published outcrop data describing joints and fractures in and above the Devonian black shale. They also may be used to better understand the reservoir heterogeneities that occur in the reservoir due to natural hydraulic fracturing and tectonic stresses.
With limited well data and production data, we cannot completely evaluate all the variables that affect production from the Marcellus. We can however, find excellent correlation between published data, in particular azimuthal analysis of joints and fractures in outcrop, and azimuthal data from subsurface seismic. Additionally, there are numerous consistent observations with regard to azimuthal velocity attributes and EURs shown from decline analysis.

A map of northern Pennsylvania and southern New York (Figure 4), revised from Lash et al 2004, shows rose diagrams from joint analysis of shales in the Finger Lakes area of New York, along with a rose diagrams from the Top Cherry Valley from the anisotropic analysis of the Analog 3D and the Clearfield 3D azimuthal data (all azimuths where anisotropy is greater than 3%, as well as with low dip gradients.) J1 joints are consistently ENE regardless of the fold axis. The J2 joints from Lash's study show an orientation perpendicular to the Alleghenian fold axes exposed in the Finger Lakes area. In these shales, the NW to SE and NNW to SSE J2 joints dominate. Similarly, the Marcellus Analog 3D, Top Cherry Valley rose diagram shows similar azimuthal trends, most like those on the eastern side of the Finger Lakes district. The northern part of the Clearfield survey, a large survey that lies on the oroclinal fold belt for the Marcellus, shows a J2 azimuth that rotates from NNW to WNW, staying more or less perpendicular to structure.

Figure 4: This figure shows how subsurface azimuths in Northern Pennsylvania compare to outcrop measurements in Southern New York. A similar trend for J2 azimuths rotating with the structure can be seen in both outcrop and subsurface data. Note that the large number of points used for the Clearfield survey increases the scatter of points used in the rose diagrams.

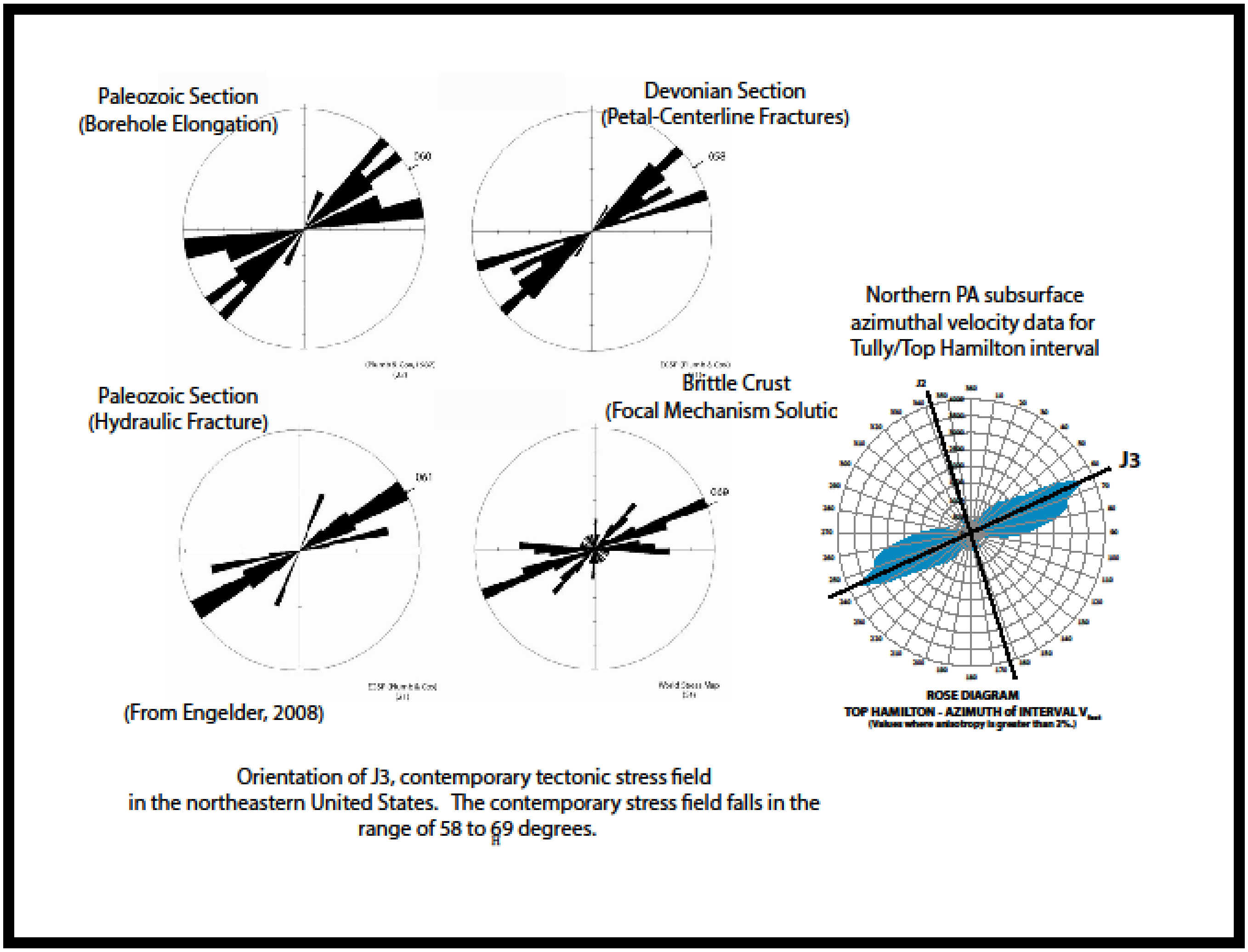


Joint diagrams from literature, in Figure 5 show the orientation of J3 based on rose diagrams from the World Stress map. The rose diagram from the Tully and Upper Hamilton Group interval shown in blue on the right matches this trend, which is typically between 58 and 69 degrees east.

Figure 5: This figure shows that shallower azimuths calculated for the Tully and Upper Hamilton for the Analog 3D compare to various measurements for the present day stress field, ShMax in the northeaster part of the US. . The dominant azimuth at the Top Hamilton shows an azimuth of ENE to WSW. Based on the previous regional work, this would put the the anisotropic proxy for stress direction at about 65 degrees, which fits well within the range of 58 to 69 degrees East which is attributed to the contemporary stress field in the literature, as shown.

For further analysis of these trends at the pad level, we can summarize what has been observed so far on the regional scale. First, the oldest J1 trend, from natural hydraulic fracturing, is shown to be in the range between 70 and 77 degrees east for both outcrop and subsurface data in the Analog survey and the Clearfield survey. The J2 trend, related to episodic natural hydraulic fracturing during maximum hydrocarbon generation, is not perpendicular to the J1 trend, but is perpendicular to Alleghenian folds, and generally trends NNW in the Analog survey. The neotectonic J3 trend is shown to be between 58 and 69 degrees east, slightly more north of east than the J1 trend in this area. The neotectonic stresses are captured in the shallower Tully interval on the Analog surveyand match very well with World Stress Map trends shown in Figure 5.

Initially, the azimuth of Interval Vfast was extracted for three horizons (instantaneous amplitude of INT Vfast Azimuth), the top Hamilton, the Top Marcellus and the Cherry Valley. Values for azimuth were limited to areas with greater than 3% anisotropy in order to insure a statistical calculation that is above the noise level for these data.



(From Engelder, 2008)

Orientation of J3, contemporary tectonic stress field in the northeastern United States. The contemporary stress field falls in the range of 58 to 69 degrees.

The vertical variation in azimuth indicated by these velocity attributes match the expected results for the geologic model. The J2 azimuths dominant in areas with higher EUR wells, are attributed to higher gas generation and longer joint length, as described in our subsurface model (Figure 3.) Areas with low EUR wells show a more dominant J1 trend, along with higher anisotropy, and more heterogeneity.

The estimated ultimate recovery (EUR) for both gas and oil assumed that the economic limit occurs when the gas rate falls below 600 Mcf/month. The economic limit is the point in time at which the production is assumed to cease because it is no longer economic. The EUR is determined by adding the cumulative historical production to the forecasted cumulative production to the economic limit. Publicly available data for historic well production is on intervals of every 6 months. To obtain a monthly production rate for decline curve forecasting, the 6 month historic production data was divided equally to the preceding 6 months. Decline curve forecasts were made assuming exponential decline, unless hyperbolic behavior was shown. For hyperbolic decline curve forecasts, the forecast converted to exponential decline when the decline rate fell to 10% unless historical data showed a different exponential decline behavior.

Decline EUR values for gas were loaded for wells in the project, and a bubble map of production was created using the center point XY values along the horizontal trajectories. Ultimate gas production values are shown, over Cherry Valley Vfast velocity, in Figure 6. Without production tests or other production data to determine the variability of production along the horizontal, bubble maps were displayed for the estimated mid-point of the horizontal. Clusters of data were analyzed for small subset areas (blue rectangles) of similar production in order to evaluate seismic attributes versus production. In map view, Figure 6 shows that the higher EUR pads are all within the lower velocity fairway (for the Cherry Valley interval) outlined by the red oval. It is hypothesized that the lower Interval Vfast velocities may be due to gas. Vertical variations in anisotropy in these subset areas were also analyzed. Seismic cross sections, including A-A’ and B-B’ shown in Figures 7 and 8 respectively show these variations.

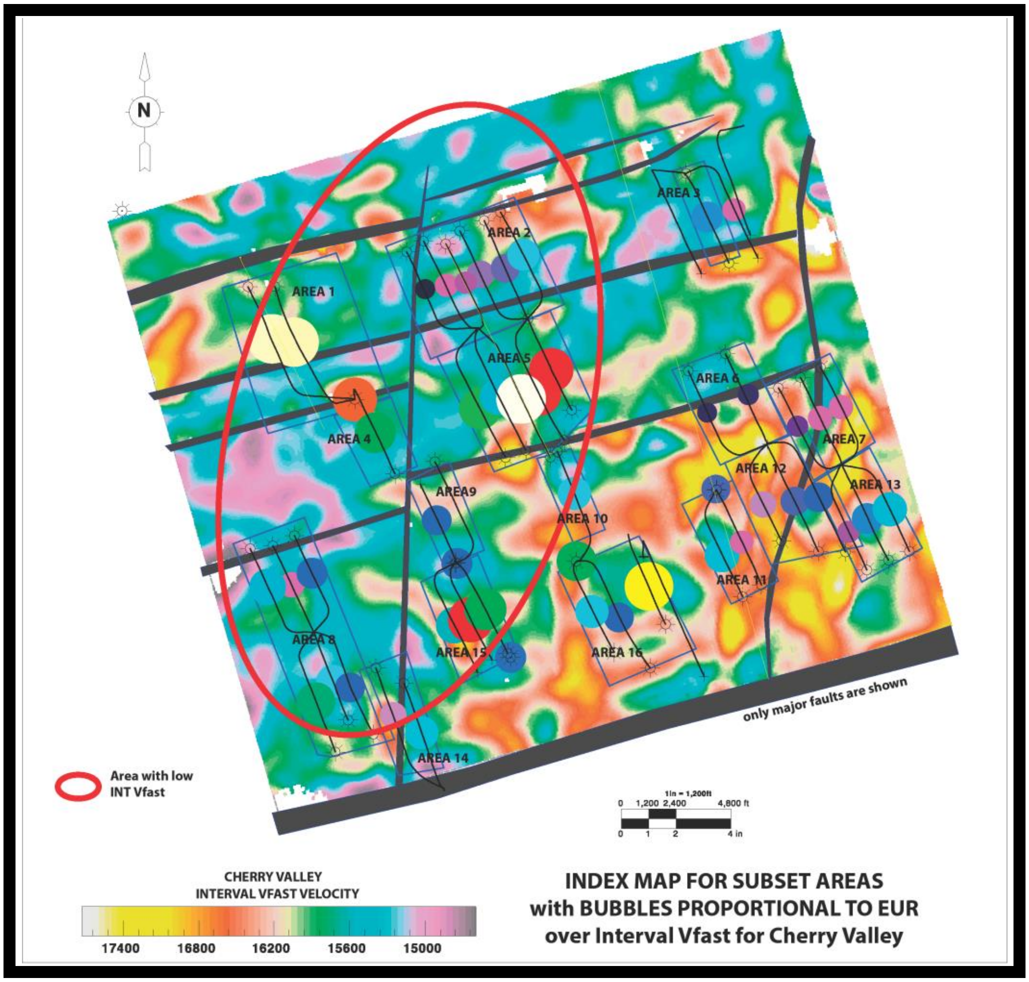
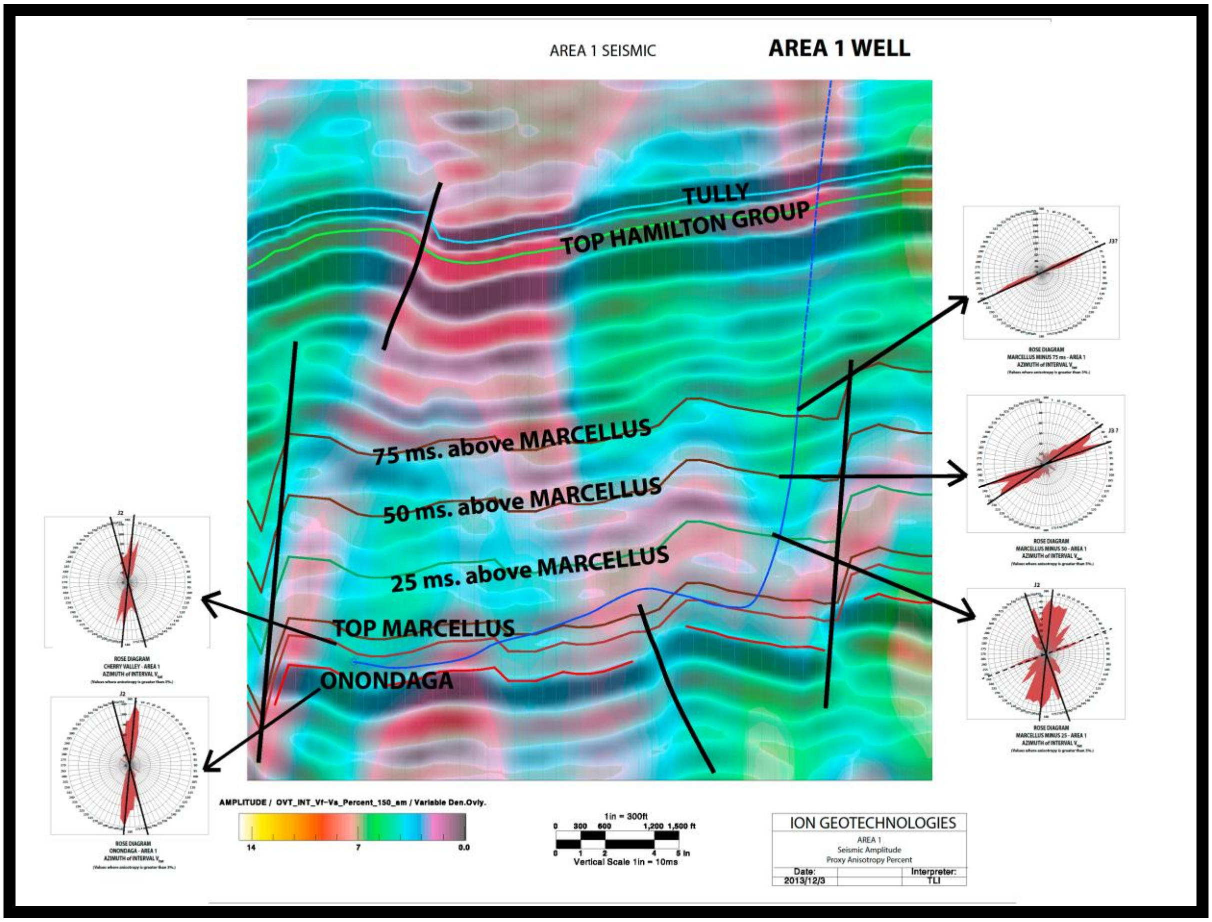


Figure 6: EUR production bubbles (size increasing with increasing EUR) is shown over the subset area index for the Analog 3D. Note that a swath of lower INT Vfast velocity, shown in orange oval, is associated with the area of higher production areas.

For Area 1, seismic cross section A-A’, shown in Figure 7, rose diagrams for the Onondaga, Cherry Valley, Top Marcellus and 25 ms. (~200 ft.) above the Marcellus show lower anisotropy overall and an azimuth of Vfast in the J2 direction. This area has the highest EURs and may be showing a strong influence from J2 joints above the Marcellus which we have attributed to more prolific gas generation, and higher TOC. From 50 ms. above the Marcellus and shallower intervals, the azimuth of Vfast shows an ENE trend, in the range of azimuths attributed to neotectonic J3 stresses or fractures.

Figure 7: This figure Illustrates the changes in azimuth that are seen for the Marcellus and intervals above the Marcellus in the High EUR Area 1 subset. While the Marcellus and 25 ms above the Marcellus show a J2 trend, 50ms and 75 ms above the Marcellus show the regional J3 trend. This NE trend is also seen in the Top Hamilton/Tully.

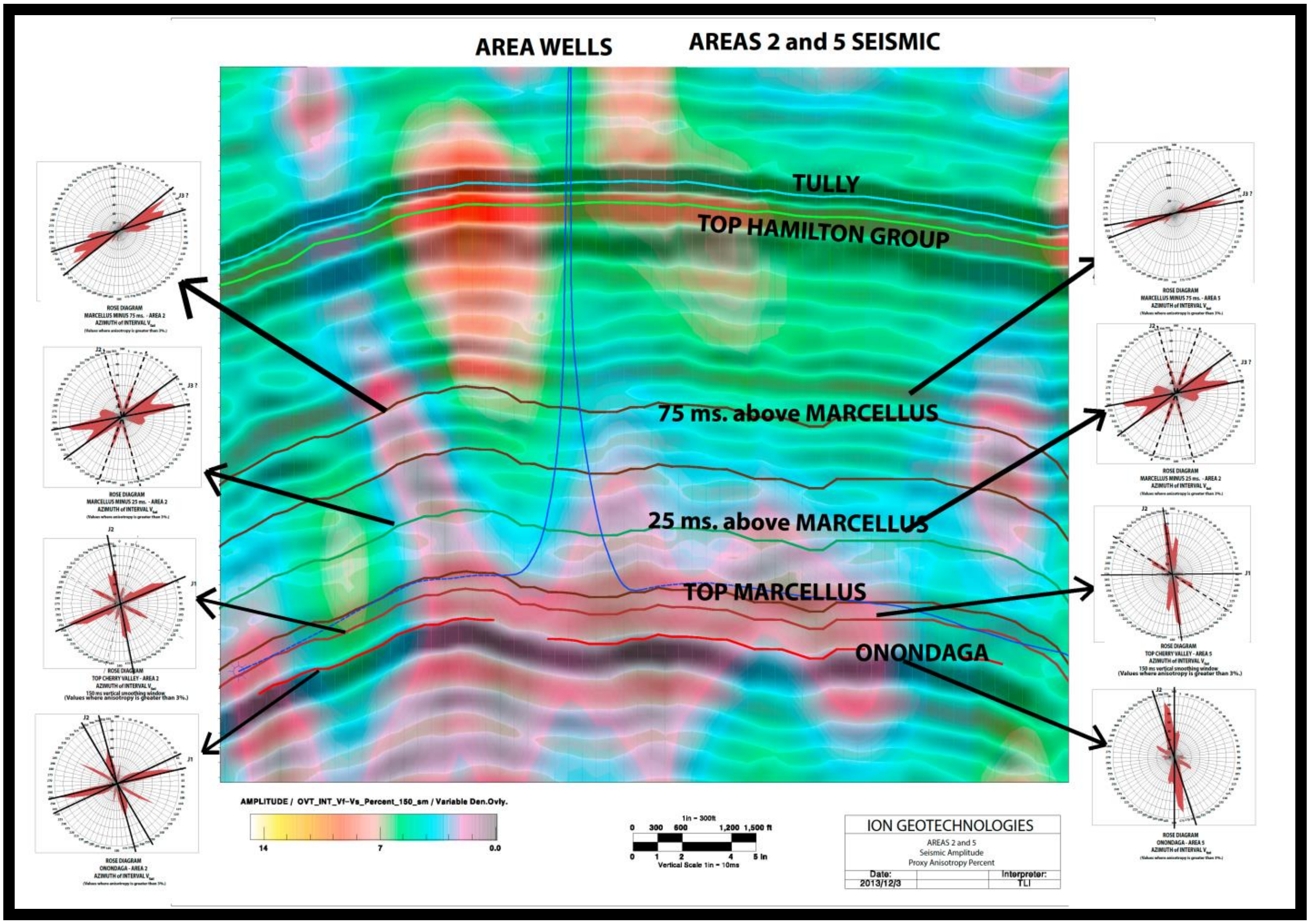
Seismic cross section B-B’, in Figure 8, shows Areas 2 and 5 in profile, and are low and high EUR respectively. Area 2, has mixed high and low velocities for the Cherry Valley, is quite close to two significant fault systems



which may have negatively affected production. The rose diagrams calculated for the Cherry Valley in Area 2 show dramatically different results than in Area 1. The low EUR area on the left side of the section shows a considerable amount of scatter in the azimuths with J1 or J3 dominant. There is a J2 component, but it is smaller than the J1 or J3 component. On the right, the higher EUR area (Area 5) shows a strong, nearly north-south, J2 trend with minimal indication of the J1 trend.

Figure 8: The lower EUR wells, to the left, show mixed azimuths for the Cherry Valley, moving to a J3 trend in the Hamilton group. The higher EUR wells, to the right, show a strong J2 azimuth for the Cherry Valley, with a small J2 trend remaining in the interval 25 ms. above the Top Marcellus. The shallower part of the Hamilton group and Tully consistently show a J3 trend. The upper part of the Hamilton group and Tully also display higher anisotropy than shown in the Marcellus for the higher EUR area on the left.

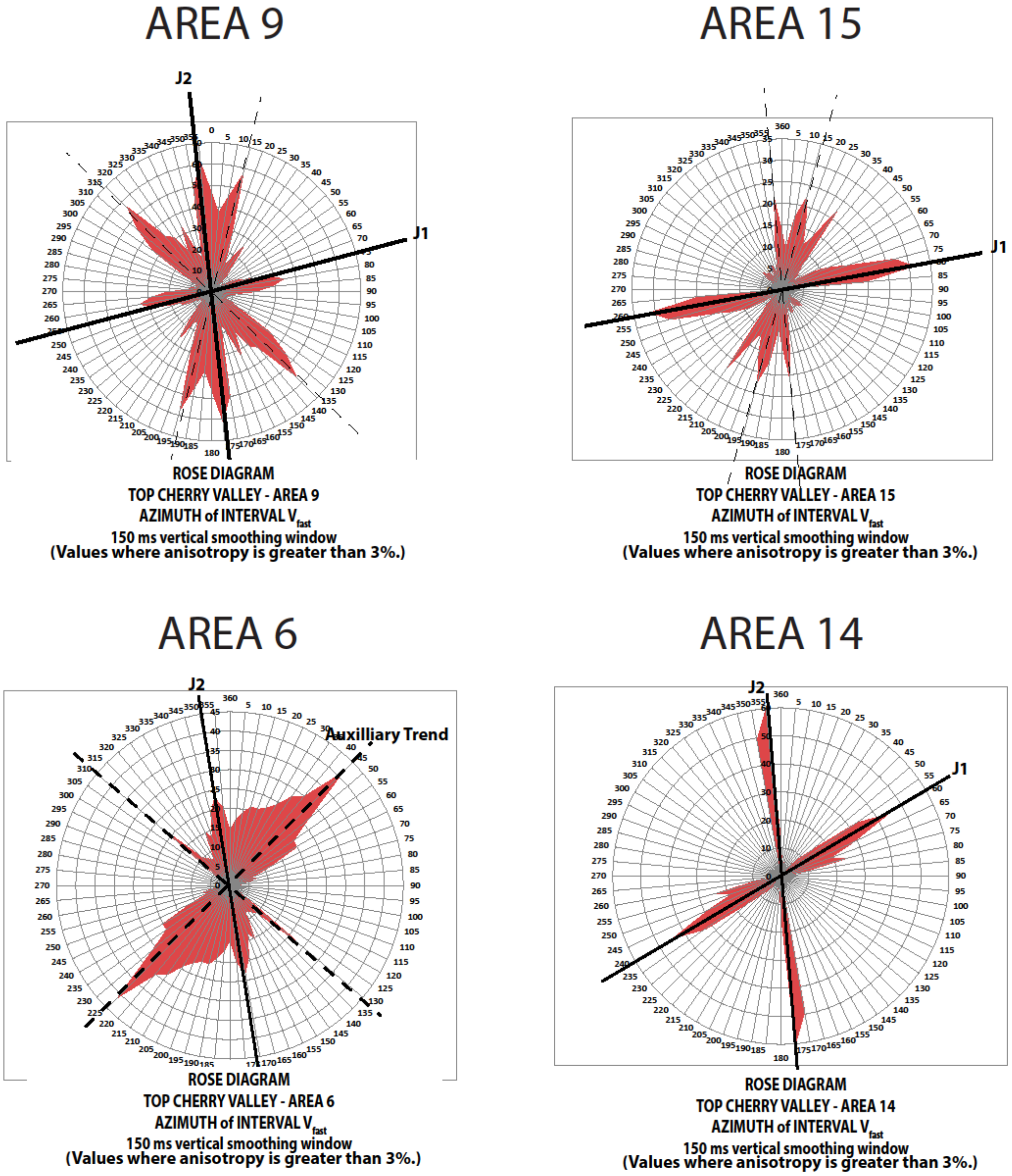
Figure 9 shows rose diagrams from several high EUR areas. These wells show a dominant J2 azimuth. This dominance of J2 shows that these joints or fractures have a significant contribution to production. In this analog area, where J2 is nearly perpendicular to the contemporary stress field ShMax, it would seem counterintuitive that J2 fractures would be open and contribute to production, however, closer examination of J2 fractures in core shows that these fractures have mineralization that act to prop open the joints or fractures. Figure 10 shows rose diagrams from two poor EUR areas. These rose diagrams show numerous azimuthal trends and a heterogeneity that is not seen in higher EUR areas. Although some of the areas show a smaller J2 trend, it is always subordinate to other trends including the J1 and J3 trend azimuths. Heterogeneity also appears to be a consistent characteristic of lower EUR areas, which have smaller areas with a consistent azimuth, and may also be adjacent to larger fault systems.
Other azimuths at N30E appear to be related to a young NNE to SSW trending fault system which dominates the eastern part of the survey. Areas with high gradient of azimuth and a high calculated Standard Deviation of anisotropy might also be considered areas that are more heterogeneous. There is a strong relationship between



higher EUR and lower anisotropy, as well as low heterogeneity, which is represented by the Standard Deviation of anisotropy across a subset area. In general the highest EUR areas have an Average Anisotropy less than 5%, with a Standard Deviation less than 1.5 in the analog area.

Figure 9: Rose diagrams generated for subset areas with High Decline Gas EUR consistently show a dominant J2 azimuth NNW to NNE in trend. Some minor trends may be indicated for a lower number of samples.

Figure 10: Rose diagrams generated for subset areas with Low Decline Gas EUR consistently show a scattered azimuths. Although the J2 trend may be present, the J1 trend may dominate. The scatter may be indicative of the heterogeniety of the area.



ROSE DIAGRAM
TOP CHERRY VALLEY - AREA 9
AZIMUTH of INTERVAL V_{fast}
150 ms vertical smoothing window
(Values where anisotropy is greater than 3%.)

ROSE DIAGRAM
TOP CHERRY VALLEY - AREA 15
AZIMUTH of INTERVAL V_{fast}
150 ms vertical smoothing window
(Values where anisotropy is greater than 3%.)

ROSE DIAGRAM
TOP CHERRY VALLEY - AREA 6
AZIMUTH of INTERVAL V_{fast}
150 ms vertical smoothing window
(Values where anisotropy is greater than 3%.)

ROSE DIAGRAM
TOP CHERRY VALLEY - AREA 14
AZIMUTH of INTERVAL V_{fast}
150 ms vertical smoothing window
(Values where anisotropy is greater than 3%.)

ROSE DIAGRAMS FOR LOW EUR AREAS
J2 Trend may be present, but other trends are shown as well.
There is often large scatter in azimuths.
J1 trend may be dominant over J2 trend.

Conclusions

This Analog study shows parameters that can be analyzed in order to evaluate undrilled areas of interest in the Marcellus play. Table 1 shows a summary, sorted by EUR, for the Analog 3D area, showing Interval Vfast – Vslow Percent as a proxy for anisotropy, the Standard Deviation of anisotropy as a proxy for heterogeneity, and the dominant azimuthal component for each subset area within the analog survey.

Area	EUR Area Averages (mcf)	Average Anisotropy	Standard Deviation of Average Anisotropy	Average Vfast (Velocity)	Dominant Azimuth Direction
Area 1	5139877	4.93	1.49	Low Vfast	J2
Area 4	3866946	4.09	0.92	Low Vfast	J2
Area 5	3827672	4.15	0.89	Low Vfast	J2
Area 12	3411334	4.76	1.41	Low Vfast	J2
Area 3	3231659	5.2	1.79	Medium Vfast	J2, small J1
Area 10	2596322	5.55	1.71	Medium Vfast	J2, J1
Area 11	2503742	4.63	1.24	Low Vfast	J2, small J1
Area 8	2386555	5.97	2.32	Low Vfast	NNE
Area 2	2214621	4.99	1.22	Medium Vfast	J1, J2, other
Area 13	2166376	5.75	2.05	Medium Vfast	J2, J1
Area 6	2028046	7.52	2.24	High Vfast	NNE, J2
Area 14	1935676	7.1	2.27	High Vfast	NNE
Area 7	1934443	8.55	3.1	High Vfast	J2
Area 15	1529289	5.91	3.85	Medium Vfast	J1, J2, other
Area 9	1207972	5.85	1.95	High Vfast	J1, J2
Area 16	1140093	7.81	2.28	High Vfast	J2, NNE, other

Table 1: Table is sorted in order of decreasing EUR. EUR's were calculated using data available from the State of PA website as of 4/18/2014. Note that, in general, the higher EUR wells have Average Anisotropy < 5%, a Standard Deviation of Anisotropy less than 1.5, Lower Vfast, and a dominant J2 Azimuth. Anisotropy, heterogeniety and velocity all increase for decreasing EUR, and azimuths become less organized with lower EUR for the Analog study.

In this study, we show that:

- Regional fracture trends inferred from seismic azimuths correlate with published joint/fracture trends and with World Stress Map trends.
- Vertical and lateral variation in azimuths can be seen at the reservoir level.
- There is a strong correlation between low anisotropy and low heterogeneity of anisotropy and high EUR. Generally, anisotropy of less than an average of 5% INT (Vf-Vs) Percent and a Standard Deviation of less than 1.5 are seen in the higher EUR subset areas. This relationship holds in spite of the lack of detailed production data.
- Reservoir characterization described in the literature for the fracturing or joints induced by gas generation, specifically the J2 trend described by Engelder and others, are supported by these analyses. J2 fractures which break into the grey shales above the Marcellus and other Devonian black shales, may give clues to the volume of gas generated and thus to TOC. It has been shown that J2 azimuthal trends which have been attributed to these joint/fracture trends persist above the Marcellus in areas that have higher EUR.

- Interpreted fracture trends differ between areas with larger decline EUR and areas with smaller decline EUR values. Some perforations are likely to perform much better than others along the borehole, based on observed heterogeneity in both vertical profiles and map view.
- Some fault and fracture trends appear to be related to late fault movement, and may adversely affect production.

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