Summary

Using a good quality northern Pennsylvania (PA) Analog 3D survey\(^1\), available well data, published outcrop data and subsurface information as well as production data available from the state, we are able to demonstrate that wide-azimuth seismic is sensitive to variations in fracturing at the scale of individual pads or even individual wells. This variation in fracturing begins to explain why production varies significantly, even locally, within the Marcellus play. Rose diagrams from quantitative fracture analysis using azimuthal seismic velocity volumes are compared to published data from Appalachian black shale outcrops and subsurface fracture models proposed in various papers in order 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 reflect rock fabric or stress, we show evidence that the likely source of these anisotropies is the presence of systematic joints.

Published data and azimuthal seismic attributes show two primary joint sets, the J1 set and a J2 set, as well as neotectonic J3 joints that affect the Marcellus and other Devonian shales in the Appalachian basin (Engelder et al., 2009.) Evidence suggests that in organic-rich Devonian black shale intervals including the Marcellus, both J1 and J2 joint sets formed in sediments at or near peak burial depth as a result of anomalous pressures generated during thermal maturation of organic matter (Lash et al., 2004.) While authors indicate that the ENE to WSW J1 joint set 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. The late cracking of oil to gas released much larger volumes of gas during the period when J2 joints propagated. Although neither contemporaneous with nor genetically related to folding, J1 and J2 joints in black shales within the Finger Lakes area of New York strike approximately parallel and perpendicular respectively to the Alleghanian orogenic fold axes exposed there. Similar patterns can be seen in seismic anisotropy for the Analog 3D survey and for the Clearfield 3D survey, to the west, in Clearfield County, Pennsylvania.

Rose diagrams from azimuthal attributes are similar to those measured for joints in outcrop in southern New York (Fillmore Glen State Park) and in Central Pennsylvania. The J2 azimuths dominate in areas with higher gas estimated ultimate recoveries (EUR) wells, which is attributed to more gas generation as well as longer joint length. High EUR areas also have generally lower “Interval V\text{fast} velocities” and show J2 joints well above the top of the Marcellus in Hamilton Group gray shales. Areas with low EUR wells have a more dominant J1 trend or no

\(^1\) This survey could be used with the caveat that the location and name of the survey are anonymous.
dominant trend, along with higher anisotropy, which suggests greater heterogeneity. The seismic velocity attributes show evidence of velocity anisotropy which could be attributed to fractures and are used to identify areas that may be more fractured. Areas showing high azimuthal gradients imply possible reservoir compartmentalization and heterogeneities that correspond with 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 = 656 ft), under relatively high sea level conditions (Kohl, et al., 2014). During the Middle Devonian, a micro-continent called Avalonia depressed the southeast 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 a depth favorable for oil and gas generation. The Marcellus, which is the oldest of the units in the Hamilton Group, consists of two major cycles of organic-rich shale accumulation, with the basal portion being particularly rich. The Marcellus and other middle Devonian black shales in the basin are limited in extent due to the tectonically controlled variations in relative sea level change. One model for the development of the richest black shale is a very rapid transgression possibly accompanying thrust loading with disrupted river systems, reducing sediment flux into the basin and 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 thus diluting the organic content of the 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, indicating improved oxygenation/circulation of a basin still receiving minimal clastic influx.

The axis of regional folding in the study area is dominantly ENE to WSW (parallel to J1,) primarily as a result of slip on a regional décollement beneath the Appalachian Plateau within the Silurian salt below the Marcellus (Davis and Engelder, 1985). Additionally, younger faults, especially NNE to SSW faults that appear to cut section above the Tully, a carbonate that caps the Hamilton Group, may allow gas to leak from the Marcellus reservoir. 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. For this reason most horizontal Marcellus wells are drilled to avoid the larger faults. In the Analog 3D survey area, wells have been drilled with laterals 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 seismic cross section oriented parallel to dip is shown in Figure 1, which displays the structural style of the project area within the Hamilton Group and adjacent formations. This line, also nearly parallel to most horizontal well trajectories, shows the variable thickness of the Silurian Salt below the Marcellus, which controls much of the larger scale structuring in this part of the Appalachian Basin. Thrust faults with a décollement in the salt, similar to faults shown in green, may be limited to the Marcellus and lower Hamilton group. Large faults, similar to the red faults, parallel to large folds related to salt deformation, are avoided when Marcellus wells are drilled. Young faults (not shown) are often parallel to dip. These faults have likely reactivated pre-existing zones of weakness, and have variable offset at the Onondaga and Marcellus. Some have significant 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 generated gas just prior to and during the Alleghanian Orogeny. These shale plays depend on fracturing to allow mobilization of the gas during stimulation, as they have low, poorly-connected, matrix porosity.
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 common mid-point (CMP) gather. As described by Tsvankin and Grechka (2011), applying a single value of normal move-out (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 Analog 3D project, Interval Vfast, Interval Vfast-Vslow Percent, and Interval Vfast Azimuth volumes revealed significant variations in subsurface trends and heterogeneities that have been correlated to production.

Horizontal Transverse Isotropy (HTI) processing corrects the time shifts remaining in gathers that are initially moved out with the best isotropic velocity. Those residual time shifts that are not corrected by the isotropic velocity are inverted to create Root Mean Square (RMS) velocity volumes, RMS Vfast and RMS Vslow. More delayed traces are those that traveled in the slow velocity direction, and less delayed traces traveled in 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 similar to an average value, as they represent the sum of anisotropies from the surface. Azimuthal
variations are 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 traveling perpendicular to the aligned system in an anisotropic 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 only useful if the percent anisotropy is calculated to be more than about 3%. If anisotropy is less than 3%, azimuthal values from these data are within the margin of error and should not be used to develop a proxy for anisotropy. If the difference between Vfast and Vslow is large, the “sinusoid” representing velocity variation with azimuth can be calculated with confidence. Then a proxy for anisotropy, defined by Vfast – Vslow percent greater than 3% can delineate the azimuth of Vfast 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 Vfast-Vslow percent (> 3% in this case) is a viable proxy for anisotropy. The azimuth of Vfast, in this case, is parallel to joints that cause anisotropy in the Marcellus.
Interval velocities are calculated from the RMS velocities using a modified form of the Dix Equation\(^2\) (Dix, 1955). This process effectively strips off shallow layers, removing near surface anisotropy. 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 user defined sliding window. 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. 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, we determined that unsmoothed volumes could still be used for analysis with production, where these anomalies can be avoided.

**Natural Hydraulic Fracturing and the Marcellus Play**

Natural fracture systems are essential for achieving the best production in Marcellus shale gas wells. Analysis of wide-azimuth P-wave seismic velocity attributes at the reservoir level, and for specific laterals or proposed laterals, to provide insight into these natural fracture systems in the subsurface. Published outcrop and core data and azimuthal seismic attributes all show two primary joint sets, the J1 set, and a J2 set, as well as a neo-tectonic J3 set of fractures that affect the Marcellus and other Devonian shales in the Appalachian basin.

For the Devonian black shale intervals, 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 (Lazacette and Engelder, 1992). The ENE J1 joints are more closely spaced, and best developed in the more organic-rich black shale units (Lash et al., 2004). While ENE joints (J1 joints) are less well developed outside the black shale intervals, joints (NW trending, J2 joints) that formed during the Alleghanian orogeny 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 fracturing of horizontal wells. The earlier J1 fracture set (ENE trending), that resulted from initial gas generation, is nearly parallel to the maximum compressive normal stress of the contemporary tectonic stress field, a coincidence.

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 (=305 m) or even as much as 4000 ft (=1219 m) 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 gray 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 Alleghanian in age and perpendicular to Alleghanian 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 simply because they are longer. 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 Analog 3D survey area to-date have been drilled in the NNW to SSE 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 ENE, parallel to J1, thus crosscutting and draining J2 joints. In spite of being perpendicular to present day maximum horizontal principal stress SHMax, J2 fractures are partially mineralized, which props open the fractures and allows them to contribute significantly to drainage of the Marcellus gas (Wilkins, et al., 2014).

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\(^2\) Mark Wallace, ION GXT, Personal communication.
Black shales in outcrops within the Finger Lakes area of New York, carry ENE J1 joints, and J2 joints approximately perpendicular to the Alleghanian fold axes exposed there (Lash et al., 2004) (Figure 4.) Similarly, azimuthal analyses for a seismic survey, west of the Analog 3D, in Clearfield County, show that J2 azimuths from subsurface seismic change orientation from NNW to WNW remaining perpendicular to the oroclinal fold. J1 azimuths in the Clearfield 3D survey are similar to those in the Analog 3D study area with an ENE trend similar but perhaps slightly more E-W than the present day stress direction SHMax. The systematic changing of J2 orientation from NNW to WNW shows that the azimuthal variations are not related to stress. Present day stress has been shown to remain consistent across Northern Pennsylvania (Engelder et al., 2008.) Unless the rock fabric shows linear variation, the small scale of the rock fabric would not be detectable at seismic scales, so the joints and fractures are the likely 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 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 compare to published outcrop data describing joint and fracture orientations in and above the Devonian black shale. These data may also 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 observations showing consistency with regard to azimuthal velocity attributes and EURs shown from decline curve analysis.

A map of northern Pennsylvania and southern New York (Fig. 4) shows rose diagrams from joint analysis of shales in the Finger Lakes area of New York, along with rose diagrams calculated from Interval Vfast azimuth for the middle Marcellus, Cherry Valley for the Analog 3D and the Clearfield 3D (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 (Fig. 4a) show an orientation perpendicular to the Alleghanian fold axes exposed in the Finger Lakes area (Lash et al., 2004). In these shales, the NW to SE and NNW to SSE J2 joints dominate. The fold axes continue south into Pennsylvania, and show a similar trend for the Marcellus Shale. The Analog 3D, Cherry Valley rose diagram (Fig. 4b, right) shows similar azimuthal trends, most like those on the eastern side of the Finger Lakes district. The Clearfield survey, a large survey that lies on the oroclinal fold belt for the Marcellus, shows a J2 azimuth (Fig. 4b, left) that changes orientation from NNW for the northern part of the survey (Clearfield Survey West) to WNW in the southern part of the survey (Clearfield Survey Southwest), staying more or less perpendicular to structure. The number of azimuth measurements used for the subsurface rose diagrams varied from about 50,000 for the Analog 3D, to 125,000 for the Clearfield Survey West. The spread in azimuths for the Clearfield survey, in part, is due to the larger number of samples, as well as the changing azimuths due to the changing orientation of the Marcellus fold axes.

Figure 4: This figure shows how a) outcrop measurements in Southern New York compare to b) subsurface anisotropy azimuths in Northern Pennsylvania. A similar trend for J2 azimuths with orientation perpendicular to the fold axis is 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 revised from Lash et al. (2004).
Outcrops of the Appalachian Valley and Ridge contain some J3 joint sets that correlate with stress orientation diagrams from the World Stress map (Hancock and Engelder, 1990) (Figure 5.) The Tully and Upper Hamilton Group, above the interval that is influenced by natural hydraulic fracturing, does not show J1 or J2 azimuths. The rose diagram calculated from the Top Hamilton azimuths in the Analog 3D, shown in blue on the right, matches this contemporary stress field trend, which is typically between 58 and 69 degrees east.

Figure 5: Shallow 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 Tully is ENE to WSW. Based on the previous regional work, this would put the the anisotropic proxy for fracturing or stress direction at about 65 degrees, which fits well within the range of 58 to 69 degrees NE which is attributed to the contemporary stress field. www.world-stress-map.org

For further analysis of these trends at the scale of a single pad, we summarize what has been observed so far on the regional scale. First, the older J1 trend, attributed to natural hydraulic fracturing, is shown to be in the range between 70 and 77 degrees (ENE) for both outcrop and subsurface data in the Analog 3D 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 Alleghanian folds, and generally trends NNW in the Analog survey. The younger J3 trend is shown to be between 58 and 69 degrees (NE), slightly more north of east than the J1 trend in this area. The NE azimuths captured in the shallower Tully interval on the Analog 3D survey match very well with World Stress Map trends shown in Fig. 5. The Tully is well above any likely influence from J1 and J2 natural hydraulic fractures or joints originating in the Marcellus shale.
Initially, the azimuth of Interval Vfast was extracted for three horizons (instantaneous amplitude of Interval Vfast Azimuth), the Top Hamilton, the Top Marcellus and the Cherry Valley. Values for azimuthal analysis 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. 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 shown in our subsurface model (Fig. 3). Areas with low EUR wells show a more dominant J1 trend, with limited influence from J2, perhaps because the joints are shorter where less gas is generated.

Gas EUR from Decline Curve Forecasts

Decline curve analysis is a reservoir engineering empirical technique that extrapolates trends in production data. The most commonly used trending equations are those first documented by J.J. Arps (1945) who was an American geologist that published mathematical relationships for the rate at which production from a single well declines over time. The gas EUR assumed an economic limit when the forecasted gas rate fell below 20 Mscf/day. The economic limit is the point in time at which the production is assumed to cease because it is no longer economic. The EUR was determined by adding the cumulative historical production with the forecasted cumulative production to the economic limit. Publicly available data for historic well production for the Marcellus wells in this study were available from the state of Pennsylvania for 6-month intervals thru December 2013. To obtain a conservative monthly production rate for decline curve forecasting, the 6 month historic production data was divided equally among the preceding 6 months creating a stair step profile. Decline curve forecasts were made assuming hyperbolic decline converted to exponential decline when the instantaneous decline rate reached 10% per year. An example decline curve for a well in the Analog 3D survey is shown in Figure 6.

Figure 6: Example gas historic stair step production rate profile on 6-month intervals with hyperbolic and exponential decline curve rate forecasts to a 20 Mscf/day economic limit to obtain EUR for a well in the Analog 3D survey.
EUR Comparisons with Seismic Attributes

EUR values for wells in the project were used to create a bubble map with bubbles located at the mid-point of the horizontal well trajectory. EUR values are co-rendered with Cherry Valley Vfast velocity, shown in Figure 7. No production tests or other production data was available to determine the variability of production along the length of the horizontal well. Clusters of data were analyzed for 16 small subset areas (blue rectangles) of similar EUR, in order to correlate with seismic attributes. In map view, Fig. 7 shows that the higher EUR pads are all within the lower velocity fairway (for amplitude extraction on the Top Cherry Valley horizon) outlined by the red oval. It is hypothesized that the lower Interval Vfast velocities may be due to the presence of gas and/or pervasive fracturing. Vertical variations in anisotropy in these subset areas were also analyzed. Seismic cross sections A-A’ and B-B’, shown in Fig. 7 for subset Area 1 and subset Areas 2 & 5, (Figures 8 and 9) show these variations.

![Figure 7: 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 Interval Vfast velocity, shown within the red oval, is associated with the area of higher EURs. Bubble size is proportional to EUR.](image-url)
For Area 1, seismic cross section A-A’ (Fig. 8), rose diagrams for the Onondaga, Cherry Valley, Marcellus and 25 milliseconds (ms) (~61m = 200 ft) above the Marcellus show lower anisotropy overall and an azimuth of Vfast in the J2 direction. Fig. 7 shows that the Interval Vfast velocity of this area is generally low. Area 1 has the highest decline gas EURs and may be showing a strong influence from J2 joints above the Marcellus which have been attributed to more prolific gas generation, and higher TOC. From 50 ms above the Marcellus and shallower intervals, the azimuth of Vfast shows a NE trend, which is in the range of azimuths attributed to younger J3 stresses or fractures.

Areas 2 and 5, shown in seismic cross section B-B’ (Fig. 9), have low and high EURs respectively. Area 2 has mixed high and low velocities (instantaneous amplitude extraction calculated from Interval Vfast for the Cherry Valley) and is quite close to two significant fault systems which may have negatively affected production. The rose diagrams calculated for the Interval Vfast Azimuth at 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 for the Marcellus and other intervals. There is a J2 component, but it is smaller than the J1 or J3 component. The higher EUR area on the right (Area 5) shows a strong, nearly north-south, J2 trend for the Marcellus with minimal indication of the J1 trend.
Figure 9: The lower EUR wells on the left show mixed azimuths for the Cherry Valley, changing to a J3 trend in the Hamilton group. The higher EUR wells on the right show a strong J2 azimuth for the Cherry Valley, with a minor 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 10 shows rose diagrams from several high EUR areas. These wells show a dominant J2 azimuth. This dominance of J2 suggests that these joints or fractures contribute significantly to production. In this analog area, where J2 is nearly perpendicular to the contemporary stress field SHMax, it may seem counterintuitive that J2 fractures would be open and contribute to production; however, closer examination of J2 fractures in core\(^3\) shows that these fractures are mineralized. Mineralization may act to prop open the joints or fractures and preserve porosity and permeability with the fracture. Figure 11 shows rose diagrams from two low EUR areas. These rose diagrams show numerous azimuthal trends and a high degree of heterogeneity that is not seen in higher EUR areas. Although some of the areas show a smaller (lower count) J2 trend, it is always subordinate to other trends including the J1 and J3 trend azimuths. A greater degree of 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 azimuthal gradient (a high rate of change in 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 3D area.

\(^3\) Scott Wilkens, personal communication, AAPG 2014 (reference) poster session.
Figure 10: Rose diagrams generated for subset areas with high decline curve 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 11: Rose diagrams generated for subset areas with low decline curve 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 heterogeneity of the area.

Discussion

In Devonian shales, a strong relationship between azimuths derived from seismic anisotropy attributes and those azimuths calculated from joints in outcrop suggest that these seismic attributes are a valuable tool for subsurface analysis of joints and fractures. Furthermore, variability in seismic anisotropy, heterogeneity, azimuth and velocity...
along individual well trajectories indicate that the relationship between these attributes and production are predictable despite their complexity. We have demonstrated that when a predominance of NNW (i.e. J2) azimuths are indicated by seismic anisotropy, along with lower velocity, lower heterogeneity and lower anisotropy, higher EURs are demonstrated for the Analog 3D area. These attributes can be used as a tool for high-grading Marcellus drilling, and for better perforation and frac planning. Potentially lower EUR areas, with more seismic heterogeneity, higher anisotropy and mixed azimuths, may be scheduled for drilling after better locations are completed. Areas with dominant J2 azimuths that are oriented more E-W, for example in the southern part of the Clearfield 3D survey (Fig. 4), where J1 and J2 joints are more oblique, may point to necessary adjustments in well trajectories for optimal drainage.

The area of our Analog 3D seismic survey is of such a limited size (approx. 49 km² = about 30 mi²) that we presume that thermal maturation was uniform within the Marcellus and did not cause pockets of higher gas content. Certainly the variation of fracture complexity is spaced at a much smaller interval and in a much more complex pattern than variations in either depositional patterns or thermal trends permit. These observations lead to the conclusion that complex patterns in productivity have another cause, maybe local variation in TOC. However, the correlation between more complex fracturing as indicated by a heterogeneity in azimuthal trends for anisotropy and low EUR suggest that over the period since maturation during the Permian there has been slow leakage of gas on a local scale and that the presence of a complex joint pattern was responsible. A single systematic joint set (i.e., J2) is not interconnected so the bulk permeability of the immediate Marcellus approaches matrix permeability (Hubbert, 1957). If these joints are partially mineralized and have a very high permeability, they still can’t leak unless interconnected (Pommer et al., 2013).

The most direct evidence that the Marcellus has leaked over geological time is the presence of mineralization of some, but not all J2 joints (Evans, 1995; Evans et al., 2012). Unfilled and mineralized J2 joints are found side-by-side in both outcrops and core (Engelder et al., 2009; Evans, 1994). By the time of propagation of J2 joints, both unfilled and mineralized, dewatering by compaction and maturation had reduced the water saturation of the Marcellus to an irreducible state (Lash et al., 2004). The coexistence of unfilled and mineralized joints indicates that capillary forces in a gas charged section prevented pervasive penetration of formation water when it invaded from deeper, more porous and permeable beds like the Oriskany Sandstone. Invasion of water from below is indicated by the presence of the mineralized J2 joints. It is likely that the combination of unfilled and mineralized J2 joints provides for the prolific gas production seen in the Marcellus.

Slow leakage through a complex system of multiple cross-cutting fractures does not necessarily signal a rock volume that will rapidly leak stimulation fluid as implied by some in the literature (Warner et al., 2012). For example, the J2 joints are more likely to have grown out of the Marcellus and into overlying rocks (Engelder et al., 2009). Yet, these are the joints that seemed to have been ‘sealed’ most effectively since early generation. Likewise, there is no indication that the less economic wells in the study area have completely leaked as indicated by a robust flow-back drive by high pressure gas. This means that a relatively effective capillary seal was maintained within the vicinity of the Marcellus since the Permian despite a complex fracture pattern (Cathles, 2001). This is true even for those wells relatively close to the zone of cross-formation faulting (Fig. 1). Perhaps the effective capillary seal might have formed as high in the section as the Tully Limestone. There is no indication of a complete pressure breach through the Tully, even where there is a major disruption of bedding on the seismic scale.

**Conclusions**

The Analog 3D study shows seismic attributes that can be analyzed in order to evaluate undrilled areas of interest in the Marcellus play. **Table 1** shows a summary, sorted by decreasing EUR, for the Analog 3D area, comparing Interval Vfast – Vslow Percent as a proxy for anisotropy, the standard deviation of anisotropy as a proxy for heterogeneity, and the dominant azimuthal component relative to EUR for each subset area within the Analog 3D survey.

In this study, we show that:

- 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% Interval (Vfast-Vslow) 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 along the horizontal lateral length.

- Interpreted fracture trends differ between areas with larger decline curve gas EUR and areas with smaller EUR values. Some perforations are likely to perform much better than others along the borehole, based on observed heterogeneity in both seismic profiles and map view.
- Regional fracture trends inferred from seismic azimuths correlate with published joint/fracture trends measured in outcrop and with World Stress Map trends.
- Vertical and lateral variation in azimuths can be delineated by calculating rose diagrams from seismic azimuthal attributes for the reservoir Marcellus and intervals above the Marcellus.
- Reservoir characterization described in the literature for the fracturing or joints induced by gas generation, specifically the J2 trend described by Engelder, Lash and other authors, are supported by these analyses. J2 fractures which break into the gray shales above the Marcellus and other Devonian black shales, may give clues to the volume of gas generated and thus to the 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.
- Some fault and fracture trends appear to be related to recent fault movement, and may adversely affect production.

<table>
<thead>
<tr>
<th>Area</th>
<th>EUR Area Averages (mcf)</th>
<th>Average Anisotropy</th>
<th>Standard Deviation of Average Anisotropy</th>
<th>Average Vf1st (Velocity)</th>
<th>Dominant Azimuth Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area 1</td>
<td>5.14</td>
<td>4.93</td>
<td>1.49</td>
<td>Low Vf1st</td>
<td>J2</td>
</tr>
<tr>
<td>Area 6</td>
<td>4.27</td>
<td>4.76</td>
<td>1.41</td>
<td>Low Vf1st</td>
<td>J2</td>
</tr>
<tr>
<td>Area 4</td>
<td>3.83</td>
<td>4.15</td>
<td>0.89</td>
<td>Low Vf1st</td>
<td>J2</td>
</tr>
<tr>
<td>Area 15</td>
<td>3.45</td>
<td>5.19</td>
<td>1.79</td>
<td>Low Vf1st, J2, J1</td>
<td></td>
</tr>
<tr>
<td>Area 10</td>
<td>2.6</td>
<td>5.55</td>
<td>1.71</td>
<td>Medium Vf1st, J2, J1</td>
<td></td>
</tr>
<tr>
<td>Area 8</td>
<td>2.49</td>
<td>4.63</td>
<td>1.24</td>
<td>Low Vf1st, J2, small J1</td>
<td></td>
</tr>
<tr>
<td>Area 16</td>
<td>2.4</td>
<td>5.2</td>
<td>1.79</td>
<td>Medium Vf1st, J2, small J1</td>
<td></td>
</tr>
<tr>
<td>Area 3</td>
<td>2.39</td>
<td>5.97</td>
<td>2.32</td>
<td>Low Vf1st, NNE</td>
<td></td>
</tr>
<tr>
<td>Area 9</td>
<td>2.21</td>
<td>4.99</td>
<td>1.22</td>
<td>Medium Vf1st, J1, J2, other</td>
<td></td>
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<tr>
<td>Area 14</td>
<td>2.17</td>
<td>5.75</td>
<td>2.05</td>
<td>High Vf1st, J2, J1</td>
<td></td>
</tr>
<tr>
<td>Area 13</td>
<td>2.03</td>
<td>7.52</td>
<td>2.24</td>
<td>High Vf1st, NNE, J2</td>
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<tr>
<td>Area 12</td>
<td>1.93</td>
<td>7.1</td>
<td>2.27</td>
<td>High Vf1st, NNE</td>
<td></td>
</tr>
<tr>
<td>Area 11</td>
<td>1.93</td>
<td>8.55</td>
<td>3.1</td>
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<td>Area 7</td>
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<td>7.81</td>
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<td>High Vf1st, J2, NNE, other</td>
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<tr>
<td>Area 2</td>
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<td>5.91</td>
<td>3.85</td>
<td>Medium Vf1st, J1, J2, other</td>
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<tr>
<td>Area 6</td>
<td>0.72</td>
<td>5.85</td>
<td>1.95</td>
<td>High Vf1st, J1, J2</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Table is sorted in order of decreasing EUR. EURs were calculated using data available from the State of PA website with production thru 12/31/2013. Note that, in general, the higher EUR wells have Average Anisotropy < 5%, a standard deviation of Anisotropy < 1.5%, Lower Vf1st, and a dominant J2 Azimuth. Anisotropy, heterogeneity and velocity all increase for decreasing EUR, and azimuths become less organized with lower EUR for the Analog 3D study.
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We thank Brian W. Horn and Stefano Volteranni at ION Geoventures for their support of this paper and ION GXT for permission to present and publish this paper. Also, thank you to Mark Wallace, ION GXT and Katie Joe McDonough for their help on various technical issues. Finally, the authors thank IS Interpretation Services, Inc., the Department of Geosciences, Pennsylvania State University and Solutions Engineering for permission to publish this paper.

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About the Authors

TANYA INKS, has been providing integrated geophysical and geologic consulting services in Denver, Colorado since 1993. She holds B.S. and M.S. degrees in Geophysical Engineering from the Colorado School of Mines. Ms. Inks is currently involved with projects in several unconventional plays including the Marcellus Shale play and the Niobrara play. She worked as a processor for Geophysical Service, Inc. and CGG prior to graduate school, and worked for Mobil Exploration and Producing US Inc. in Rocky Mountain and Gulf of Mexico Exploration for the first six years following graduate school. Since 1993, she has consulted for many clients, initially as manager of Vector Interpretation Services and later (1998) as a partner in IS Interpretation Services, Inc. In addition to her work in the Marcellus, she has contributed geoscientific expertise to both exploration and field development projects in structurally and stratigraphically complex areas such as the Bearpaw uplift and Disturbed Belt in Montana, The Greater Green River, Wind River and Big Horn Basins of Wyoming, Utah’s Uinta Basin, the North Slope of Alaska, California’s Sacramento and San Joaquin Basins, Oklahoma’s Arkoma Basin, as well as international projects in Columbia’s thrust belt, Chile’s Fell Block and Venezuela’s thrust belt. Ms. Inks is a longtime member of the SEG, AAPG, DGS and RMAG.

TERRY ENGELDER, a leading authority on the recent Marcellus gas shale play, holds degrees from Penn State B.S. ('68), Yale M.S. ('72) and Texas A&M, Ph.D. ('73). He is currently a Professor of Geosciences at Penn State and has previously served on the staffs of the US Geological Survey, Texaco, and Columbia University. Short-term academic appointments include those of Visiting Professor at Graz University in Austria and Visiting Professor at the University of Perugia in Italy. Other academic distinctions include a Fulbright Senior Fellowship in Australia, Penn State’s Wilson Distinguished Teaching Award, membership in a US earth science delegation to visit the Soviet Union immediately following Nixon-Brezhnev détente, and the singular honor of helping Walter Alvarez collect the samples that led to the famous theory for dinosaur extinction by large meteorite impact. He has written 160 research papers, many focused on Appalachia, and a book, the research monograph "Stress Regimes in the Lithosphere". In the international arena, he has worked on exploration and production problems with companies including Saudi Aramco, Royal Dutch Shell, Total, Agip, and Petrobras. In 2011 he was named to the Foreign Policy Magazine’s list of Top 100 Global Thinkers.

BRUCE GOLOB is a geophysicist with ION-GXT in Denver, Colorado and works as a seismic inversion specialist, well integration and processing QC resource. Bruce also assists clients in interpreting azimuthal anisotropy volumes produced from wide-azimuth seismic. Before joining ION-GXT, Bruce worked in Denver interpreting 3D seismic for an independent oil and gas company in the US mid-continent. Bruce was originally hired and trained by Amoco – working for 18 years within a team of geoscientists and engineers, generating economic drilling prospects worldwide, his last five years with the company working in Cairo, Egypt as Senior Consulting Geophysicist. Mr. Golob earned a B.S. in geophysics from Bowling Green State University and a M.S. in Information Technology (dual major in database design and object-oriented programming) at Regis University. He is currently a member of SEG, AAPG, DGS and RMAG.

JACKI HOCUM is a Senior Processing Geophysicist at ION GXT in Oklahoma City, and has over 30 years of experience working in the seismic industry. Jacki has a bachelor’s degree in mathematics from Arkansas State University, and after a brief stint as a high school teacher, she began her geophysics career in 1981 at Western Geophysical where she processed on- and off-
shore and transition zone data from around the world, including North America, South America, the Gulf Coast, Alaska, and North Africa. As a group leader with Western, she was instrumental in training new processors. Before joining GXT in 2009, she spent 10 years with ECHO Geophysical where her role as a seismic processor expanded to include customer support and technical marketing. Since becoming part of the GXT team, Jacki has concentrated on North American processing, with emphasis on Niobrara and Marcellus plays. She is a member of DGS and GSOKC.

DARIEN G. O'BRIEN, P.E., MBA, is Director of Engineering with Solutions Engineering in Lakewood, Colorado. Mr. O'Brien's technical expertise is in domestic and international reservoir engineering, drilling and work-over assessments, reserves and economic evaluations, reservoir modeling, environmental issues and technology development. Mr. O'Brien has evaluated numerous oil and gas opportunities throughout the country, ultimately making significant acquisition and divestiture recommendations. He has prepared independent proved, probable, possible reserve reports for banks and investment groups and worked with the U.S. Securities and Exchange Commission to obtain sanction for proved resources in emerging exploration and resource development plays. Mr. O'Brien earned a B.S. in Petroleum Engineering from the Colorado School of Mines and a MBA from the University of Alaska. He has been an active SPE member throughout his career, serving as Continuing Education Chairman for the Denver Section, SPE Distinguished Lecturer, Chairman of SPE's International Continuing Education Committee and recipient of SPE's Regional Service Award. Mr. O'Brien is a member of the Petroleum Technology Transfer Council’s National Board of Directors, Society of Petroleum Evaluation Engineers and the National Society of Professional Engineers. Mr. O'Brien is a registered Professional Engineer in Colorado, Wyoming and California.