Multicomponent seismic data analysis for interval rock properties in the Marcellus Shale

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ABSTRACT

The Devonian Appalachian Basin in the Northeast United States holds vast reserves of hydrocarbons. The Marcellus Formation is a black shale that contains one of the world's largest unconventional tight gas plays. In this paper, a three component 3D seismic dataset acquired in Northeast Pennsylvania, near the New York border, is used to analyze the Marcellus Formation. A general seismic interpretation and a more specific interval rock property analysis is performed. The mildly dipping, East-West trending thrust fault structure in the Marcellus and surrounding formations is explained. Interval V_p/V_s ratios are found for several of the important intervals in the Appalachian Basin, and potential sweet spots for hydrocarbon generation are speculated. A correlation between anisotropy and high V_p/V_s ratio was found.

INTRODUCTION

The Marcellus Shale is growing unconventional resource play in the Appalachian Basin, located in the northeast United States. The Marcellus Formation covers and area greater than 100 000 square miles (259 000 km^2). The United States Department of Energy estimates a technically recoverable resource of 140 500 TCF, the production trend from the Marcellus Shale is shown in figure 1. The production to the beginning of 2013 was just under 8 BCF/day.

The Marcellus Formation is a low porosity, low permeability natural gas bearing shale. The hydrocarbons are only economically produced using modern hydraulic fracturing techniques. A multicomponent 3D seismic dataset was provided by Geokinetics for use in this project. Multicomponent seismic is valuable in understanding unconventional reservoirs and several rock physics parameters can be estimated from the dataset. Important rock physics parameters in tight gas reservoirs include: porosity, lithology, permeability, anisotropy, pore fluids, elastic parameters and permeability. Understand these parameters can reduce drilling risk and allow for increased economic production in resource plays.

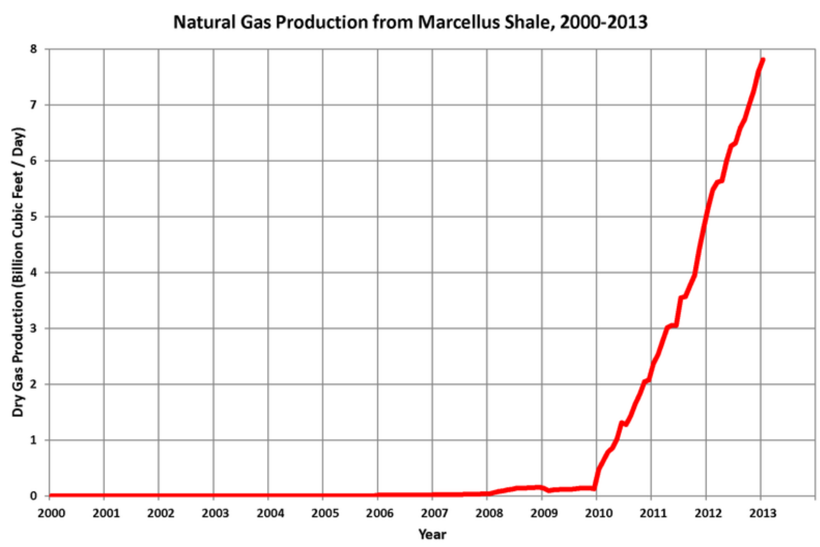

FIG. 1. Gas production from the Marcellus Shale. (Plazak 2013)

Geological setting

The Marcellus shale was deposited in the Middle Devonian in the Appalachian Basin. Figure 2 depicts a paleo-geographical representation of the North American continent in the Middle Devonian, at approximately the time of deposition of the Marcellus Fm. The Appalachian Basin in the Middle Devonian, based on the paleogeography, is a marine depositional system. The lithology of the Marcellus is dominantly black shale, deposited in relatively deep water in an anoxic environment. There are also lighter shales and limestone beds in the Marcellus. The sedimentation of these secondary lithologies arose from slight sea level variations in the Devonian. The genetic origin of the black shale Marcellus sediments were erosive clastics from the Appalachian Orogeny. The TOC (total organic carbon) in the Marcellus Formation ranges from 1% to 11%. Hydrocarbon generation usually requires a minimum source rock TOC of 2%, hence the Marcellus has adequate organic carbon content to generate hydrocarbons. A cross section of the Devonian strata in the Eastern United States is shown in figure 3, the study area is approximately at the Pennsylvania/New York border on the right side of the cross section. Figure 4 shows an isopach of the Marcellus Shale. The formation ranges from 0 to over 350 feet in the Northeastern United States.

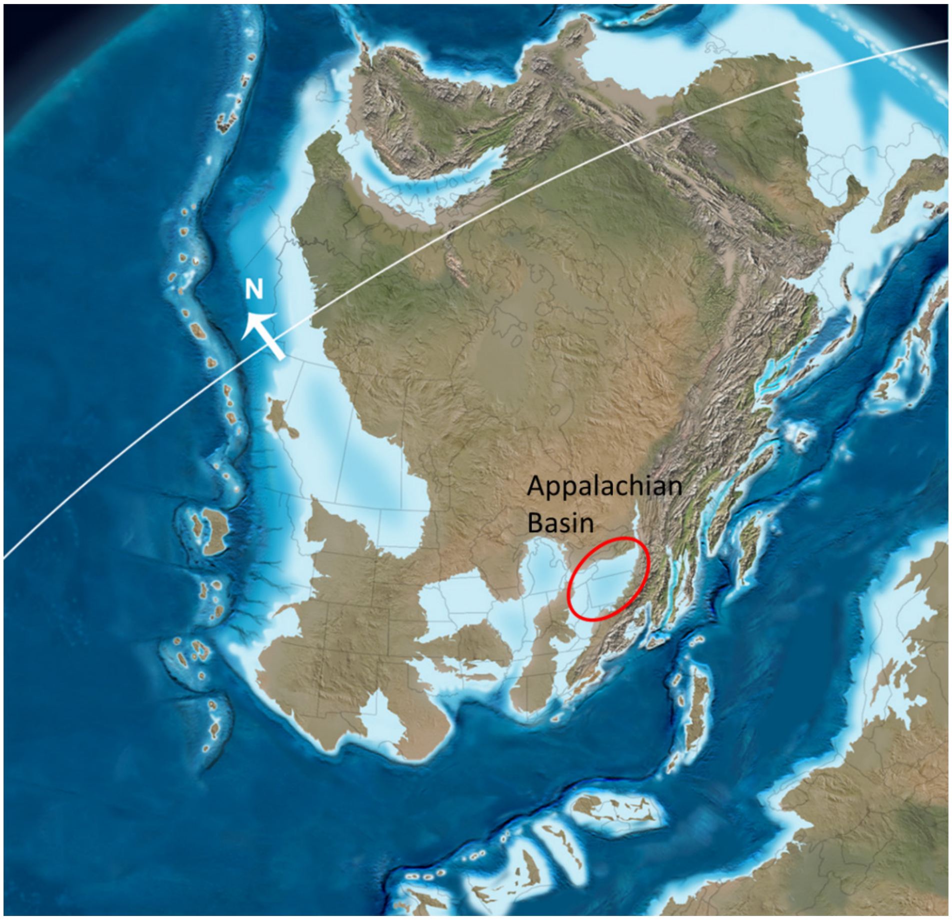

FIG. 2. Paleogeography of the North American Continent in the Middle Devonian. The location of the Appalachian Basin annotated in red. (Modified from Blakey 2011)

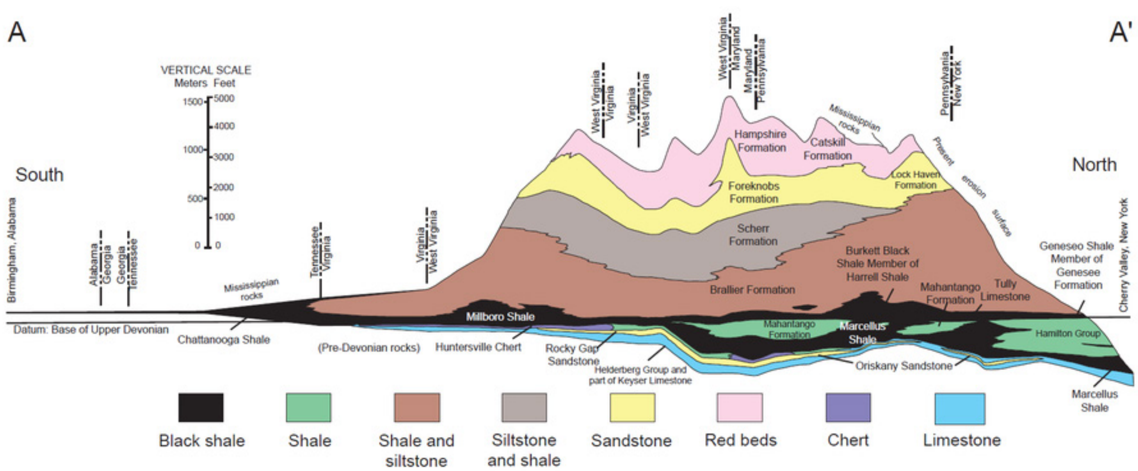

FIG. 3. Geologic cross section from South to North of the Devonian strata in the Appalachian Basin. (Boughton and McCoy 2006)

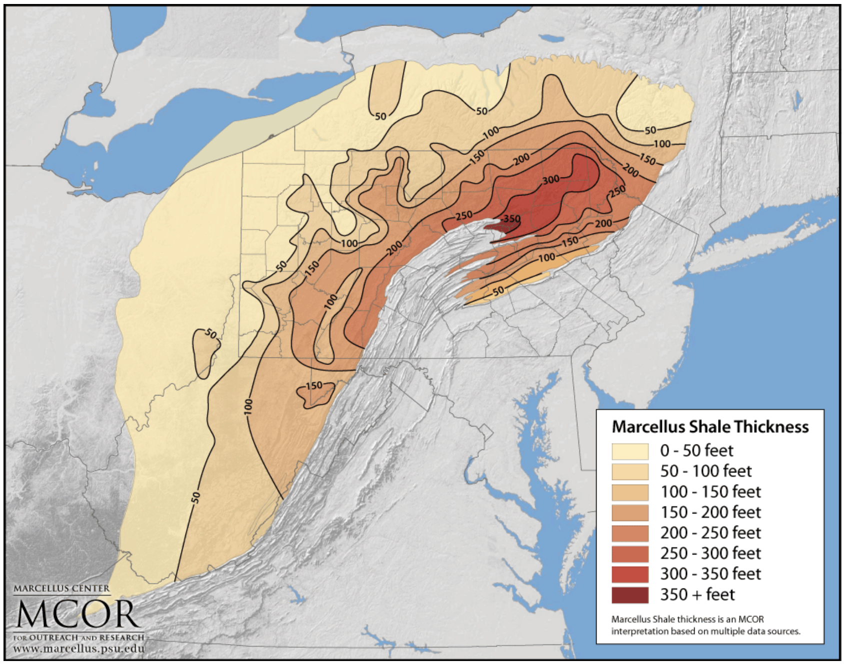

FIG. 4. Marcellus shale isopach, the project area is annotated in red. (Modified from Marcellus Center for Outreach and Research (accessed April 6 2015))

The Bradford 3D-3C seismic survey

A three component 3D seismic dataset acquired in Bradford Country in Northeast Pennsylvania will be utilized for understanding the rock physics parameters and geology of the Marcellus shale in a hydrocarbon exploration context. The seismic dataset covers an area of approximately 9 square miles (24 km2) and is a 3 by 3.1 mile rectangle oriented orthogonally to the Appalachian Mountain range. That is, the inlines and crosslines of the 3D dataset are oriented Southeast-Northwest and Southwest-Northeast. Total record length for the seismic was 4 seconds, using a 2 ms sample rate. The line and trace spacing of 110 feet (33.5 m) was used in the acquisition. Figure 5 shows the project area. The seismic data lies in a region where the Marcellus shale is relatively thick, and is currently producing natural gas. A sample line for the PP, PS1 and PS2 data is provided in figures 6, 7 and 8. The sample line in figures 6, 7 and 8 run Northwest to Southeast in the center of the 3D. The dominant frequencies in the interval of interest for the three volumes are: 5-50 Hz for the PP seismic data, 10-40 Hz for the PS1 shear seismic data and 10-35 Hz for the PS2 shear seismic data. These frequency ranges are conducive to high quality converted wave seismic interpretation and will provide adequate resolution for understanding the tight unconventional gas reservoir in the Marcellus Formation.

The PP seismic data processing flow will be outline in this section. From the vertical component recording, first arrival picks were made and refraction statics corrections were made. Spherical divergence corrections and surface consistent scaling attempt to recover amplitudes. Surface consistent deconvolution was performed to enhance frequency content. Two passes of both velocity analysis and residual statics were followed by prestack Kirchhoff migration velocity analysis and a prestack Kirchhoff migration. A final residual velocity analysis was performed, and finally data was stacked and filtered.

Processing of converted wave seismic data follows a very similar flow to the PP data processing with in the inclusion a number of shear wave specific processing steps. Following the refraction statics calculations and corrections, the data is rotated to radial and transverse coordinates. The fast (S1) and slow (S2) shear axes are determined and the data is rotated into the coordinate system of fast and slow shear components. Amplitude corrections for the converted wave data follow the same algorithms as the PP seismic data. Instead of conventional velocity analysis, two passes of Vp/Vs analysis was used. Otherwise the processing of the converted wave seismic data follows the same flow as the compressional wave data.

FIG. 5. The project area near the Pennsylvania/New York border.

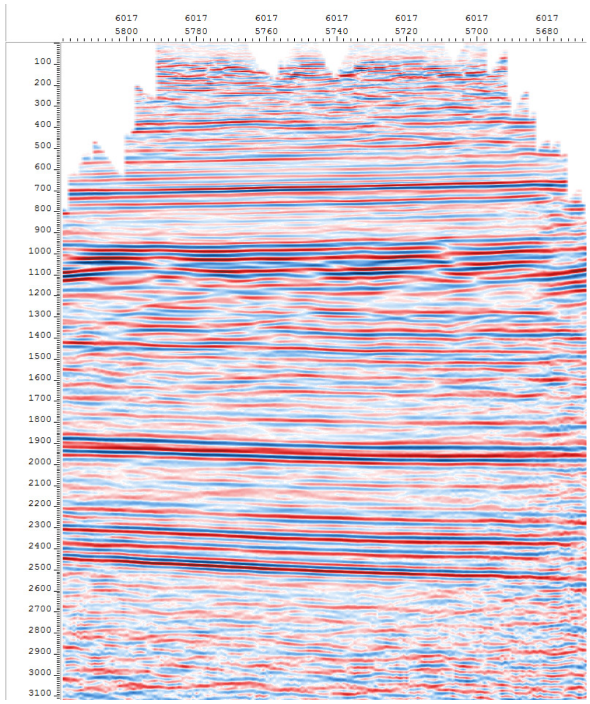

FIG. 6. An example seismic section from time 0 to 3 seconds of the PP compressional dataset

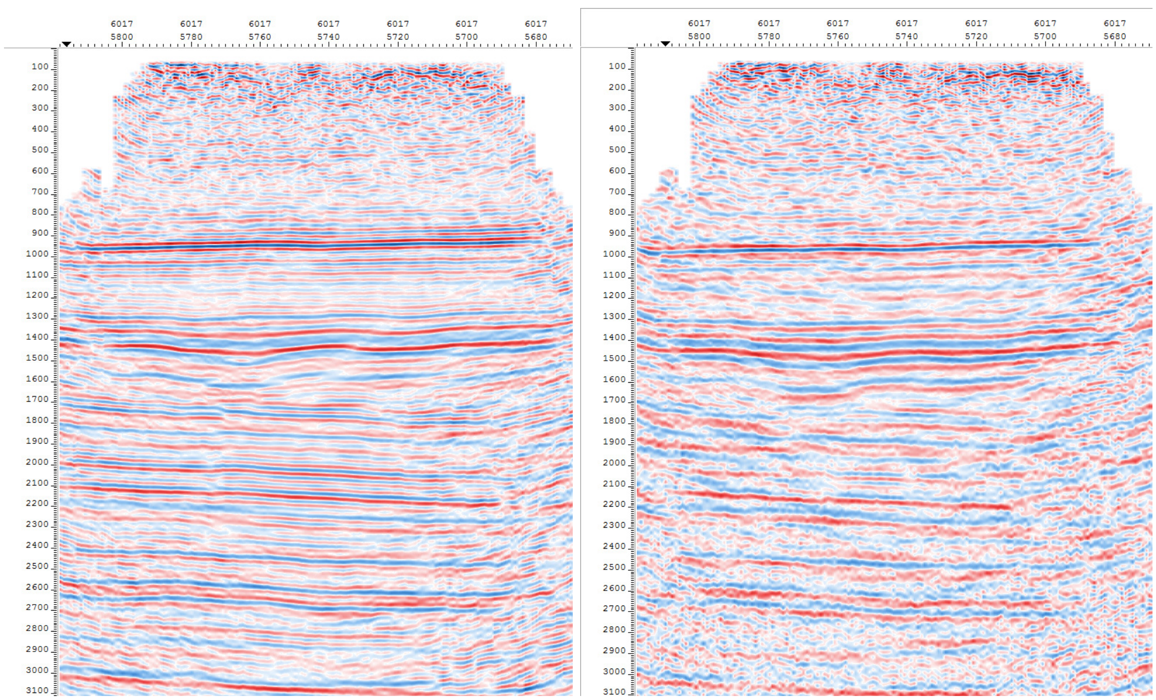

FIG. 7. (left) An example seismic section from time 0 to 3 seconds of the PS1 (fast) shear dataset. (right) An example seismic section from time 0 to 3 seconds of the PS2 (slow) shear dataset.

Background physics

Interval Vp/Vs ratios can provide valuable insight into rock parameters and are especially valuable in unconventional resource plays. In basins with pervasive seismic reflections, interval Vp/Vs ratios are calculated easily from traveltime isochrons. Figure 8 and the following equations, show how interval Vp/Vs ratios can be found using compressional and converted wave seismic data.

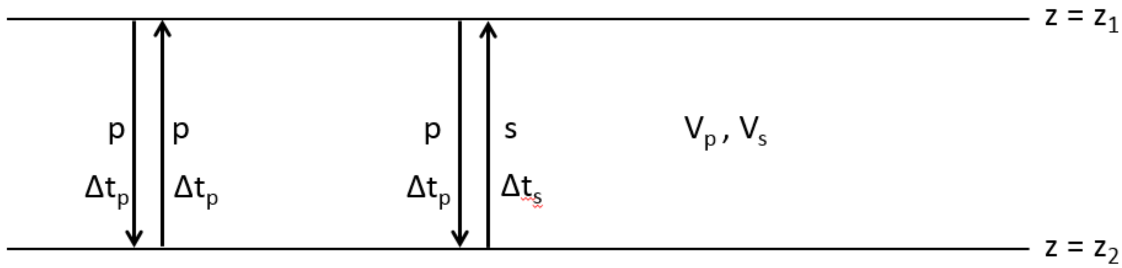

FIG. 8. Example scenario with compressional and shear seismic reflections between two layers

In stacked shear wave seismic data, the traveltimes of reflections can be considered normal incidence, meaning boundaries are struck by mechanical waves orthogonally. The amplitudes, however, are not completely correct because mode conversion at acoustic impedance boundaries only occur at non-normal incidence. The final converted wave stack gives an average of the offset-dependent P-S reflectivities (Stewart et al. 2002). Using the assumption that converted wave event traveltimes are normal incidence reflections, we can derive interval V_p/V_s ratios. From the scenario in figure 8, we want to find V_p/V_s and we have two knowns, $\Delta t_p + \Delta t_p = 2\Delta t_p = \Delta t_{pp}$ and $\Delta t_p + \Delta t_s = \Delta t_{ps}$, where Δt_{pp} and Δt_{ps} are the isochrons between the events at depths z_1 and z_2. Δt_p and Δt_s are one-way traveltimes for the compressional and shear waves respectively. P wave velocity is given by $\frac{z_2 - z_1}{\Delta t_p}$ and S wave velocity is given by $\frac{z_2 - z_1}{\Delta t_s}$. To obtain V_p/V_s ratio we divide V_p by V_s given by $\frac{V_p}{V_s} = \frac{\Delta t_s}{\Delta t_p}$. Doing some algebra and subbing in the known values from reflection isochrons can give a simple expression for interval V_p/V_s ratio: $\frac{V_p}{V_s} = \frac{\Delta t_s}{\Delta t_p} = \frac{\Delta t_p + \Delta t_s - \Delta t_p}{\Delta t_p} = \frac{\Delta t_{ps} - \frac{1}{2}\Delta t_{pp}}{\frac{1}{2}\Delta t_{pp}} = 2\frac{\Delta t_{ps}}{\Delta t_{pp}} - 1$. The derivation of interval V_p/V_s ratios are confirmed in the paper by Stewart et al. 2002.

ANALYSIS

General seismic data interpretation

Following the general stratigraphic understanding of the Paleozoic Appalachian Basin and the work done by Chaveste et al. (2013), a general seismic interpretation was completed. Figure 9 (left) depicts a general stratigraphic chart of the geology in the vicinity of the 3D seismic survey. For the general seismic interpretation 6 main reflection events were picked: Tully Limestone, Marcellus shale top, Lower Marcellus Shale, Onondaga Limestone, Trenton Limestone, and the Basement reflection. All 6 events are present on the PP seismic data, however the converted wave 3D volumes are missing some of the reflections. On the fast shear wave section (PS1) all events are present with the exception of the basement reflection and on the slow shear wave section (PS2) the Trenton Limestone and the basement reflection are not present. Figure 9 (right) shows a sample Northwest to Southeast PP seismic line, the 6 horizons used in the general interpretation are shown here. Generally speaking, the reflections in the Appalachian Basin are gently dipping pervasive events, this character is seen in the Tully Limestone, Trenton Limestone and basement picks. However, the Marcellus top, Lower Marcellus and Onondaga Limestone have more complex structure. In the example seismic line in figure 9, a fault is present around 1000 ms and crossline location 5705.

Time structure and amplitude maps were made for the present horizons on each of the 3D seismic volumes. The basement reflection displays mildly dipping structure towards the south. The basement time structure from the PP seismic data is shown in figure 10 below. The events above the basement follow the same gently dipping structure, but the dip angle decreases with elevation, and around the depth of the Marcellus Formation structure changes. The Tully Limestone, the structurally highest pick, shows this more variable time structure which can be seen in figure 11. The most structurally complex unit, based on the seismic data, happens to be the Marcellus shale. Figure 12 displays the structural complexity of the Marcellus shale and Lower Marcellus picks on the PP seismic volume. The east-west trending structural highs and lows are fault blocks that can be seen on the interpreted seismic section in figure 13. Amplitude maps of the Marcellus Formation top give a very good representation of the fault blocks, the fault planes can be mapped easily, as seen in figure 14.

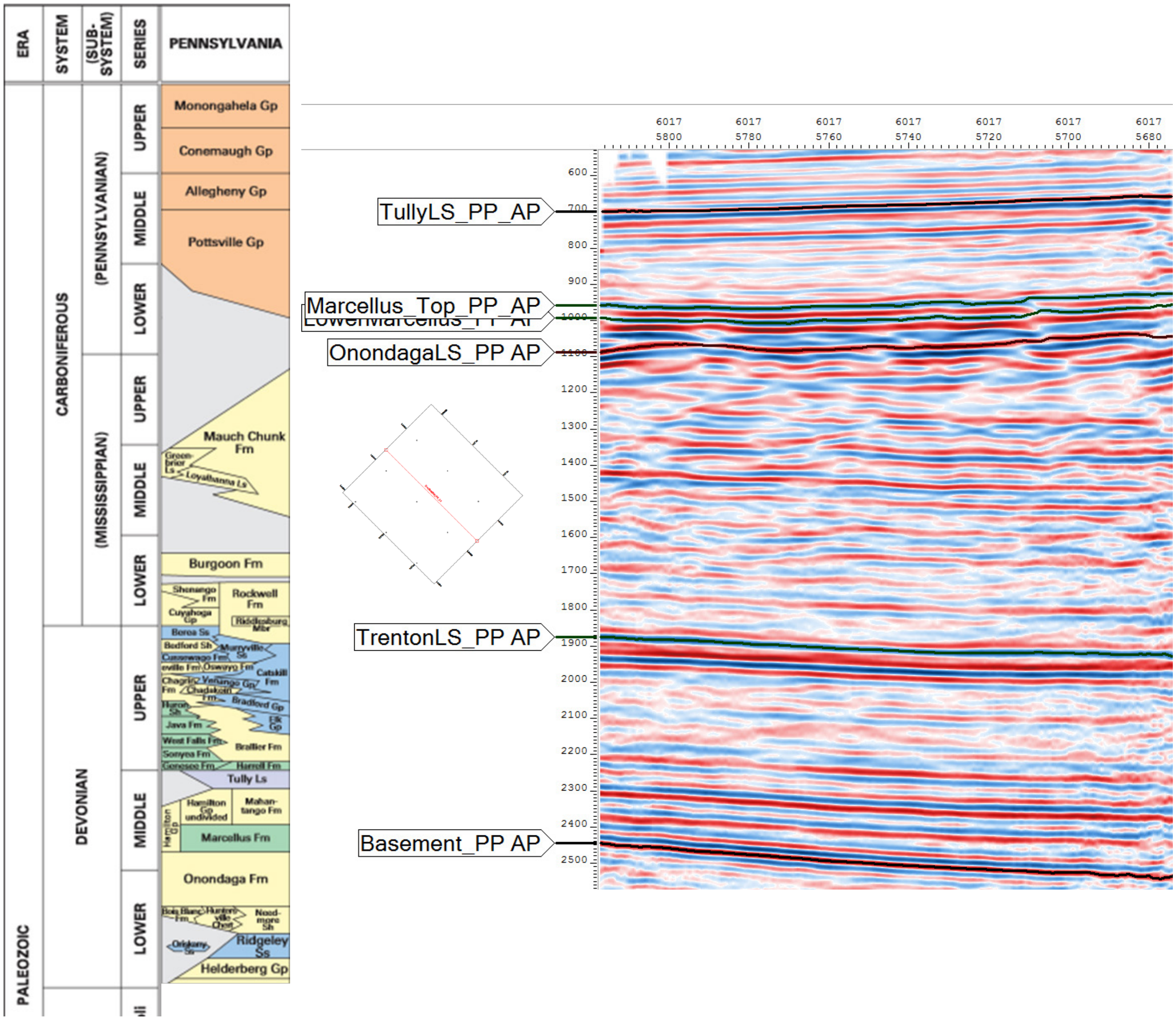

FIG. 9. (left) Stratigraphy of the subsurface in Pennsylvania, note the location of the Marcellus Formation in the Middle Devonian. (right) Sample seismic line depicting the 6 pervasive reflection events, note the fault at time 1000ms and crossline 5705.

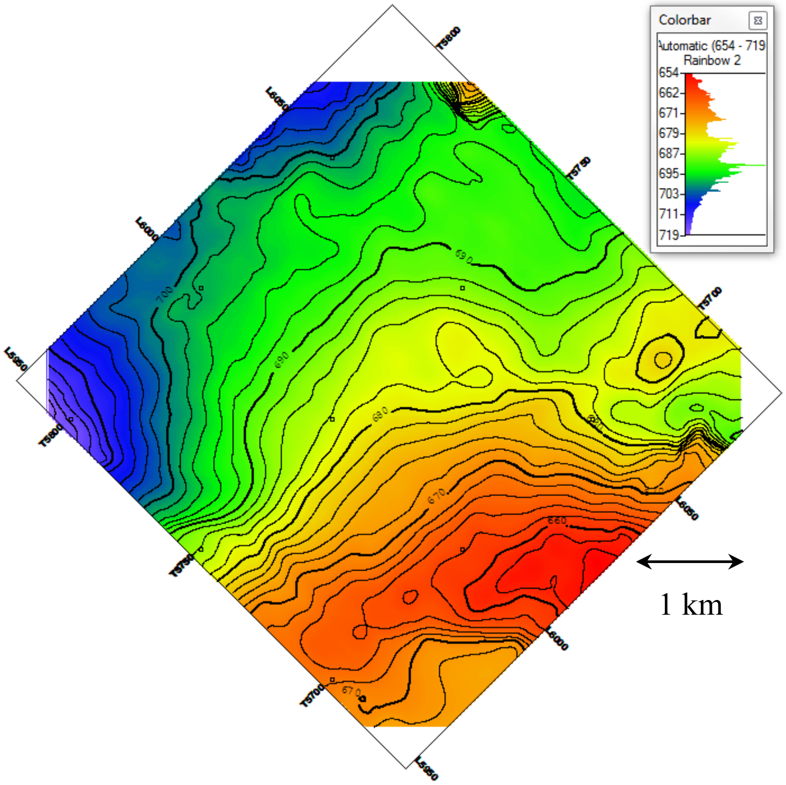

FIG. 11. Time structure of the Tully Limestone, displaying more variable structure than the basement reflection.

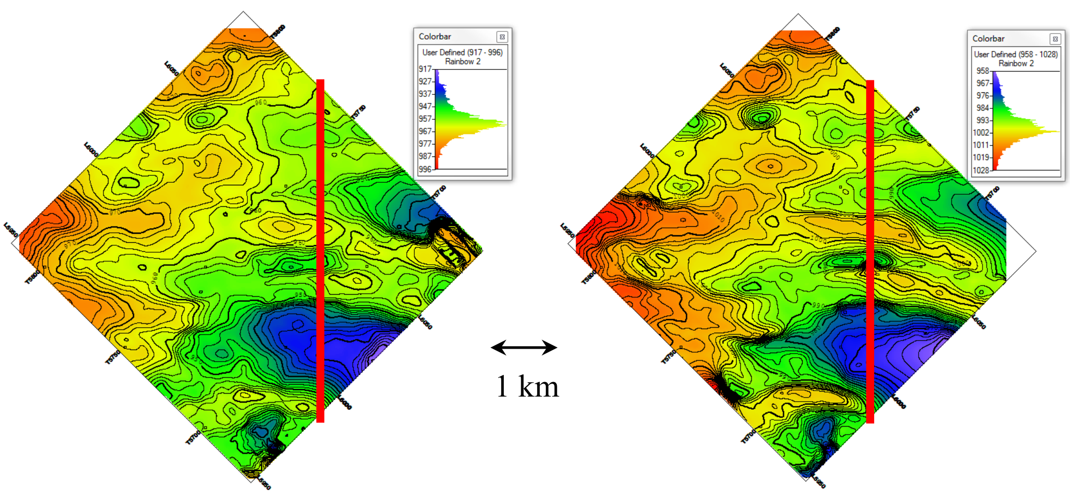

FIG. 12. (left) Marcellus top time structure, (right) Lower Marcellus time structure. The east-west trending features are fault blocks. Red line indicates seismic section in figure 13.

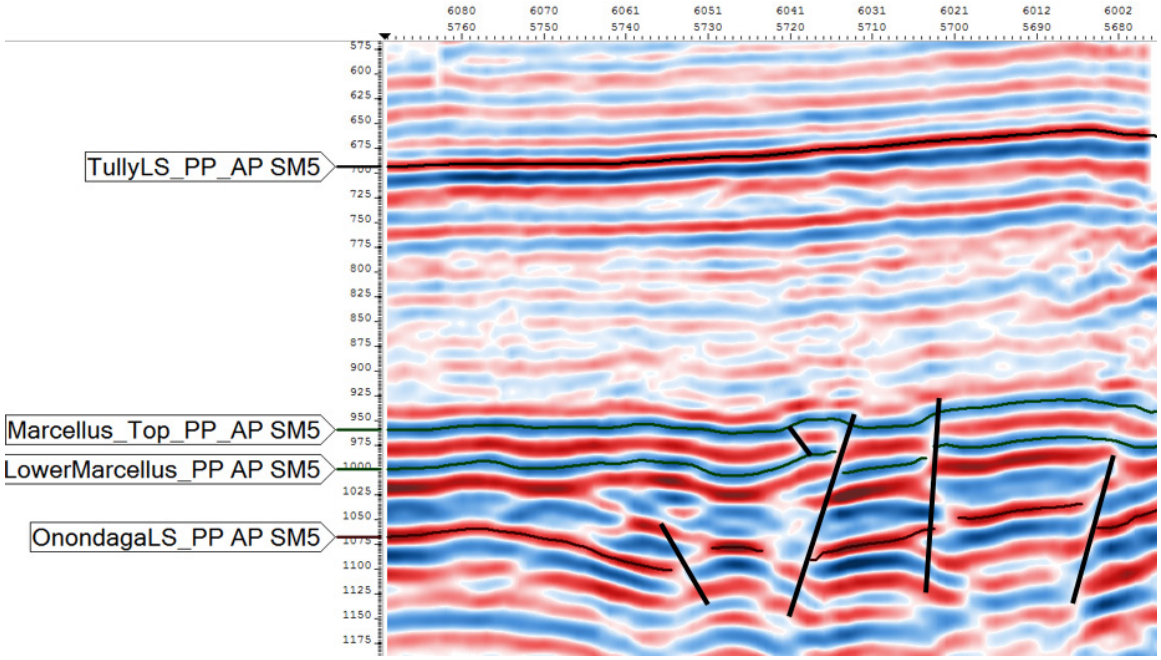

FIG. 13. North to South running PP seismic line, displaying complex structural style in the Marcellus Formation and Onondaga Limestone.

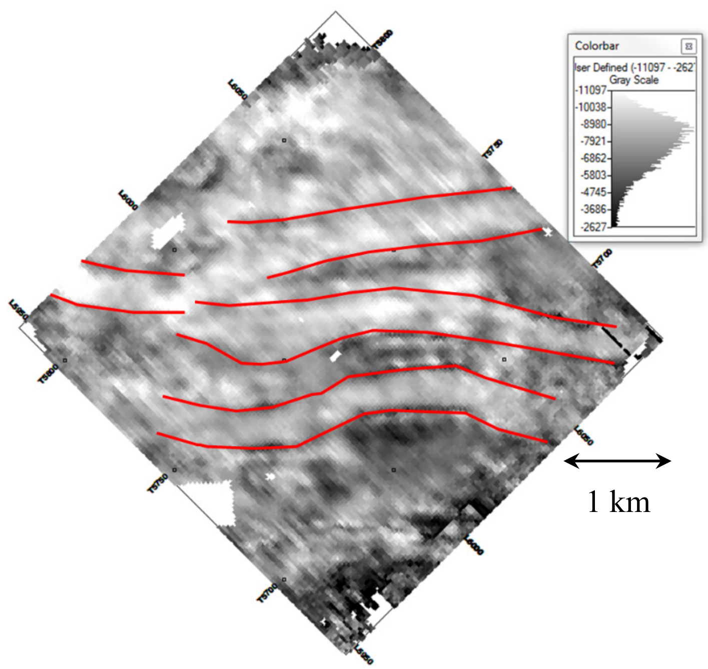

FIG. 14. Amplitude of the Marcellus Formation Top seismic pick on the PP seismic data. Faults interpreted in red.

Converted wave interpretation and interval V_p/V_s ratios

Introducing the converted wave seismic data can constrain interpretation made based solely on PP seismic. The high quality converted wave seismic data can be used to explore interval rock properties and help delineate sweet spots for hydraulic fracture and reduce drilling risk in unconventional reservoirs. The main structural trends interpreted from the converted wave data tend to agree with the PP seismic interpretation. The deepest pervasive reflection present on both the PP and PS1 seismic data, the Trenton Limestone, shows gently dipping relatively flat structure on both volumes. Figure 15 shows these time structure maps. The mild southern dip is present in the Trenton pick on both the PP and PS1 volumes. The PS1 volume exhibits some fairly major edge effects, so an exclusion polygon was included in the gridding of the Trenton Limestone. The truncations of the PS1 time structure in the corners arise from the exclusion polygon. The structural trends of the other horizons picked also match relatively well between the compressional and converted wave seismic datasets.

The east-west trending faults present on the PP seismic data are also visible on the converted wave volumes. However, some of the faults present on the PP seismic data, are not seen on the PS1 seismic data and vice versa. Sometimes, the faults are visible on both seismic sections, but their dips appear different. Some examples of these variations in fault existence and geometry can be viewed in figures 16 and 17. Faults are labeled in figures 16 and 17, and structures common to both the PP and PS1 seismic data share the same label. In figures 16 and 17, the PS1 seismic data shows the fault A very well. The displacement and separation of the reflection events is easily interpreted on the converted wave section. The compressional seismic data does not show the fault as clearly. In fact, there doesn't appear to be any discrete separation on the Marcellus, Lower Marcellus or Onondaga picks. Fault B is present on both volumes in the same orientation and Fault D is only present on the PP seismic. The edge effects on the converted wave dataset interfere with the structure at the position of fault D. Fault C has reflection displacement on both the converted and conventional seismic data, but the dip of the fault appears to be opposite between the two datasets. The fault dip on the converted wave seismic data makes more sense geologically than on the P wave section. The case in fault A in the PP seismic data, where there appears to be no reflector separation may also be present in fault C. The Onondaga reflection does not appear to be displaced by fault A or fault C on the PP seismic data. This missing fault displacement has caused a misinterpretation of fault C on the PP seismic dataset; the fault geometry of fault C is best depicted in the interpreted PS1 seismic section in figure 17.

Following the derivation for interval Vp/Vs ratio in the background physics section, isochrons and interval Vp/Vs ratios were calculated for several of the formations with pervasive reflections. An example of these isochrons, showing the two way traveltimes between the Marcellus and Lower Marcellus on both the PP and PS1 seismic volumes is shown in figure 18. The regions with the most edge effect influence has been excluded to best represent the isochrons. The two isochrons show very similar structural trends, but the PP isochron is smoother than the PS1 isochron. This difference in smoothness may be accounted for by unresolved static errors in the shear seismic volume. For the purposes of understanding interval rock properties, the shear data is of adequate quality. Interval Vp/Vs ratio was found for the Marcellus-Lower Marcellus, Marcellus-Onondaga, Lower

Marcellus-Onondaga, and Tully-Marcellus intervals. These interval rock physics maps are shown in figures 19 and 20. The range of interval Vp/Vs ratios in the study go from about 1.5 to 3. Typical Vp/Vs ratio ranges for shales and similar clastics are in this range (Bourbie, Coussy and Zinszer, 1987). Having overlapping interval Vp/Vs ratios can help constrain the understanding of various intervals' rock properties. For example, the Marcellus-Onondaga interval Vp/Vs ratio looks most similar to the Lower Marcellus-Onondaga interval. This suggests that the most influential component changing the interval Vp/Vs ratio is the Lower Marcellus; the Marcellus Shale should be looked at as a whole and in separate components to best understand the rock physics. The trends of the interval Vp/Vs ratios are similar to the structural trends in the project area. East-West trending high and low Vp/Vs ratios match East-West trending faults. This trend is especially present in the Lower Marcellus-Onondaga interval Vp/Vs ratio map.

We can attempt to correlate the V_p/V_s ratio maps with the difference in traveltimes between the two shear modes. The difference in traveltimes between the two shear modes can aid in understanding anisotropy. Where there are major traveltime differences between the fast and slow shear modes, anisotropic media is suspected. In figure 21, the V_p/V_s ratio map for the Marcellus-Onondaga interval is shown with the difference in isochrons for the two shear modes. Anomalies that are common to both maps are labelled as features 1, 2 and 3. The isochron difference map on the right hand side in figure 21 is fairly nebulous, and the isochron differences are centered around zero. However, there are 3 East-West trending anomalies; these features are labelled numerically. Isochron anomalies 1, 2 and 3 are interpreted as regions with high shear wave anisotropy, and lie adjacent to major faults in the project area. The anisotropic anomalies map to features with high V_p/V_s ratios. The low V_p/V_s ratio regions, the blues and purples on the left in figure 21, don't correlate to anisotropic anomalies on the right hand side map. It is more likely that the low V_p/V_s ratio areas have variable physical or fluid parameters.

Without the aid of well data, it is challenging to make meaningful interpretations on the hydrocarbon system in the Appalachian Basin but some high level qualitative conclusions can be drawn. Sun et al. (2013) states that high V_p/V_s ratio can be associated with high total organic carbon in hydrocarbon source rocks. Given this relationship, the regions with low V_p/V_s ratio in the Marcellus shale can be avoided when exploring for hydrocarbons. Natural fracturing is also incredible important in the economic feasibility of the Marcellus Formation. According to Walton and McLennan (2013), the Devonian shales of the Appalachian Basin can only be produced when extensive networks of natural fractures exist. In terms of natural fracturing within the project area, fracture networks are more likely to exist locally along faults. Since the faults are easily mapped with amplitude maps, natural fracture networks should be fairly trivial to explore for.

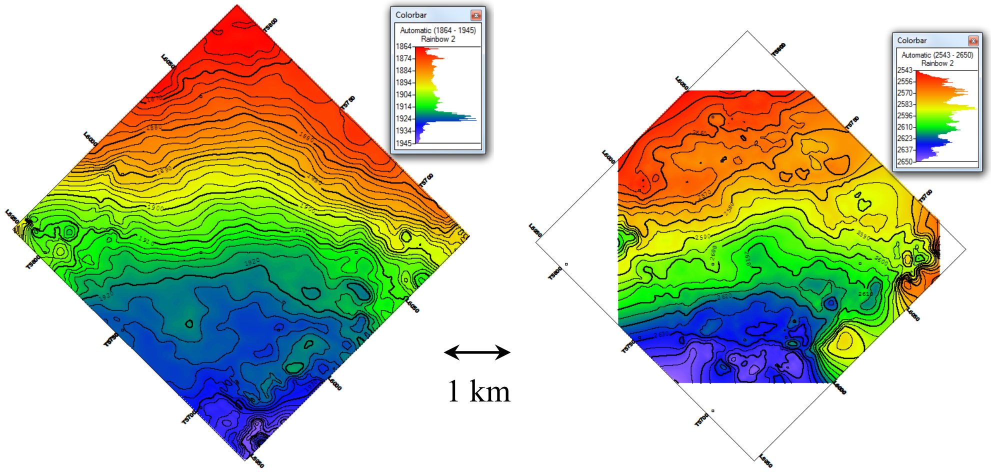

FIG. 15. Time structure for the Trenton Limestone for the PP (left) and PS1 (right) seismic data

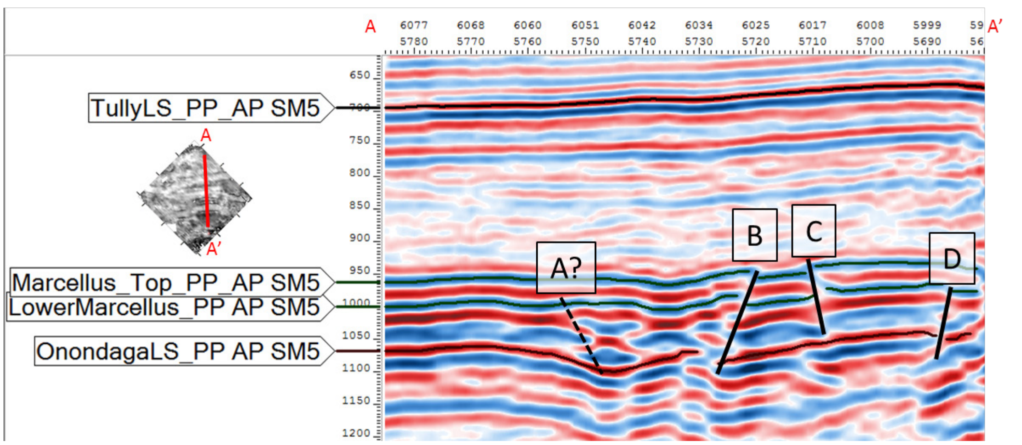

FIG. 16. North to south PP seismic line displaying complex structure in the Marcellus and Onondaga formations

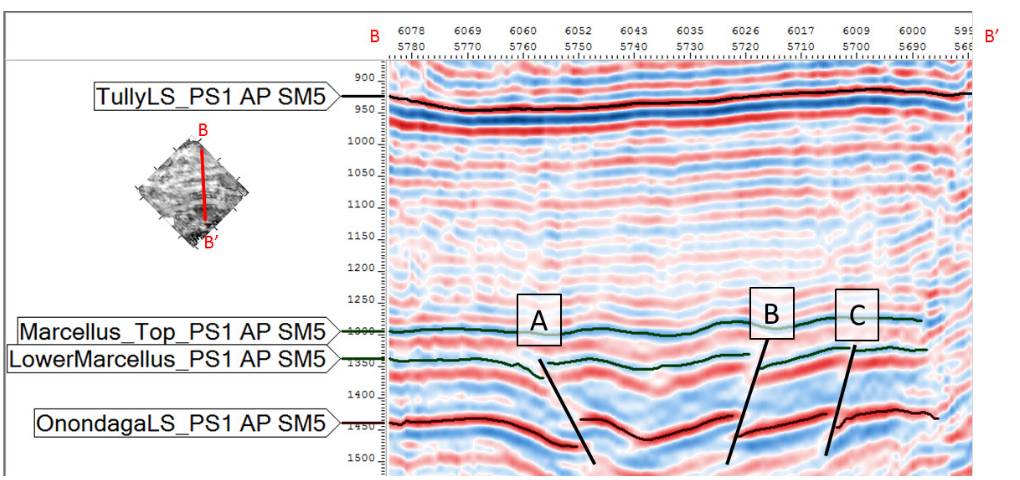

FIG. 17. North to south PS1 converted wave seismic line displaying complex structure in the Marcellus and Onondaga formations

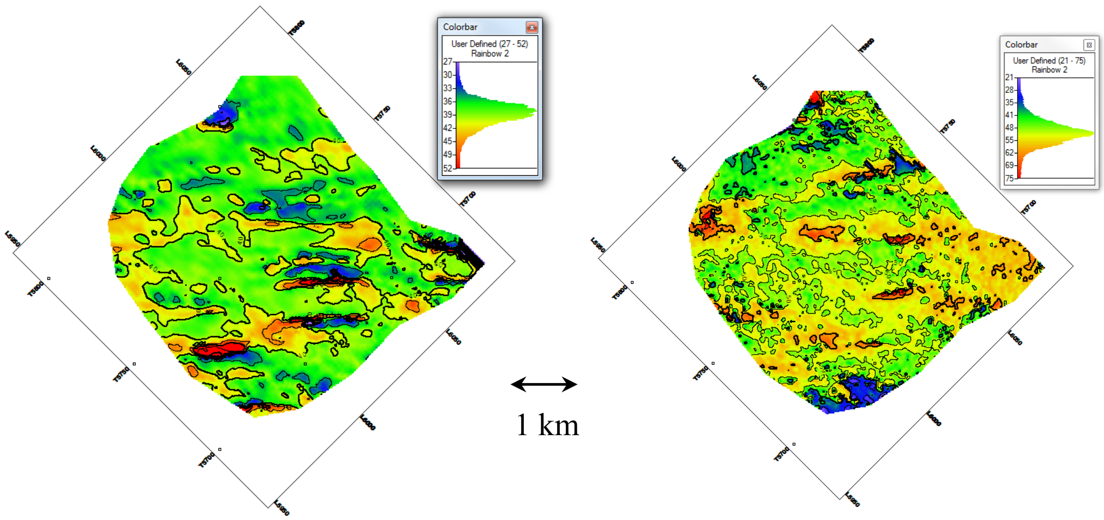

FIG. 18. Isochron between the Marcellus and Lower Marcellus picks on the PP (left) seismic volume and the PS1 (right) seismic volume. An exclusion polygon crops the data to remove regions with most extreme edge effects.

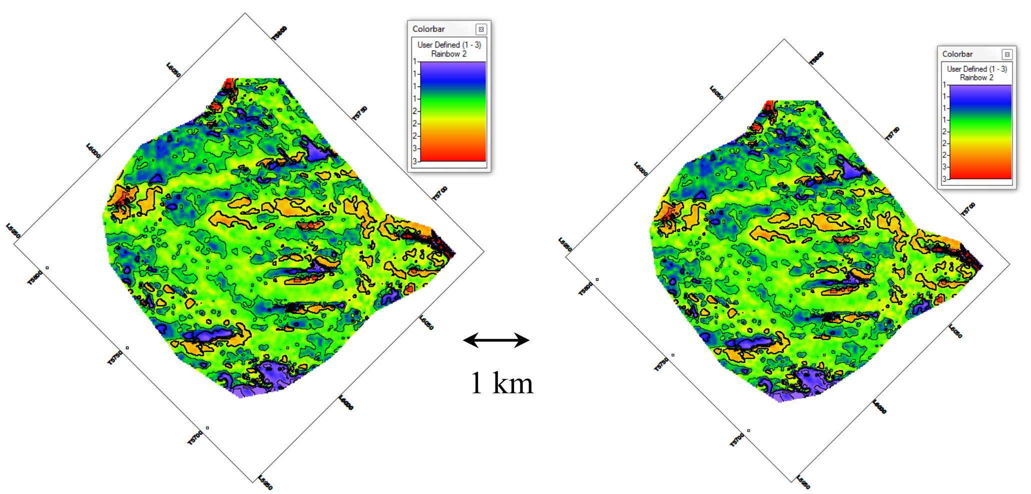

FIG. 19. Interval V_p/V_s ratio for the Marcellus-Lower Marcellus interval (left) and Marcellus-Onondaga (right)

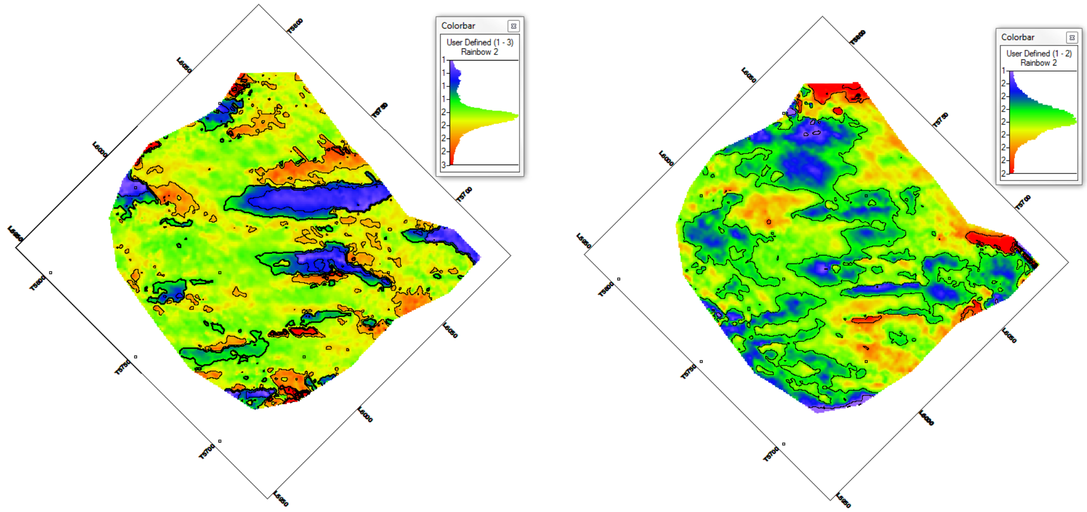

FIG. 20. Interval V_p/V_s ratio for the Lower Marcellus-Onondaga interval (left) and Tully-Marcellus (right)

Conclusions and future work

A 3D multicomponent seismic dataset was acquired in Northeast Pennsylvania near the New York border. The 3D seismic data volume targeted the Marcellus Shale in the Appalachian basin. The seismic data was of high quality and pervasive reflections exist on major geologic interfaces throughout the PP, PS1 and PS2 seismic datasets. Interval rock properties and their implications on economic hydrocarbon production were explored using the multicomponent seismic volume. A general seismic interpretation was performed. The Marcellus Shale and surrounding formations have a mildly dipping structural style with East-West trending faults. The fault geometry is somewhat complex and the fault dips may have been misinterpreted based only on the PP seismic data. The converted wave datasets best constrain the structural geometry of the geologic features in and around the Marcellus Formation. Interval V_p/V_s ratios were found for the Marcellus-Lower Marcellus, Marcellus-Onondaga, Lower Marcellus-Onondaga and Tully- Marcellus intervals. The interval V_p/V_s ratios were compared with the isochron difference between the two shear modes. A correlation was found at fault edges between anisotropy and high V_p/V_s ratio. Making complete interpretations with implications on hydrocarbon production is unrealistic without the aid of well data, but qualitative general trends and potential sweet spots were speculated.

Going forward, the most important factor in understanding the Marcellus Shale and the Appalachian Basin is comparing interpretations with well data. Well logs and production trends are incredibly valuable in evaluating the economic potential of the Marcellus in the project area. Impedance inversion could be a great tool for understanding important unconventional reservoir properties such as brittleness or existence of natural fracture networks. The Marcellus Shale is an exciting unconventional resource play with many more seismological avenues to explore.

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