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# Seismic Anisotropy of the Marcellus Shale: Feasibility Study for Fracture Characterization

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## Summary

Recent interest in the Marcellus shale play in Pennsylvania, USA, is growing rapidly. An orthogonal set of fractures could play an important role to define optimal gas production. In this study we investigate the feasibility of measuring azimuthal anisotropy from a 3D-3C dataset. If the anisotropy exhibits an orthorhombic symmetry, fracture characterization of two principal crack densities, an infill fluid factor and isotropic background velocity is possible by inversion of NMO ellipses and zero-offset traveltimes of P-waves and the two split S-waves. P-wave data quality appears to be very good and accurate elliptical NMO velocity analyses indicate consistent 5% differences in VTI anisotropy between the fast and slow directions. Also, there is a similar amount of S-wave splitting along the vertical axis of 3% to 5%. The high S/N and resolution of the fast PS1-wave data, and a well defined event at the top and bottom of the Marcellus suggest an accurate inversion of traveltime information is feasible for characterizing interval properties of an orthogonal set of fractures. One impediment could be the higher attenuation observed on the slow PS2-wave; however, this might be important information related to the fluid infill of the fractures.

## Introduction

Multicomponent seismic, using converted P- to S-waves (PS-waves), is potentially a cost effective way to characterize fractures in numerous hydrocarbon reservoirs. Grechka et al., (1999) demonstrate in a physical modelling study that it is possible to reconstruct the azimuthally dependent NMO velocities of the pure shear modes with PS-waves and to find the anisotropic parameters that cannot be determined from P-wave data alone. The NMO ellipses and zero-offset traveltimes of P-waves and two split shear waves (S-waves) of an orthorhombic medium are necessary to invert for isotropic background velocities, two principal crack densities and an infill fluid factor (Grechka and Kachanov, 2006). Previous studies that used only azimuthal P-wave NMO (Jenner et al., 2001) or S-wave splitting (Gaiser and Van Dok, 2005) are insufficient to constrain the crack density of multiple fracture sets.

In this study we investigate the feasibility of measuring azimuthal anisotropy over the Marcellus shale interval from a 3D-3C, wide-azimuth dataset to invert traveltime information for fracture characterization. These data are acquired in Pennsylvania, USA, in a complex near-surface and topographic environment. This presents a challenge to obtain the necessary azimuthal velocity and S-wave splitting information for characterizing multiple fracture sets in an orthotropic medium where strong near-surface statics and heterogeneities are present. Below the near surface the overburden is relatively flat and homogeneous, but the Marcellus formation is conformable with the local Syracuse salt tectonics, exhibiting lateral heterogeneity in the form of folding and faulting. The ultimate goal is to use PS-wave seismic data, not pure mode S-waves, to invert for the two background P- and S-wave velocities, fracture density of two fracture sets, and a fluid factor. An important aspect of this feasibility study is to ensure that the PS-wave data has sufficient resolution for joint inversion with the P-waves.

## Fracture Characterization using PS-waves

The elastic properties sufficient to describe a medium with multiple vertical fracture sets (Grechka and Kachanov, 2006) are the background elastic constants (Lamé parameters) of the host rock, $\lambda_b$ and $\mu_b$, the fracture densities, $e_1$ and $e_2$, of the two principle fracture sets, and a fluid factor, $0 \leq \varsigma \leq 1$, where $\varsigma \approx 0$ for dry, and $\varsigma \approx 1$ for fluid filled fractures. Traveltime data necessary to invert for these properties (Vasconcelos and Grechka, 2007) are the three pure mode NMO ellipses for $\mathbf{W}^{P}$, $\mathbf{W}^{S1}$ and $\mathbf{W}^{S2}$, the P-wave, fast S1-wave and slow S2-wave, respectively. Also, the two average $V_P/V_S$ ratios, $\gamma_{0,S1}=V_{P0}/V_{S1}$ and $\gamma_{0,S2}=V_{P0}/V_{S2}$ for the fast and slow S-waves are needed.

When P-wave and S-wave source data are available, analysis is straight forward. However, for PS-wave surveys, pure mode S-wave NMO velocities must be determined from PS-waves and take into account P-wave NMO (Grechka et al., 1999). Alternatively, S-wave traveltime differences between the fast and slow modes as a function of offset and azimuth can be used to solve for this information. Fast and slow principal anisotropy S-wave axes can be determined from common-receiver gather (CRG) stacks or prestack time migration (PSTM) image gathers of offset-vector tile (OVT) data. Vertical velocity ratios are determined from high resolution registration analyses of the fast, PS1-wave, and slow, PS2-wave, with the P-wave.

## Marcellus Shale

In north-eastern Pennsylvania, the Marcellus shale ranges from 50 to 250 ft thick and is found at depths from 6500 to 9000 ft. It occurs in the lower Hamilton group of middle Devonian age and has a total organic content (TOC) of 3-9% similar to the Fayetteville shale in Arkansas. There is a dominant fracture set, J1, oriented roughly east-west (about N75E) in the principal horizontal stress direction, and an orthogonal set, J2. The key for successful gas production is identifying shale with high TOC and maturation, volumetric factors of porosity, thickness, areal extent, and gas saturation and transmission factors of permeability, diffusivity and how easily it can be stimulated (fracturability) to create pathways to the wellbore. At the top of the Marcellus, there are numerous faults and heterogeneous areas as well as folding with east-west axes which are related to the local tectonics of Syracuse salt movement.

## Bradford 3D Multicomponent Data

A 3D-3C pilot data set was acquired during a larger vertical component only, wide-azimuth survey in the Bradford area. Dynamite sources and 3C Vectorseis sensors were used to provide an image of about 25 square kilometres.

Processing the PS-wave data is challenging, particularly separating near-surface statics from S-wave splitting traveltime differences between the fast, PS1- and slow PS2-wave. P-wave source statics are applied to PS-waves, and the S-wave velocity used for elevation statics can be obtained from the fundamental mode of the surface wave. However, there are no refracted S-waves at Bradford, so CRG stacks are effectively employed to determine long wavelength S-wave statics. Estimating S-wave statics is an iterative process along with the average $V_P/V_S$ ratios, and the magnitude and orientation of S-wave splitting. Here, CRGs are also employed for determining $\gamma_0$ by correlating PS-wave stacks with P-wave stacks. For S-wave splitting analyses, CGR azimuth stacks (Figure 1) are used. Traces are sorted into 36 source-receiver azimuth groups at a 10 deg increment, NMO corrected with initial velocity estimates, and stacked. Additionally, the two horizontal components are rotated to a source-centred, cylindrical coordinate system (Gaiser, 1999), where the radial component is oriented parallel to the source-receiver azimuth, and the transverse is orthogonal.

In this domain, traveltime variations of PS-wave reflections can be observed as a function of azimuth. The fast PS1-wave occurs near 90 and 270 deg, and the slow PS2-wave occurs near 180 and 360 deg (Figure 1a). Between these azimuths the fast and slow interfere with one another. A more precise indication of the principal axis directions can be seen on the transverse component at the polarity reversals (Figure 1b). This is where there is only one PS-wave, in the fast or slow direction. Numerous CAG analyses indicate 3% to 5% average S-wave splitting where the fast PS1-wave direction is about N80E, similar to the maximum horizontal stress direction. Rotating the horizontal components to these principal directions (H1 to N80E, and H2 to N170E) effectively separates PS1 and PS2. These separated wavefields are then processed thru PSTM.

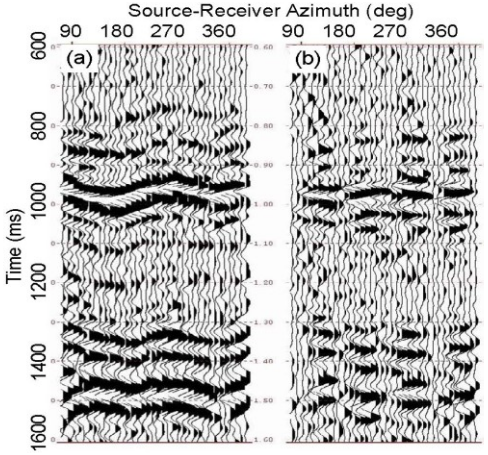

Figure 1: PS-wave radial (a) and transverse (b) components of a common-azimuth gather. The radial shows azimuthal traveltime variations of the fast and slow PS-waves, and the transverse shows the principal axis directions at polarity reversals (N80E and N170E).

Pre-processing of the P-wave data followed a conventional flow to prepare the data for PSTM. Careful surface-consistent statics analyses included elevation, refraction, and residual statics determined during NMO velocity analyses. Other signal processing such as surface-consistent deconvolution and surface-wave noise attenuation were performed with a view to preserve traveltime information, and Kirchhoff PSTM was performed on OVT data to preserve offset and azimuth information. Figure 2 shows the quality of the migrated data on an inline section and the synthetic tie from sonic log data. Note that the fast PS1-wave data has remarkably good S/N and resolution considering the heterogeneous near surface. The slow PS2-wave (not shown) has a lower S/N ratio and appears more attenuated than PS1, perhaps due to the interaction with fractures.

The Marcellus shale is a low velocity interval characterized by a distinct reflector at the top, just below 900 ms P-wave time and around 1300 ms PS-wave time. Marcellus time interval is about 60 ms P-wave time and 80 ms PS-wave time. There is also a distinct event marking the bottom of the Marcellus so estimating interval velocity from NMO ellipses, $\mathbf{W}^{P}$, $\mathbf{W}^{S1}$ and $\mathbf{W}^{S2}$, and interval Vp/Vs from fast $\gamma_{0,S1}$ and slow $\gamma_{0,S2}$ is entirely feasible. The structural features are due to the tectonic flow of the Syracuse salt formation below the Marcellus. Thus, it might be important to take into account lateral heterogeneous features of regional dip and salt tectonics when determining azimuthal interval properties.

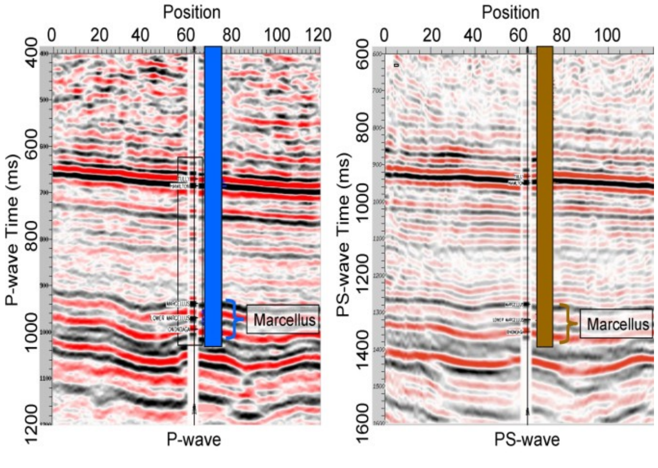

Figure 2: PSTM and synthetic tie of the P-wave and PS1-wave data. The Marcellus shale is a distinct low velocity interval below 900 ms P-wave time, and 1300 ms PS-wave time. The reflectors at top and bottom are conducive for interval NMO velocity analyses.

After PSTM the $\gamma_0$ fields can be refined by high resolution registration analyses of the fast and slow converted wave images with the P-wave image. Excellent correspondence of the two wavefields yield interval $\gamma_{0,S1}$. A similar analysis with the PS2-wave can provide the $\gamma_{0,S2}$ interval velocity ratio field. Over the 3D-3C survey, the amount of interval S-wave anisotropy is around 5% on average and exceeding this in some areas. Again, the resolution of the PS-wave data is remarkably similar to the P-wave when transformed to P-wave time. However, further bandwidth corrections to the PS-waves are necessary to correct for wavelet distortion due to registration. After matching wavelengths of PS-wave data to P-wavelengths, the proper resolution comparison is achieved with considerably higher frequency content. This resolution should be sufficient to perform

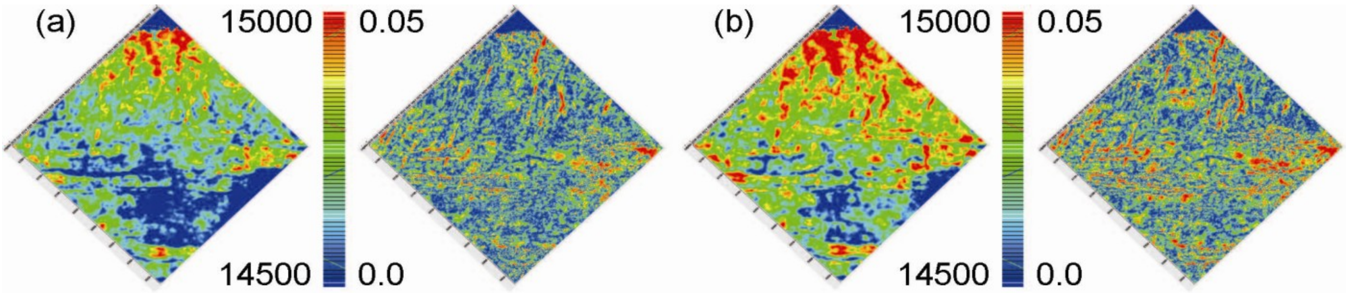

Figure 3: Azimuthal P-wave NMO velocity from the upper (a) and lower (b) portions of the Marcellus shale. Average velocity (ft/s) is shown on the left and azimuthal anisotropy on the right. Note the increase in values from upper to lower.

individual azimuthal NMO velocity analyses on OVT migrated fast and slow S-waves. From these analyses, azimuthal interval NMO ellipses of the $\mathbf{W}^{S1}$ and $\mathbf{W}^{S2}$ can be determined. These consist of a fast, $W_{11}$, and slow, $W_{22}$, NMO term and an orientation of the principal interval velocities.

P-wave azimuthal velocity analyses were performed over the upper and lower portions of the Marcellus. This consisted of both a four-azimuth sectored and full azimuth inversion for $\mathbf{W}^{P}$ from OVT data. Figure 3 shows a plan view of the average velocity estimates and anisotropy over the upper and lower portions of the Marcellus shale. These are related to the 2x2 principal P-wave effective NMO matrix terms, $W_{11}+W_{22}$ and $W_{11}-W_{22}$, respectively. There is up to 5% P-wave elliptical NMO anisotropy which increases over the Marcellus interval. This suggests that it is feasible to compute interval elliptical NMO anisotropy by a generalized Dix type differentiation (Grechka and Tsvankin, 1999) from these effective NMO velocity estimates.

## Conclusions

Data quality of the 3D-3C Bradford survey appears to be very good for accurate elliptical NMO velocity analyses of the P-wave and the two split S-waves. The high S/N and resolution of the PS-wave data, and a well defined event at the top and bottom of the Marcellus shale suggest an accurate inversion of traveltime information is feasible for characterizing an orthogonal set of fractures. One impediment could be the higher attenuation observed on the PS2-wave; however, this might be important information related to the fluid infill of the J1 fractures.

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