9th Biennial International Conference
& Exposition on Petroleum Geophysics

"HYDERABAD 2012"

P-332

Case Study Demonstrating the Ability of 3D3C Seismic Data to Predict Petrophysical Properties of Shale

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Summary

This project was performed to determine the value of seismic in determining lateral changes in rock properties of shale and if the use of multi-component (3D3C) seismic could be used to increase production and help optimize completion strategies in the exploitation of shale plays.

Keywords: *Multi-component, 3D3C, full wave, shale gas, shale play, Marcellus, joint inversion*

Introduction

The Devonian age Marcellus is a major shale play in North America that has drawn international attention. It covers approximately 250,000 square kilometers, trending northeastward from West Virginia into New York. The Marcellus is believed to have the potential to become the second largest gas field in the world, with original gas-in-place estimated at nearly 1500 tcf. Commerciality was established in 2004 and the basin now has over 100 rigs actively drilling. The majority of these wells are drilled as horizontal wells with laterals 1 to 2 kilometers in length. Hydraulic fracturing is required to stimulate a sufficient volume of shale that will produce commercial quantities of natural gas. Within the study area, the Marcellus is approximately 60 meters thick and buried at a depth of 2.6 kilometers.

The challenges of this play include:

1) identifying shale 'sweet spots' which represent areas of higher productivity and driven by several petrophysical properties including porosity, permeability, brittleness and total organic content (TOC);
2) optimizing well designs and geo-steering through detailed, seismically derived structure maps that also identify subsurface features such as faulting and karsting;
3) optimizing the stimulation program by understanding the variances in rock properties within the shale zone and the areal distribution of Young's Modulus, Poisson's Ratio, and local stress regimes.

Method

To address these challenges, a 67 square-kilometer, wide-azimuth, multi-component (3D3C) seismic survey was recorded in central Pennsylvania. Its purpose was to determine the effectiveness of modern 3D3C seismic data in extracting certain rock properties from the Marcellus Shale to identify 'sweet spots' and optimize both the drilling and stimulation programs.

In parallel, a rock physics study was conducted on well logs penetrating the Marcellus Shale within the survey area to model the predicted seismic attribute response. Analysis of the modeled attributes provided valuable insight into shale porosity, brittleness, kerogen content, Vp/Vs and density.

Seismic attribute volumes that reflect elastic properties were generated from the seismic data along with geometric attributes of curvature and coherency. Multiple inversion techniques were also investigated, including a ***P-wave simultaneous inversion*** and a ***joint PP/PS inversion*** to document the value derived from the 3D3C seismic data. All elastic and seismic attribute volumes were

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calibrated to the existing subsurface data including wireline data, core data, microseismic events and production information for use in 'sweetspot' prediction.

Challenges in Multi-component Technology

Processing of multi-component seismic is one of the toughest challenges in geophysical applications today. The lack of success in this area of geophysics has been one of the biggest reasons for non-acceptance of this technology. Another reason there has not been more success in multi-component technology has been improper acquisition design for 3D3C surveys. A survey design that might provide decent data for a conventional 3D P-wave survey usually is not sufficient for a 3D3C survey. The survey needs to have a full azimuth design with aspect ratios of at least .8 (inline to cross-line offsets), and preferably as close to 1.0 as possible. Offsets may need to be longer than is acceptable for a conventional survey depending of the structural complexity of the targets and the Vp and Vs velocities. Modeling should be performed to determine the optimum acquisition designs. A survey designed for the converted wave data usually provides much better P- wave data as well. This talk will focus more on the processing and interpretation of the multi-component data.

Processing

Since the survey for this project was acquired using 3C sensors, it was possible to apply several processing techniques to extract maximum value from the data. Unlike a conventional geophone which records energy only along a vertical axis, these multi-component sensors contain three components -- one vertical and two orthogonally paired horizontals. The two horizontal components record 'converted' wave (C-wave) energy, i.e., acoustic energy that has converted from a pressure wave (P-wave) on the downward-traveling wavefield to shear wave (S-wave) energy on the upcoming wavefield.

Noise Removal and P-wave Processing: In the case of this survey, the P-wave data was processed in a fairly conventional manner. The noise was removed through proprietary adaptive subtraction techniques that are not the focus of this paper. After the application of a fairly standard, amplitude-preserving PreSTM method, high-resolution images were developed. One variation from typical P-wave processing was sectoring of the azimuths before migration to match up with the C-wave migrations. This will be discussed later in this paper. In addition to the images themselves, the P-wave processing helped to determine the appropriate Vp/Vs that were used in the beginning work on the C-wave processing.

C-Wave Processing Objectives

The goals of the converted wave processing stage were to:

Obtain a high-resolution structural image that had compatible detail and frequency content when stretched to P-wave time

Extract geophysical attributes that could help in determining brittle zones that fracture more easily and ductile zones that are poor for fracturing with hydraulic stimulation but good for keeping the frack's stimulation energy within the desired zone.

Map fracture patterns within and around the reservoir interval by assessing shear-wave splitting along the predominantly fast and slow velocity directions

Processing the C-Waves: Horizontal rotation was performed to align one of the horizontal components with the source-receiver azimuth (Radial component) and the other orthogonal to the source receiver azimuth (Transverse component). Rotation from H1/H2 to Radial/Transverse is an appropriate and necessary step for an isotropic, flat-layered sub-surface. After rotation, all of the reflected energy should be concentrated onto the Radial component, while the Transverse component should consist only of random noise only. For azimuthally anisotropic data and where shear-splitting is prevalent as is the case at this survey, a further series of rotations to the fast and slow directions is required later in the processing workflow. The examples in figures 1 and 2 are good examples of shear wave splitting to show the effect, but are not from this area.

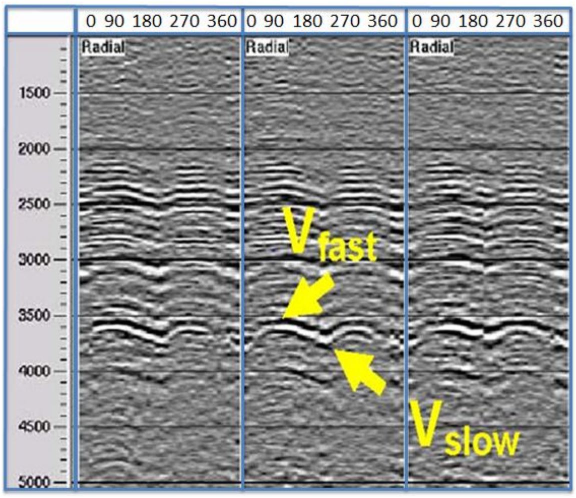

Figure 1. Radial C-wave azimuth sector gathers.

A difference in V_{fast} and V_{slow} is evidence of shear wave splitting or anisotropy. The amount of difference between the fast and slow velocities can be due to a combination of fracture density, fracture aperture and fluid fill in the fractures.

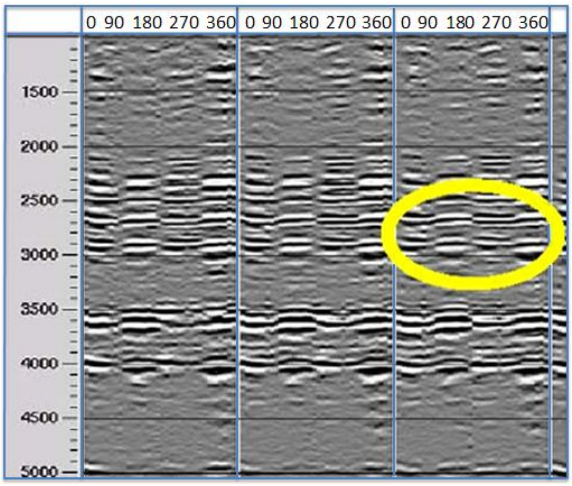

Figure 2. Transverse C-wave azimuth sector gathers.

Note the strong azimuthal anisotropic evidence of coherent data on the Transverse component with polarity reversals every 90^{o}. These reversals show very accurately the orientation of the anisotropic behavior. The processing workflow for both the P-wave and S-wave data, and how it fed into subsequent reservoir analyses, is shown in Figure 3.

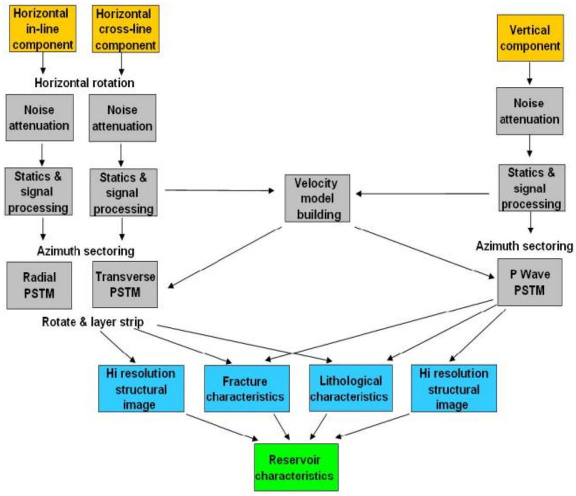

Figure 3: processing flow for the 3D3C survey

Processing the C-Waves: Azimuthal Static Corrections and Polarity Reversals and Shear wave splitting: High resolution C-wave migration volumes were created by combining the Radial and Transverse volumes. In the process, shear wave splitting and correction (SEAC)1 is performed which places all of the usable energy onto the radial as it would be in an isotropic case. Since migrations are designed to be run on isotropic data, this is the best data to input for PSTM. To properly handle shear wave splitting where there are multi levels and orientations of anisotropy, layer stripping of the anisotropic data should be done. For each layer, this process yields detailed information with respect to both fracture orientation (based on analysis of the fast/slow direction) and fracture magnitude (based on the fast/slow static). Not handling the anisotropy in this manor will yield incorrect results.

Integrated Reservoir Interpretation

Upon completion of the data processing portion of the project, all available well data, near and far offset VSP data, 3D VSP data, walk around VSP data, microseismic data, and core analyses was integrated with the newly acquired 3D3C seismic data to better define the regional geologic model, build structural and stratigraphic models for the area, understand the area anisotropy, map fracture patterns and intensity, and determine the best locations for future drilling.

Geology: The Middle Devonian age Marcellus shale is bounded by the Hamilton shale above and the Onondaga limestone below. The Marcellus was deposited during a time when convergence was occurring between tectonic plates. Sediments were shed west into the newly formed Appalachian Basin due to the rising Acadian orogenic belt. This anoxic environment resulted in the development of its highly organic state. These two orogenic events were responsible for the J2 fracturing orientation of NW/SE. Today, the Marcellus is a very expansive shale gas play covering 200,000 km2 in the northeastern United States with estimated recoverable reserves of over 300 TCF.

Rock Physics Study: Petrophysical analysis was performed on available well data in the survey area. One well had dipole logs providing shear velocity information and three wells had full suites of conventional logs. There was also core data available from one well. All available data were incorporated into a rock physics study to determine the best attributes from seismic to determine elastic parameters for determining brittleness and other key rock properties prediction.

VSP work and Fracture Detection from 3D3C Seismic: Fracture direction and anisotropic information from cores, zero offset, offset, walk-around and 3D VSPs were used to validate the fracture prediction work from the shear wave splitting work that was performed on the C-wave data.

Attribute and Interpretation Results: The key attributes determined from the rock physics study that would provide the best rock property predictions were generated from the P-wave as well as from joint inversions utilizing both P-wave and C-wave data. Well data validated the attributes generated from the joint inversion provided were the best for determining brittle zones that would fracture more easily versus ductile zones that could be good fracture barriers (see figure 4 below). Knowing where both rock types are located can be an advantage to optimizing hydraulic stimulation programs which are very expensive. Darker colors are more rigid in this figure whereas reds and greens are more brittle. The colors on the small circles represent microseismic events from different frack stages.

Note the more ductile zones which are located both above and below the lower Marcellus formation near the bottom of the section. These ductile layers keep a very high percentage of the frack energy within the brittle portion of the highly organic reservoir zone. There also appears to be a strong correlation between the amount of these events that stayed in zone and the thickness of the ductile layer above the fracked zone, as would be expected.

To determining zones of better brittleness and gas in place, other combinations of the joint inversion elastic parameters were used to determine areas of better reservoir rock (see figure 5). These better rock property areas match the engineering and production results from these wells. New wells with additional tools to measure production flow and rock properties are currently being drilled to further validate how to optimize the use of the data obtained from this multi-component seismic data.

Conclusion

Upon completion of the project, this multi-discipline integrated work team concluded that 3D3C seismic data allowed us to predict a set of rock properties from composite inversions and attribute volumes within the Marcellus shale that were validated by well data. This presentation shows that by utilizing these multiple attribute volumes and inversion products, changes in rock properties can be identified to optimize drilling locations and stimulation programs for increases production and reduced drilling costs.

Acknowledgements

Our sincere thanks to Anadarko Petroleum for permission to use these data for this study and to both Anadarko Petroleum and ION Geophysical for giving permission to give this talk.

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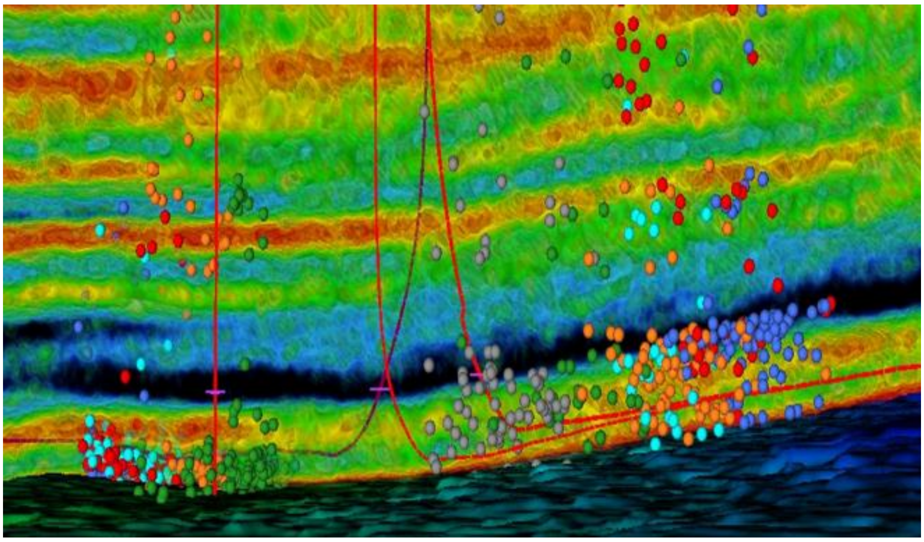
Figure 4 Shear Modulus (μ) is a measure of Rigidity

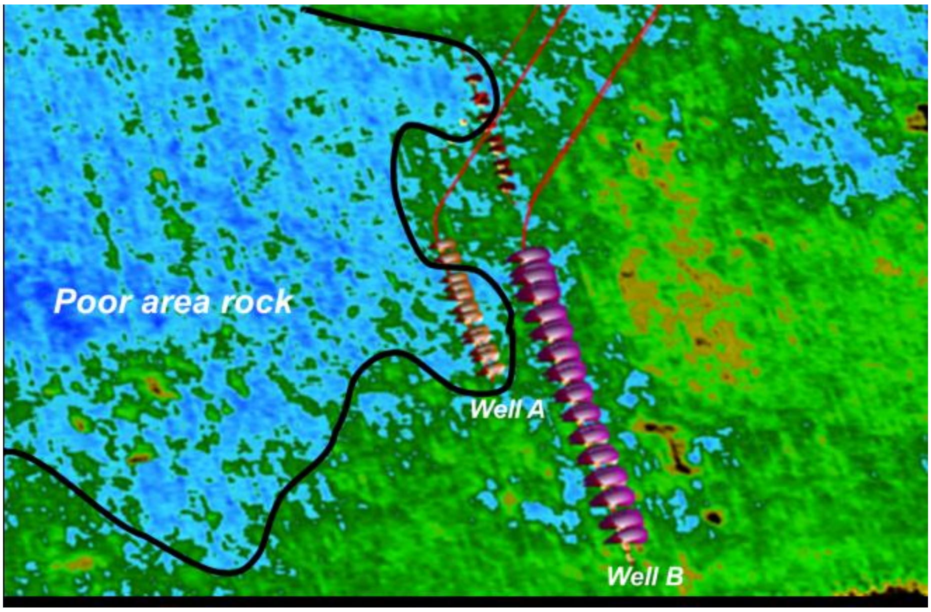

Figure 5 Time slice through target zone showing spatial distribution of rock property attributes