Towards application of nonlinear time-lapse AVO to the Pouce Coupe data set

Shahin Jabbari, Jeff Grossman, Helen Isaac, and Kris Innanen

ABSTRACT

Time-lapse is a cost-effective approach for monitoring the changes in the fluid saturation and pressure over a period of time in a reservoir. A multicomponent time-lapse seismic data set was acquired during hydraulic fracturing of two horizontal wells in the unconventional Montney Reservoir at Pouce Coupe Field in the Peace River area by Talisman Energy Inc. In this study, we are analyzing this data to validate our linear and nonlinear theoretical results for the difference data during the change in a reservoir from the baseline survey relative to the monitor survey, $\Delta R_{PP}(\theta)$. Prestack time migrated common depth point gathers (PSTM CDP) for the baseline and two monitor surveys are used. We are now well-positioned to pick events whose time-lapse AVO (amplitude variation with offset) signatures may be analyzed for nonlinearity.

INTRODUCTION

Production or employment of enhanced oil recovery techniques (EOR) affects the reservoir properties such as fluid flow and pressure. A time-lapse survey makes an important monitoring contribution to the production of hydrocarbons around the world by measuring the changes in the behavior of a reservoir over time. Comparison of repeated seismic surveys over months, years, or decades adds a fourth dimension, calendar time, to the seismic data. In a time-lapse seismic survey the baseline survey, which is acquired prior to utilization of a reservoir, is compared with the monitoring survey acquired after a particular interval of time following several geological-geophysical reservoir changes. The difference data is the difference between the baseline survey and the following monitor surveys (Greaves and Fulp, 1987; Lumley, 2011; Landrø, 2001). Perturbation (scattering) theory and amplitude variation with offset (AVO) methods can be used as a framework to model and invert the difference data in a time-lapse survey. The baseline survey is taken to describe the background medium against which to measure the perturbation detected in the monitor survey. The perturbation quantifies the changes in P wave and S wave velocities and density from the time of the baseline relative to the monitor survey (Innanen et al., 2013).

There is a strongly nonlinear relationship between P-wave velocity changes and pressure changes in a reservoir during production (Landrø, 2001). This is suggestive that large local variations in seismic parameters, leading to non-negligible AVO nonlinearity, are possible.

A framework has been formulated to model linear and nonlinear elastic time-lapse difference AVO ($\Delta R_{PP}(\theta)$) for P-P sections (Jabbari and Innanen, 2013). The framework is a series expansion for the difference reflection coefficient $\Delta R_{PP}(\theta)$ in orders of (1) $\sin^2\theta$, (2) elastic property contrasts across the reflector (e.g., caprock over reservoir) at the time of the baseline survey, and (3) elastic property time-lapse perturbation. To first order our

$\Delta R_{PP}(\theta)$ is an agreement with that used by Landrø (2001). The higher order terms provide corrections when contrasts are large. In the second part of the study, Jabbari and Innanen validated the linear and nonlinear $\Delta R_{PP}(\theta)$ modelling terms using physical modelling data acquired at the CREWES/University of Calgary facility.

In the present study in conjunction with Talisman Energy Inc., a time-lapse data set acquired during hydraulic fracture stimulations of two horizontal wells in the Montney Shale at Pouce Coupe Field, Alberta, Canada has been used to compare our theoretical linear and nonlinear difference data AVO with real data.

Theory

The amplitudes of reflected and transmitted P and S waves striking on the boundary of a planar interface between two elastic media, incident medium (cap rock) and reservoir with rock properties V_{P0}, V_{S0}, ρ_0 and V_{PBL}, V_{SBL}, ρ_{BL} as in baseline survey, are calculated. Setting boundary conditions in the problem leads to Zoeppritz equations which can be rearranged in a matrix form (Aki and Richards, 2002). Reflection coefficients for the baseline and monitor surveys are determined by using Cramer's rule and forming auxiliary matrices. For the monitor survey, rock properties for cap rock are the same, but reservoir properties change to V_{Pm}, V_{Sm}, ρ_m. The difference data reflection coefficients between the baseline and monitor survey is then calculated as:

$$\Delta R_{PP}(\theta) = R^m_{PP}(\theta) - R^b_{PP}(\theta) \tag{1}$$

In our time-lapse study we have considered two groups of perturbation parameters (Innanen et al., 2013; Stolt and Weglein, 2012). We use the same standard scattering nomenclature found in Stolt and Weglein (2012). The first group expresses the perturbation caused by propagating the wavefield from the first medium to the second medium in the baseline survey:

$$b_{VP} = 1 - \frac{V^2_{P_0}}{V^2_{P_b}}, \;\; b_{VS} = 1 - \frac{V^2_{S_0}}{V^2_{S_b}}, \;\; b_\rho = 1 - \frac{\rho_0}{\rho_b}. \tag{2}$$

The second group is to account for the change from the baseline survey relative to the monitor survey, the time-lapse perturbation, we define:

$$a_{VP} = 1 - \frac{V^2_{P_b}}{V^2_{P_m}}, \;\; a_{VS} = 1 - \frac{V^2_{S_b}}{V^2_{S_m}}, \;\; a_\rho = 1 - \frac{\rho_b}{\rho_m}. \tag{3}$$

$\Delta R_{PP}(\theta)$ is then expanded in orders of all six perturbations, $\sin^2\theta$, and $\sin^2\phi$.

$$\Delta R_{PP}(\theta) = \Delta R^{(1)}_{PP}(\theta) + \Delta R^{(2)}_{PP}(\theta) + \Delta R^{(3)}_{PP}(\theta) + ... \tag{4}$$

More details can be found in Jabbari and Innanen (2013). The derived equations for the first, second, and third orders can be found in our technical report in 2012 (Jabbari and Innanen, 2012).

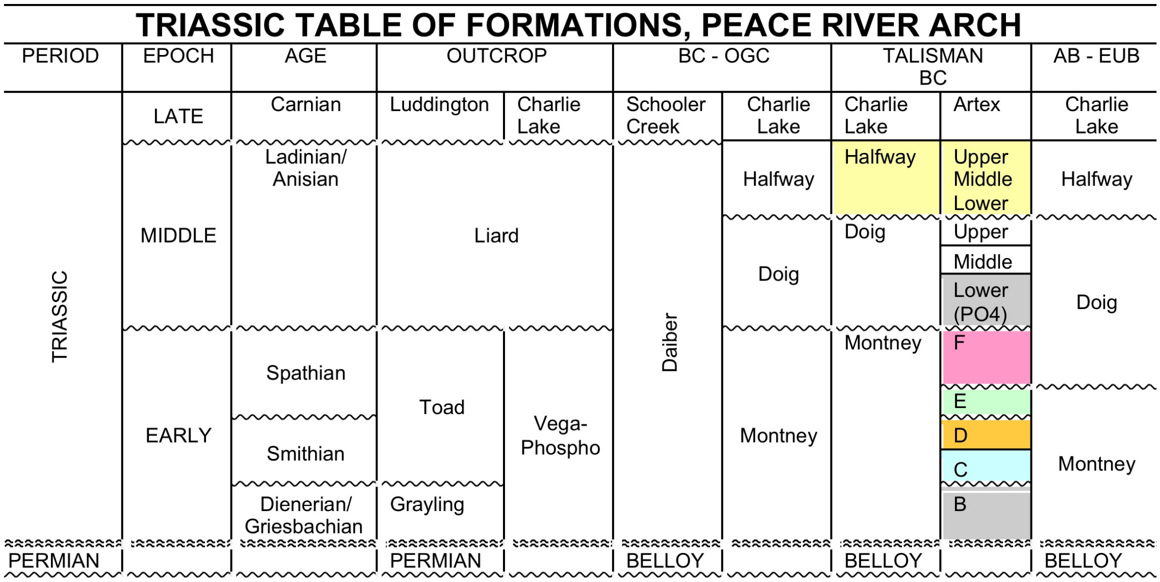

FIG. 1. Triassic Montney Formation in the Peace River Arch region. Pouce Coupe Field is represented by the colored formations in the Talisman BC chart section (courtesy of Talisman Energy).

Pouce Coupe time-lapse, Multicomponent Seismic Data

4D time-lapse, multicomponent seismic surveys were acquired by Talisman Energy Inc. at the Pouce Coupe Field which is located on the border of Alberta and British Columbia in the Peace River area . The target formation in these seismic acquisitions was Triassic Montney Shale reservoir (Figure 1). The Montney Formation is fine-grained, pseudo-turbidites proximal to the shoreface deposition and is classified as an organic-rich argillaceous siltstone and sandstone package. Based on information obtained by Talisman Energy Inc., the Montney reservoir has a matrix permeability of 0.01-.02 mD and porosity of 6-10 % within the Pouce Coupe Field. The unconventional Montney reservoir at Pouce Coupe has tight gas silts and sands and produces both gas and liquid hydrocarbon. For economic production, enhanced permeability pathways of natural and induced fractures are required due to the tight nature of the Montney (Davies et al., 1997; Davey, 2012). The baseline, acquired in March 2008, was conducted after completion and stimulation of the 00/7-7 well, but before production was initiated. Monitor 1 was acquired from December 8 to 10, 2008, after 8 months of Montney gas production from the 00/7-7 well. The purpose of acquiring this survey was to characterize the reservoir condition prior to hydraulically fracturing of the two horizontal wells. The hydraulic fracture operations took place in two separate stages on the two horizontal wells, and another two subsequent monitor surveys were acquired after each fracture event. Monitor 2 and 3 were acquired between December 13-14 (after fracturing the horizontal well 02-07) and between December 18-19 (after fracturing the horizontal well 07-07) ,respectively, as in Figure 2 (Atkinson, 2010; Atkinson and Davis, 2011). In this study, we will consider monitor 1 as the baseline survey, and monitors 2 and 3 as the first and second monitors respectively.

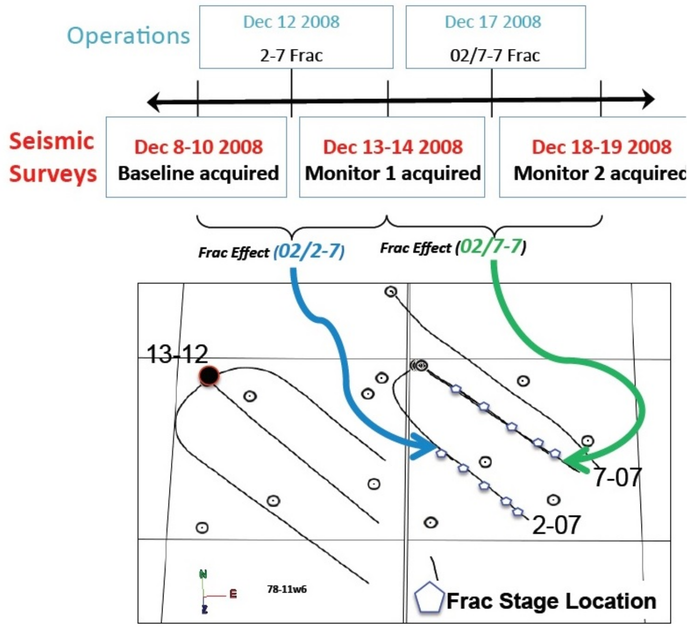

FIG. 2. Pouce Coupe time-lapse seismic and field operations timeline. Two horizontal wells hydraulically stimulated (2-07 well and 7-07 well) and the location of the vertical shear sonic log (13-12 well). Modified from Atkinson (2010).

Analyzing the data

Seismic data was recorded by CGGVeritas on a patch grid of about 5 km^2 (Figure 3). The survey grid consists of 144 buried 3C receivers and 1241 shot holes forming a field layout of 41 inlines and 101 crosslines. The bin size is 50 m $\times$ 100 m (patch is twice bigger in E-W direction). The recording length is 6 seconds with a sampling interval of 2 ms. A result of the survey design was uniform $360°$ azimuth for different offset distribution which provides data for future AVO/AVAZ analysis. The processing was completed by Sensor Geophysical Ltd. in July 2013. The processing flow includes statics, prestack noise attenuation, surface consistent deconvolution, CDP (common depth point) stacking, FK (frequency enhancement) filter, radon multiple and normal 2-term moveout. Subsequently, Sensor Geophysical Ltd reprocessed the data making use of a set of new methods to enhance time-lapse repeatability and improve prestack shear wave splitting analysis. Receiver Azimuth Detection and Rotation (RADAR) was utilized to detect and correct receiver azimuths and this improved the quality of the subsequent steps of processing the horizontal receiver components (Grossman et al., 2013; Steinhoff, 2013). Further details of multicomponent processing are outlined in Steinhoff's thesis (2013).

The multicomponent surface seismic data set in the Pouce Coupe includes a baseline survey with two consequent monitors. The acquisition was designed to cover a full 360 degree azimuth and offset range from 340 to 3011 meters to a bin size of 50 m by 50 m. Sensor Geophysical Ltd. reprocessed the Pouce Coupe seismic surveys. Figure 4 shows prestack time migration common depth points (CDP) gathers for the baseline and monitor 2.

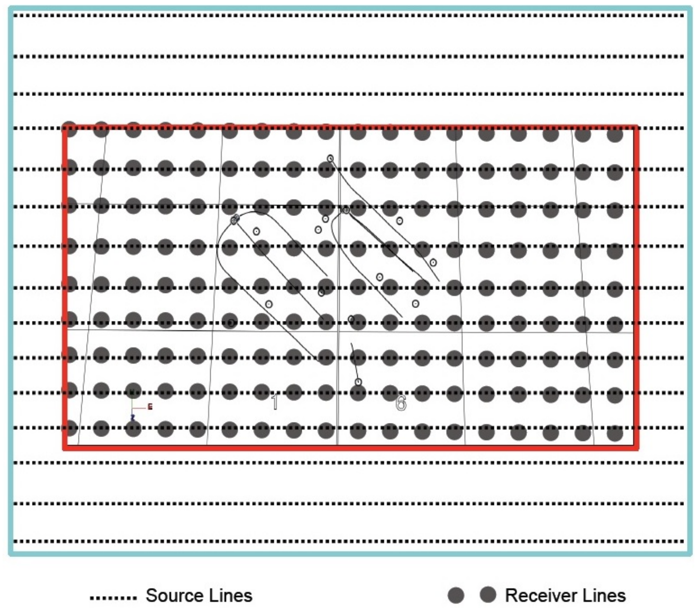

FIG. 3. Pouce Coupe time-lapse, multicomponent seismic survey acquisition layout. Resulting 1.6 km $\times$ 3 km patch centered over horizontal wells 2-07 and 7-07. Modified from Atkinson (2010).

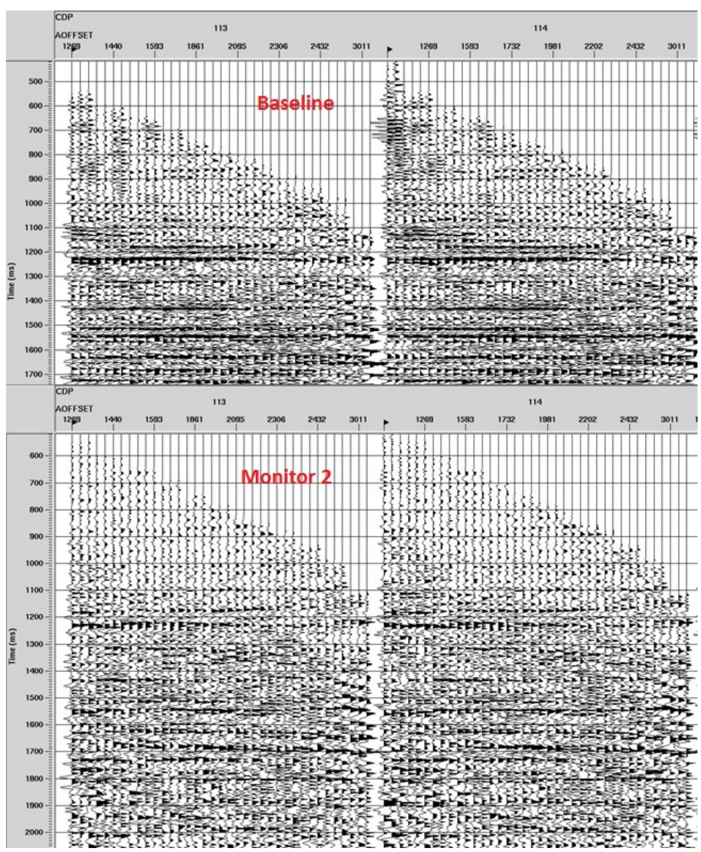

FIG. 4. PSTM (Pre stack time migration) CDP (common depth point) gathers for the baseline and monitor surveys.

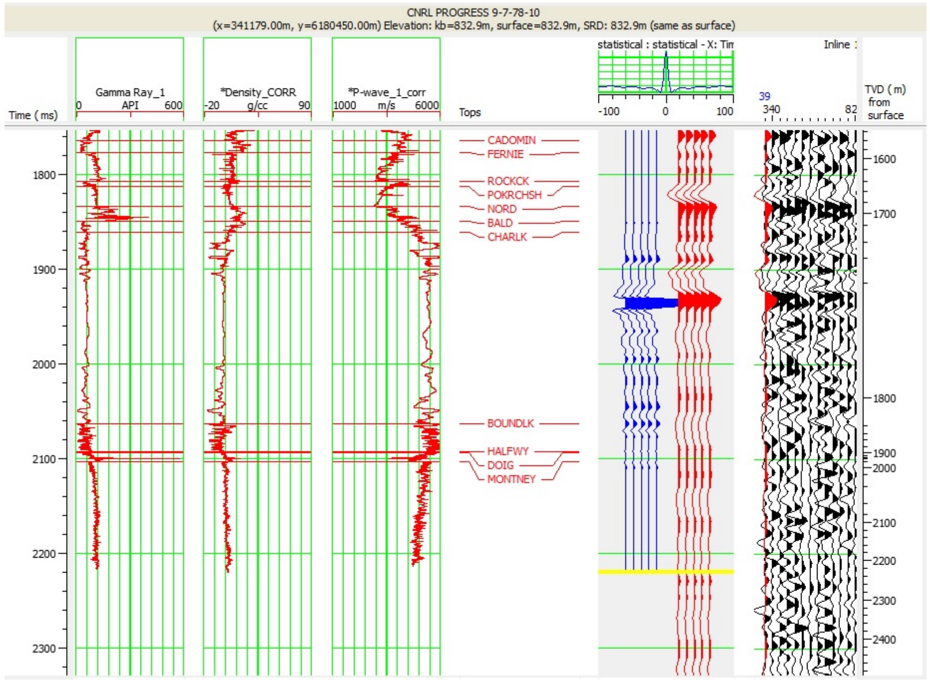

FIG. 5. Vertical well tie with baseline P-wave seismic.

The well tie of the P-wave is done using a statistically extracted wavelet and the acquired P wave sonic logs at the vertical well 09-07-078W6. Figure 5 shows the well tie for the baseline. Interpreting the Montney formation using this well tie can lead to an estimation of the seismic event in the formation. Using this estimation and AVO analysis, amplitude versus offset can be obtained.

Figure 6 shows the AVO analyzing for the whole range of offsets and azimuths for the same well in the Montney formation which is done using AVO gradient analysis.

Plan forward

We are now able to pick events whose time-lapse AVO signatures can be analyzed. We will investigate nonlinearity of P-wave time-lapse changes by focusing our analysis on the fracture area where near initial reservoir pressure is expected, in the vicinity of the induced fracture.

From review, hydraulic fracture stimulations resulted in a shear-wave splitting produces measurable results as a monitor of time-lapse changes (Atkinson and Davis, 2011). Thus, following the P-wave time-lapse investigation, we will monitor any converted wave time-lapse changes to model the hydraulic fracture stimulation.

CONCLUSIONS

Changes in the fluid saturation and pressure will have an impact on elastic parameters, such as P-wave and S-wave velocities and density of the subsurface, which can be approximated by applying time-lapse AVO analysis methods. An increase in pore pressure has

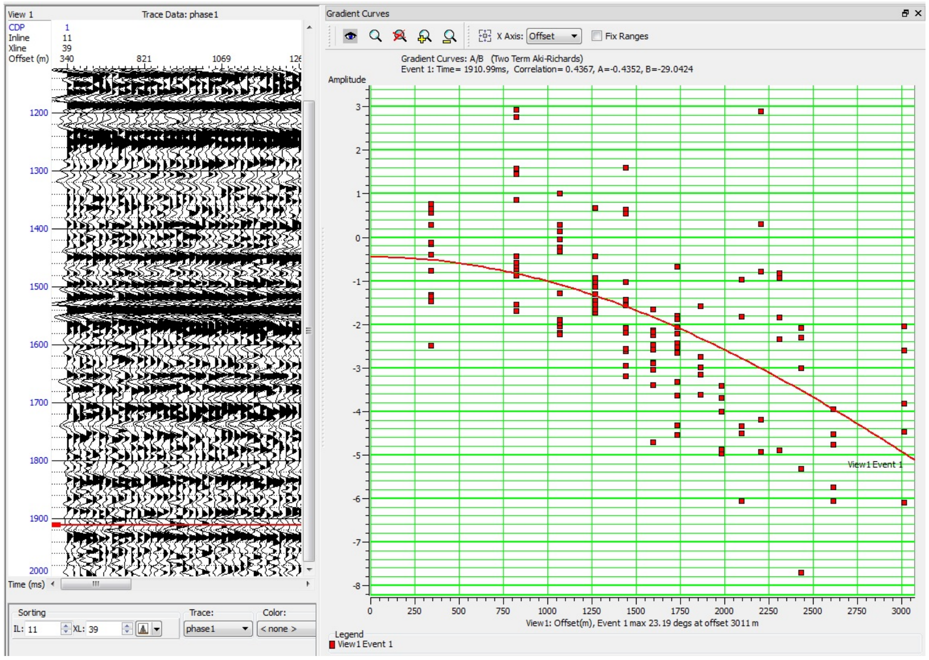

FIG. 6. Amplitude versus offset for the Montney formation for offset and azimuth ranged from 340-3011 meters and $0°$-$360°$ respectively.

been induced following the hydraulic fracture operations in the unconventional Montney shale reservoir. This will affect the seismic parameters including the compressional wave velocity. Due to the tight nature and low permeability of the Montney reservoir, the injection of fluid into the reservoir during the fracture operations will affect only the close vicinity of the fractures. For this reason, the change in P-wave velocity should be investigated in the vicinity of the hydraulic fractures in the horizontal wells. We have initiated the investigation and are analyzing methods to quantify the P-wave time-lapse difference AVO. Data analysis is still under review pending more well data information.

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