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Numerical Modeling of Shear-wave Splitting and Azimuthal Velocity Analysis in Fractured Media

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Abstract

This paper presents the processing and interpretation of seismic modeling data of the earth models for a fractured layer, based on well logs associated with potash mining. The purpose of the work is to study azimuthal seismic anisotropy, shear-wave splitting, and time-lapse seismic signals caused by vertically aligned fractures. The results show that seismic velocity anisotropy can be detected by both vertical and horizontal components of the HTI earth model; it is especially evident on radial component. Shear-wave splitting is evident and the fracture orientation determined from the polarization of fast and slow shear waves is consistent with the input model. The time-shift and amplitude changes due to anisotropic layer are also apparent on both vertical and radial component data. The time-shift on radial data is up to 5ms and the amplitude change is up to 46%.

Introduction

A major problem for potash mining can be brine inflow. In the studied Saskatchewan potash mining area, potash ore is situated 20-30m below a formation (the Dawson Bay Formation) composed of fragile rocks, mostly dolomite and dolomitized limestone (Fuzesy, 1982). Above this formation, there can be two aquifers in this area. Any fracturing of normally impermeable carbonate rocks could create a brine inflow path that might compromise potash mining operations. To investigate the feasibility of using multi-component and repeated (time-lapse) seismic methods for crack mapping and monitoring, rock-physics modeling and synthetic seismogram were used to predict seismic velocity changes and seismic signatures of cracks in the carbonates (Zhang and Stewart, 2008). The results indicate that P-wave and S-wave velocities will decrease (often significantly) with cracks or fractures. Vertically aligned cracks may also display azimuthal anisotropy. Synthetic seismograms (for isotropic velocities) calculated using the original well logs and those with cracks show observable changes.

To study the seismic signatures of anisotropy caused by aligned fractures, seismic modeling data for unfractured (isotropic) and fractured (anisotropic) models are used for shear-wave splitting, seismic velocity anisotropy, and time lapse seismic signature analysis in this paper.

3C-3D seismic data acquisition and processing

An exhaustive wide azimuth survey was designed for 3D-3C seismic data acquisition. The input earth models are laterally homogeneous (Figure 1): the isotropic earth model was built from the blocked well logs at the study area; the anisotropic (HTI) model was created by replacing rock properties of the full Dawson Bay Formation (40 meters thick) by the rock physics modeling results (Zhang and Stewart, 2008) from 1% vertically aligned fractures. Since the earth models are laterally homogeneous, for each model only one shot was modeled with the source location at the center of the survey. The recording coordinate X is normal to the fracture (isotropy axis); Y is along the fracture (isotropy plane). The seismic modeling uses frequency-wavenumber method. A 3C processing workflow (Gray et al, 2008; Stewart and Gaiser, 2007; Van Dok et al, 2001) was used, including loading geometry information, horizontal rotation for x & y components, spherical divergence compensation, deconvolution, velocity analysis and NMO, noise attenuation using FK filter, then the data were divided into common azimuth gathers: 0°-360° by increment 6° with a tolerance of ±3°, finally the data were stacked for interpretation.

Velocity anisotropy

Azimuthal velocity analysis was carried out for both vertical and radial components for anisotropic (HTI) model. Figure 2 shows the velocity picked at seven selected azimuths from 0° to 90° by increment 15° for vertical and radial component focused on the fractured formation. From the

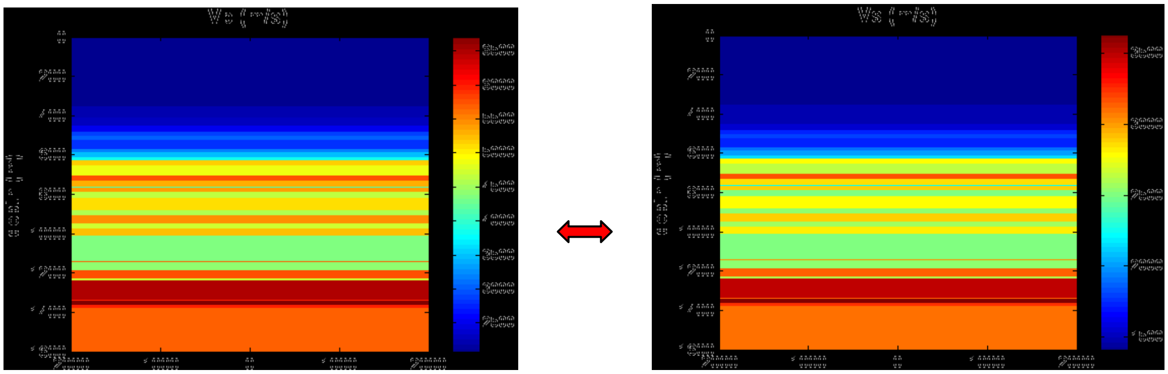

Figure 1: Input interval P-wave and shear-wave velocity layered models for numerical modeling. The anisotropic layer (the Dawson Bay Formation) location is denoted by red arrow.

azimuthal velocity analysis, we can see the difference from the top of the First Red Bed Shale, about 665ms on vertical component, and 848ms on radial component. From the velocity plots, we can see the velocities are constant above the top of the Dawson Bay. The maximum variation of stack velocity with azimuth exists at the bottom of the fractured Dawson Bay. For the P wave data, the maximum stacking velocity at the bottom of the Dawson Bay Formation is at azimuth 0°, which is parallel to the isotropy plane. The minimum stacking velocity of the base of the Dawson Bay Formation for the PS data is found to be at azimuth 45°.

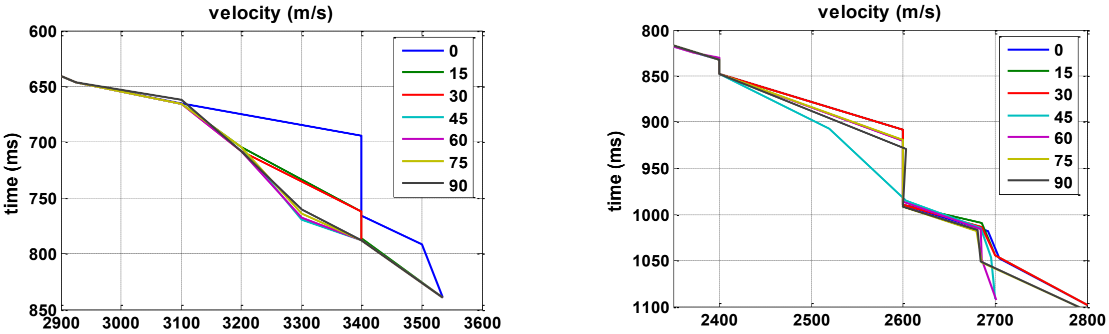

Figure 2: Stack velocity plots at seven azimuths from 0° to 90° for vertical (left) and radial (right) components.

Shear-wave splitting analysis

Figure 3 shows the azimuth bin stack of radial data for both isotropic and HTI models. The stack results were also correlated to synthetic seismograms from well logs. The correlations between synthetic seismograms and azimuth bin stack are quite good. Above Event 1 (above fractured formation) picked on the data, stacks of isotropic and anisotropic models are quite consistent. Below Event 1, the reflections are coherent with azimuth on stack results of isotropic model. On the stack results of anisotropic model, however, there are variations of amplitude and time. From the differences between stack results of isotropic and anisotropic models, we can see the minimum difference is at azimuth 0° and 180° (along fracture plane), the maximum difference is at azimuth 90° and 270° (along fracture normal direction). On the bin stack of transverse component (bottom of Figure 4), only the reflections below the top of the Dawson Bay can be seen and no sinusoidal shape reflections time variation is found. However, polarity flip happens across 0°, 90°, 180° and 270°.

Figure 4 shows the interpretation result of fast and slow shear-wave directions. Fast shear-wave S1 is along 0°-180° direction, which is consistent with the fracture plane direction of the input model. Slow shear-wave orientation is along 90°-270° direction, the direction normal to the fractures of the input model.

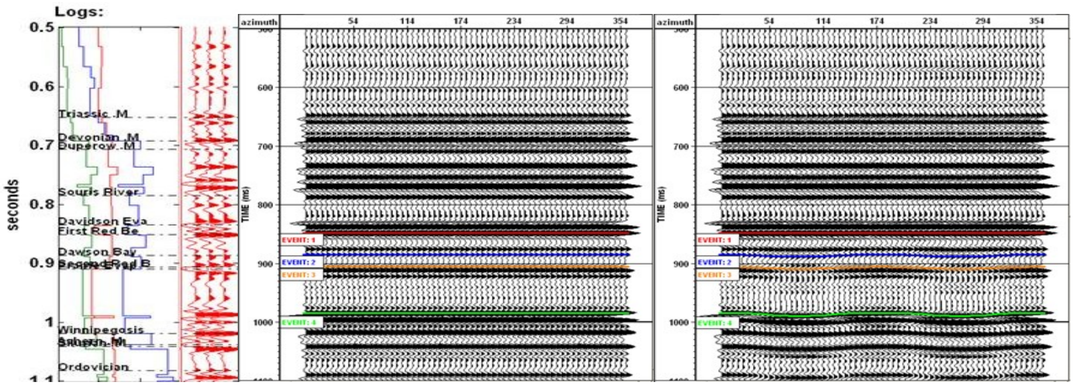

Figure 3: From left to right: blocked well logs, synthetic seismogram, azimuth (0°-360°) bin stack of radial data for isotropic model and anisotropic (HTI) model. The four events picked (from top to bottom) are the top of First Red Shale (red), the top of Dawson Bay (fractured formation, blue), the base of Dawson Bay (yellow), and the top of Shell Lake Anhydrate (green).

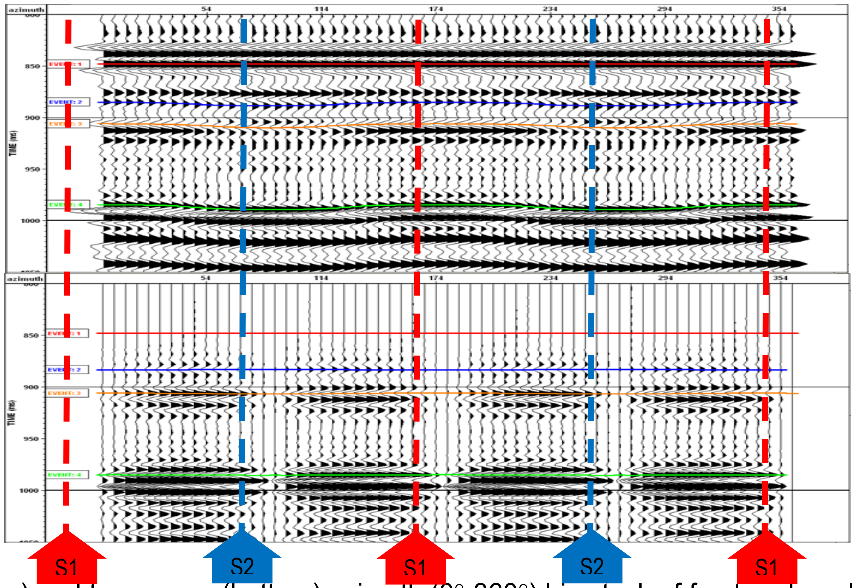

Figure 4: Radial (top) and transverse (bottom) azimuth (0°-360°) bin stack of fractured model. The red dashed lines show the fast shear-wave (S1) polarization direction and the blue dashed lines show the slow shear-wave (S2) polarization direction. The four events picked are the same as in Figure 3.

Time-lapse attributes analysis

Time lapse attributes analysis was performed for time and amplitude of the three picked events mentioned before, E1 above the fractured formation, the base of fractured formation E2, and E3 below the fractured formation. Figure 5 displays the time and amplitude differences of the three events for vertical and radial component of isotropic and HTI models. At picked horizon 1 (E1), since all the overlying strata of the two models are same and isotropic, there is almost no time shift from azimuth 0 to 360 degree on both vertical and radial component. However, small amplitude differences, up to 3.2% increase on vertical component and 2.2% increase on radial component, exist at the top of the fractured layer. At the bottom of the fractured Dawson Bay (E2), up to 0.75ms time delay and ±3.7% amplitude change can be seen on vertical component due to the fractures. On radial component, we can see a larger time delay (up to 3.75ms) and amplitude change (up to 46% decrease) compared with vertical component. Although all the formations underlying the Dawson Bay are totally the same for the two models and both isotropic, larger time delay (up to 1.1ms) and 4.9 on radial component) and amplitude change (up to 12.2%) are found on vertical component at deeper reflections, e.g., at E3. The time delay is up to 4.9ms and the amplitude change is up to 30% on radial data at this interface. The reason for the increases of time delay and amplitude change could be the incidence angle difference for E2 and E3 when P- and shear-waves travel through the anisotropic layer.

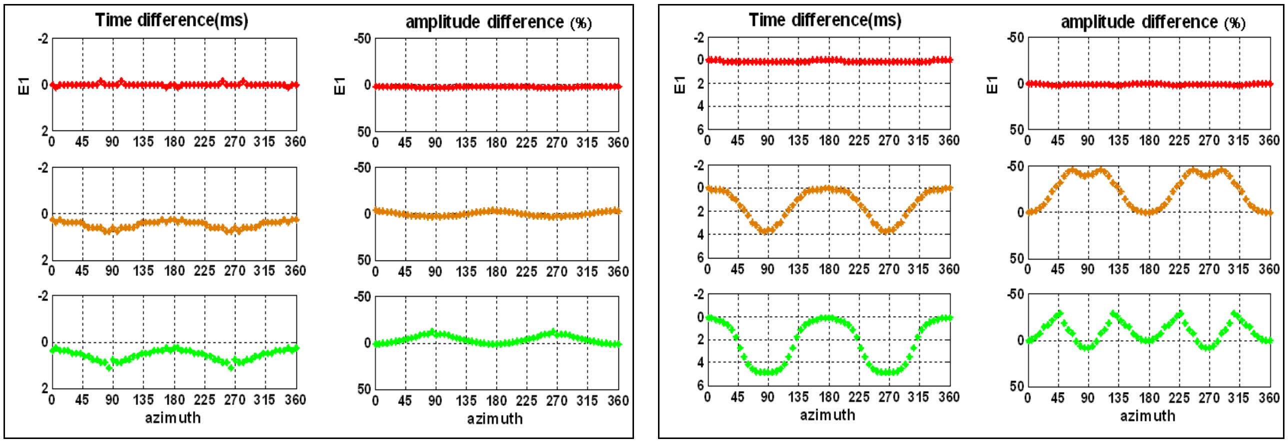

Figure 5: Time and amplitude (in percentage) difference plots of the three events on the vertical and radial component azimuth bin stack between unfractured and fractured models. The three events are the top of First Red Shale (E1), the base of Dawson Bay Formation (fractured formation, E2), and the top of Shell Lake Anhydrite (E3).

Conclusions

This paper presents the processing and interpretation of seismic modeling data of the earth models generated based on well logs in a potash mining area of western Canada. The goal of the work is to study the evidence of azimuth seismic anisotropy, shear-wave splitting and time-lapse seismic signals caused by HTI anisotropy from vertically aligned fractures in the Dawson Bay Formation. The results show that seismic velocity anisotropy can be detected by both vertical and horizontal components of the HTI earth model, it is especially evident on radial component. Shear-wave splitting is distinct and the fracture orientation determined from the polarization of fast and slow shear waves is consistent with the input model. The time-shift and amplitude changes due to anisotropic layer are also apparent on both vertical and radial component data. The time-shift on radial data is up to 5ms at the top of Shell Lake anhydrite, and the amplitude change is up to 46% at the base of Dawson Bay.

Combined with the correlation results of well and surface seismic data in the previous study (Zhang and Stewart, 2008), this suggests that multi-component seismic data could be interpretable in this potash area of western Canada. This also suggests that by searching for seismic anisotropy, shear-wave splitting on the multi-component seismic data or by looking for changes in repeated seismic surveys, we may be able to detect/monitor fractures and fracture orientation in the Dawson Bay and similar intervals.

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