Seismic Detection of Cracks in Carbonates Associated with Potash Mining

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Summary

Brine inflow in a mine, resulting from cracks or fractures in overlying strata, can be a significant problem. This paper investigates whether cracked or fractured rock, associated with potash mining in western Canada, might be detectable by multi-component seismic methods. Rock physics modeling was carried out to simulate cracked rocks overlying a potash ore zone. The Kuster-Toksöz procedure modeled randomly distributed cracks while Hudson's formulation was used for aligned cracks in a carbonate interval (the Dawson Bay including the Second Red Bed Shale) overlying the Prairie Evaporites. We find that cracked rocks can display a significant velocity decrease for both P- and S-velocities. For aligned cracks, velocity anisotropy was also observed. Synthetic seismograms for these cracked media show some character change (time shifts, amplitude variation with offset) compared with uncracked responses. The results provide promise for the detection of cracked rock using multi-component seismic data and repeated surveys.

Introduction

A major problem for potash mining in this area can be brine inflow. An effective way to mitigate the risk posed by brine flows is to map and predict the volume and location of potentially affected areas prior to mining. In the potash mining area, there can be an aquifer at the bottom of the Souris River Formation. Between the aquifer and ore zone, lies the First Red Bed Shale and the Dawson Bay. These formations are composed of shale, dolomite and dolomitized limestone. All these rocks are apt to be cracked. Any fracturing of normally impermeable carbonate rocks could create a brine inflow path that might compromise potash mining operations. For predicting cracks induced by mining processes, multi-component and repeated (time-lapse) seismic methods might be useful. In this study, rock-physics modeling for cracked media was used to assess the feasibility of detecting cracks by multi-component and time-lapse seismic methods. Kuster-Toksöz modeling (Kuster and Toksöz, 1974; Berryman, 1980) was undertaken to simulate randomly distributed cracks while Hudson's model (Hudson, 1981) was used for aligned cracks.

Modeling the cracked media

Both the Kuster-Toksöz and Hudson's methods assume isolated cracks, thus they are only valid at high-frequencies. For low-frequency moduli calculation, dry moduli were first predicted using effective moduli theory for cracked media. Then, the saturated moduli were calculated through fluid substitution using the Gassmann equation for randomly distributed cracks and Brown and Korringa's (Brown and Korringa, 1975) low-frequency relations for aligned cracks. The sequence for modeling fractures and cracks is:

1) Edit the well log values (especially shear logs) and predict shear logs using P-velocity and density logs where the shear log is not reliable;

2) Model dry cracks using the Kuster-Toksöz method and undertake fluid substitution using Gassmann equation for randomly oriented cracks;
3) Model dry cracks using Hudson's theory and fluid substitution using Brown-Korringa's low frequency relation for aligned cracks;
4) Calculate P- and S-velocities for cracked media.

Before modeling the cracked media with values from well logs, we investigate the quality of the logs and find shear-wave velocities are very poor in the salt interval in this well, while the P-wave velocity and density log are reasonable. Following the method proposed by Han and Batzle (2004), the shear velocities are predicted from P-wave velocity and density. Figure 1 shows the predicted and actual shear velocity logs and their differences, which are mostly within 200m/s. All the shear velocities over the questionable intervals will be replaced by the predicted values.

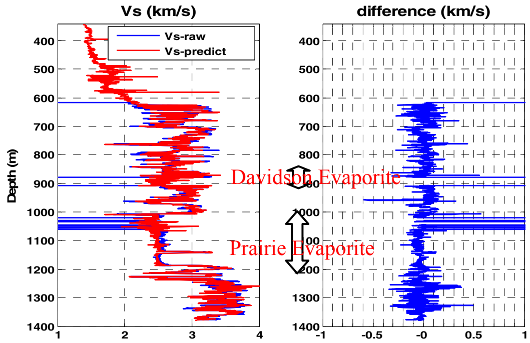

Figure 1. Predicted (red, left) and actual Vs (blue, left) and their difference (right) for Well A.

We first use the Kuster-Toksöz theory to calculate the effect of cracks on velocities. For the modeling, we assume that the porosity introduced by penny-shaped cracks is 1%, the aspect ratio is 0.01. Figure 2 displays the modeled logs of Well A using Kuster-Toksöz model for randomly oriented brine saturated cracks. The density and P-velocity of brine are set to be 1.1g/cm^3, 1430m/s respectively. The P-velocity drops about 0.7km/s (12.5%), and the shear velocity decreases by 0.6km/s (20%). For a 40m cracked interval, this amounts to about a 2ms push down in P waves and 3.5ms delay in PS reflection traveltime.

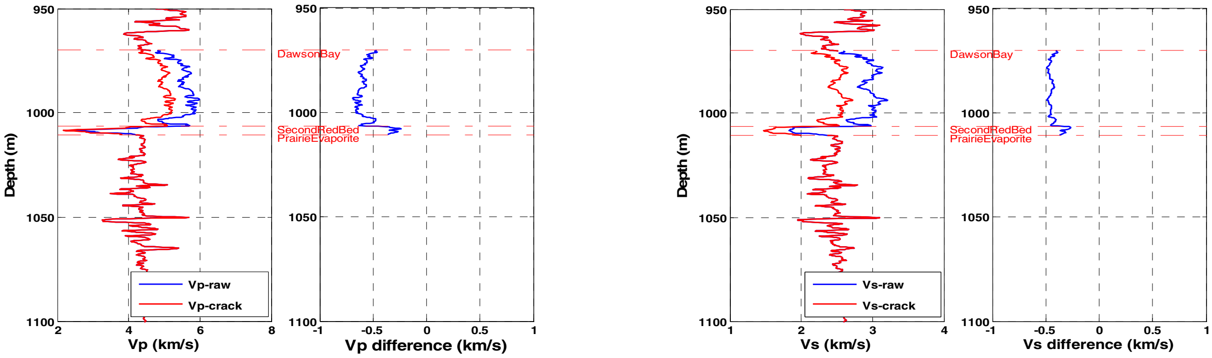

Figure 2: Velocity of cracked media from Kuster-Toksöz model and velocity difference between uncracked (blue curve) and cracked (red curve) rock for Well A. Left: P-wave velocity; right: shear-wave velocity.

If the cracks are aligned with specific directions, the elastic properties of rock can be modeled by Hudson's (1981) theory, and the rock will display anisotropy. Figure 3 shows the modeled logs of Well A assuming vertically aligned cracks in the formations overlying the mining interval. The rock displays transverse isotropy with respect to x-axis (horizontal) or azimuthal anisotropy in the x-y plane. The P-velocity along the vertical direction shows a small decrease, less than 0.2km/s (3.5%), while the SV-velocity propagating vertically drops significantly, about 0.8km/s (26%). For horizontally traveling waves, the P-velocity decreases by about 0.75km/s (13.5%) and the SV-velocity drops at the same amount as vertical propagation.

Figure 4 shows the velocity variation with angle from the symmetry axis (the x-axis). The P-velocity will gradually drop at small incidence angle from 0° to 45°, and then increase from 45° to 90° incidence. The SV-wave velocity reaches its minimum at 0 and 90 degree incidence, and maximizes at a 45° incidence. The SH-wave velocity drops gradually from vertical to horizontal propagation.

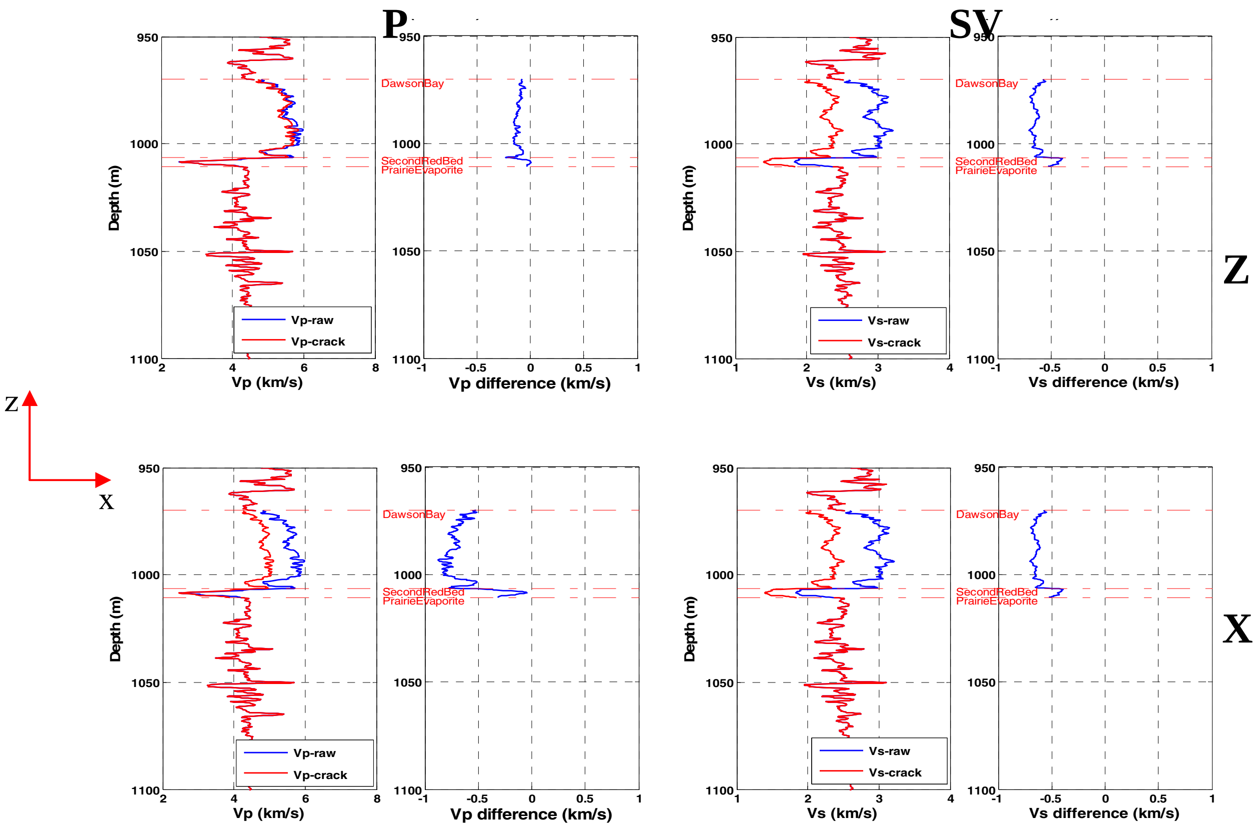

Figure 3: Top: vertical propagation velocity of a vertically cracked medium from Hudson's formulation and the velocity difference between uncracked and cracked rock (Left: P wave; right: S-wave) for Well A. Bottom: the same plots for horizontally propagating waves through a vertically cracked medium.

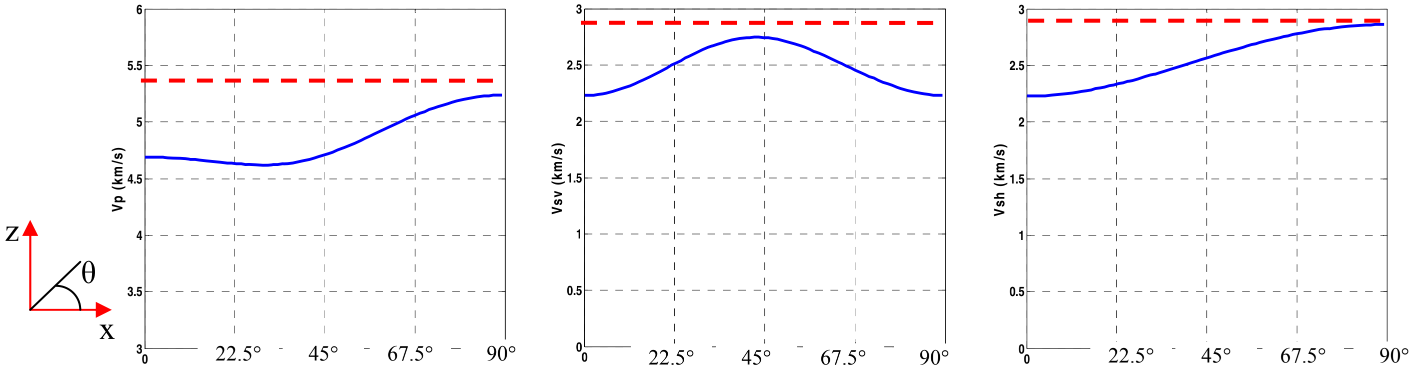

Figure 4: P- (left), SV- (middle) and SH- (right) velocity variation with angle (θ) from the symmetry axis (x-axis) for the cracked medium. The rock properties of uncracked media (velocities shown by red line in each plot) are the average over Dawson Bay and the Second Red Bed Shale of Well A.

SYNTHETIC SEISMOGRAMS FOR P- AND CONVERTED WAVES

We then use these "cracked" and uncracked logs to generate synthetic seismograms using Ricker wavelets based on the likely bandwidth of field seismic. The purpose of this simulation is to investigate the changes in the seismograms caused by the cracks. The software used for synthetic seismogram generation assumes isotropic velocities, so vertical velocities from Hudson's model were used. Figures 5 show the original well logs and their accompanying synthetic seismograms along side the "cracked" well logs and their synthetic seismic response. From the synthetic seismograms, we observe the following changes caused by cracks in the Dawson Bay and the Second Red Bed Shale: some push-down (time increase) in the PP wave and an amplitude versus offset (AVO) effect; push-down and dimming (amplitude loss) in the PS wave. We also find that the effects are much stronger on the PS data than on the PP data. It indicate that PS data will be very useful for searching for anomalies caused by cracks associated with mining.

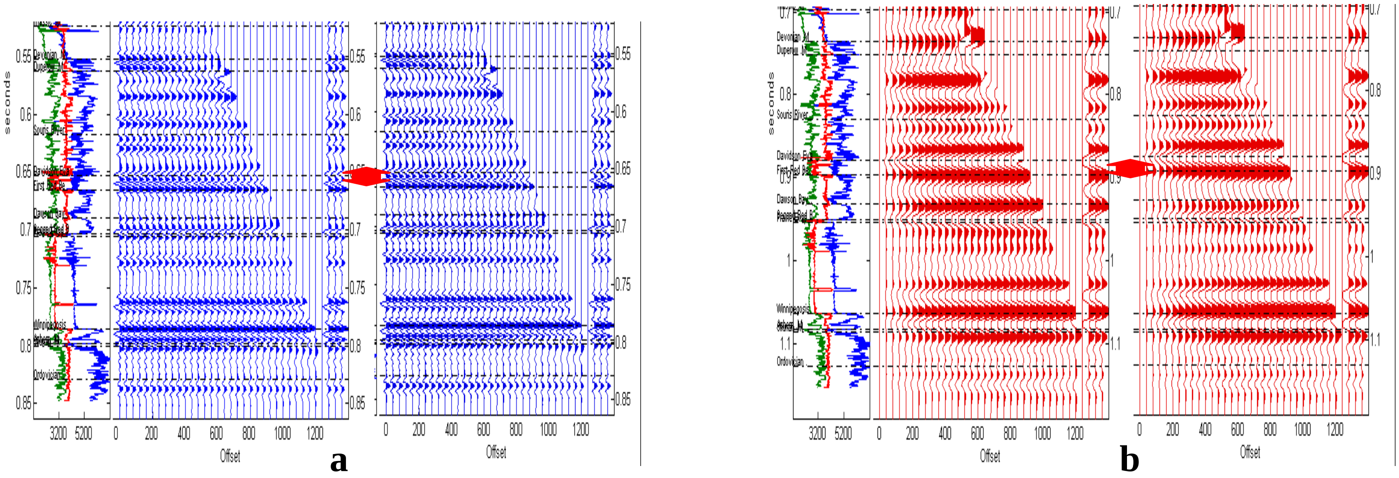

Figure 5: Well logs (P velocity in blue, S-velocity in green, and density in red) and synthetic PP (a) and PS (b) seismogram (NMO removed gather and summed response, duplicated 3 times) for Well A. Left: uncracked rock; right: cracked rock. The red arrow marks the strata cracked.

Conclusions

This paper presents the results of a petrophysical and seismic simulation study in a potash mining area of western Canada. The goal of the work is to model the effects of cracked rocks in the Dawson Bay formation on seismic reflection character. Shear-wave sonic logs sometimes display unrealistic values. We can effectively edit these values, in this study, by using P velocity and density logs. Rock physics modeling (from Kuster- Toksöz and Hudson) indicates that P-wave and S-wave velocities will decrease (often significantly) with cracks or fractures. These cracked strata may also display various types of anisotropy or velocity variation with direction. Synthetic seismogram calculation using the original log values and those with cracks shows observable changes. Those changes include "push-down" effects or time lags and amplitude variations with offset. The seismic character differences are especially evident in the PS reflections. This suggests that by searching for anomalies in the multi-component seismic data or by looking for changes in repeated seismic surveys, we may be able to detect cracks in the Dawson Bay and similar intervals.

Acknowledgements

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