Using time-lapse VSP data to constrain velocity-saturation relations

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SUMMARY

Quantitative interpretation of time-lapse seismic data is an ongoing challenge. Understanding the velocity-saturation relations and changes caused by CO₂ injection play an important role for the application of seismic monitoring techniques to carbon dioxide storage projects.

High uncertainties associated with well log measurements affected by borehole conditions can affect our ability to constrain a rock physics model. Seismic measurements, such as Vertical Seismic Profile (VSP), that span both the near-well region and far beyond the borehole can provide good control for correcting these measurements and reducing the uncertainties thereafter.

In this paper, we analyse the observed time delays in time-lapse VSP data from the Frio CO₂ injection test site by employing an integrated approach of rock physics and seismic forward modelling to reduce uncertainties in the choice of the dry frame modulus and velocity-saturation relations. First, we confirmed the quality of pre-injection well logs velocities with VSP data. Afterwards, we use inverse Gassmann relations to calculate the dry frame properties of the reservoir with different input parameters for the grain moduli with fluid substitution applied for uniform saturation of brine and CO₂. Finally, forward modelling of the results is implemented to compare the response with field VSP data.

Our investigation shows that VSP data can help constrain the choice of dry frame modulus, and thus the velocity-saturation relation. The rock physics model best matches the VSP results using large grain moduli and uniform saturation for fluid substitution.

Key words: CO₂, Rock Physics, Time-lapse, VSP, Modelling

INTRODUCTION

Time-lapse (TL) seismic is a powerful tool for monitoring fluid movement in reservoirs. However, interpretation of TL data is often qualitative. The use of TL data to estimate change in the spatial distribution of saturation and pressure, so called quantitative interpretation, remains a challenge. A key problem for quantitative interpretation is understanding the effect of fluid saturation on elastic properties of rocks. While such relationships can be obtained from rock physics theory, its predictions need to be calibrated for seismic frequencies at reservoir scales.

In this case study, we investigate the effect of CO₂ injection on elastic properties of a high porosity and permeability sandstone using time-lapse vertical seismic profile (VSP) data, and attempt to build a rock-physics model that describes this effect.

The Frio brine pilot was a small scale project with 1,600 tons of CO₂ injected into a brine aquifer during a period of 10 days (Daley, et al.,2008). Two wells about 30 m apart were used in the project, with the updip well for observation and the injection well downdip. The CO₂ was injected into the upper part of the Frio-C sandstone having about 16° dip to the south, with a regional seal at the top (Hovorka, et al.,2006). Many geophysical measurements were acquired, such as baseline sonic, density and resistivity logs along with time-lapse saturation logs. Crosswell seismic and VSP data were acquired before and after injection for time-lapse monitoring. Eight shots were used as seismic sources near the observation well with offsets between 110-1500 m using seismic explosive at various azimuths to map the plume extent, Figure 1 (Daley, et al.,2008).

In previous analysis of the time-lapse response (Daley, et al.,2008), (Dougherty, et al.,2008) the rock physics model was based on a high porosity sand described in Carcione, et al. (2006) which matches the time-lapse velocity response observed in the crosswell tomography. Although this model captures the time-lapse changes, it does not describe the properties of this specific reservoir.

Figure 1. Frio VSP Geometry. Shots are numbered and wells are indicated. Shots 1-4 are in close proximity to the injection well with less than 300 m offset. The receivers are in the injection well. Modified from (Daley, et al.,2008)
Work reported by Kharaka, et al. (2006) has shown that CO₂ injection into the Frio C caused calcite to dissolve from the rock matrix possibly changing the rock frame properties (Hovorka, 2009). These chemical interactions are dependent on the reactive surface area, which is largest at the borehole with high CO₂ saturations (Vanorio, et al., 2011). This fact means that after injection, velocities from time-lapse logs might not represent the changes in the reservoir away from the injection well. On the other hand, seismic data from VSP surveys with their typical high signal-to-noise ratio and coverage beyond the borehole wall may give a better representation of the reservoir before and after CO₂ injection. Further, we are able to analyse both downgoing (including those travelling through the CO₂ plume) and upgoing waves.

In this work, we investigate the use of VSP data to constrain the dry frame properties of the Frio-C reservoir. The paper is structured as follows. First, a quality check of the baseline well logs is performed using VSP velocities. Then, the sonic velocities are used to create a site-specific rock physics model for the Frio-C interval. Afterwards we perform forward modelling to predict the time-lapse VSP response due to CO₂ saturations. We focus on the first arrivals that pass through the plume as they provide - high signal-to-noise ratio information about the time delay caused by CO₂ plume thickness and saturations. We analyse the observed time delays in the time-lapse VSP data by employing an integrated approach of rock physics and seismic field forward modelling to reduce uncertainties in the choice of dry frame properties and fluid substitution.

**ROCK PHYSICS MODEL**

The first step is to carry out a quality control of the available data. The baseline sonic well logs in Figure 2 are confirmed by comparing them to the VSP interval velocities. The VSP velocities are at seismic resolution, so an upsampling of the well logs is performed using Backus averaging (Mavko, et al., 2009). The upscaled well log velocities show good agreement with the VSP for both compressional and shear wave velocities.

The porosity used in the modelling is calculated from the density log. An average porosity of more than 32% is estimated for the top 10 m of the injection interval except for an intermediate shaley-sand where porosity drops to about 27%. Large uncertainty is associated with the estimation of the dry frame modulus and the grain properties, whereas fluid-properties, pressure and porosity are constrained by core measurements and well logs.

The mineralogical composition of the Frio-C sand is not adequately constrained, but quartz, orthoclase and plagioclase feldspar and rock fragments have been reported from core analysis and XRD (Sakurai, et al., 2006), (Hovorka, et al., 2006).

In our analysis, we first created a rock physics model based on the mineralogical composition reported above. A constant feldspar content of 20% is assumed, and the clay content is calculated from the gamma ray log; Table 1 shows the mineral properties. The grain bulk and shear moduli $K_F$ and $\mu_F$, respectively, are calculated using the arithmetic average of the Hashin-Shtrikman bounds (Hashin and Shtrikman, 1963).

<table>
<thead>
<tr>
<th>Constitute</th>
<th>Density(kg/m$^3$)</th>
<th>$K$ (GPa)</th>
<th>$\mu$ (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>2650</td>
<td>37</td>
<td>45</td>
</tr>
<tr>
<td>Feldspar</td>
<td>2630</td>
<td>75.6</td>
<td>25.6</td>
</tr>
<tr>
<td>(Plagioclase)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td>2260</td>
<td>25</td>
<td>9</td>
</tr>
</tbody>
</table>

Table 1 density and moduli of minerals used in the initial Frio-C rock physics modelling. (From Mavko, et al., 2009)

We apply the inverse Gassmann equation to estimate the dry frame properties, $K_{dry}$ from well logs velocities over the interval of interest. The shear modulus is assumed to be constant and does not change for saturated and dry frame (Smith, et al., 2003). The moduli are given by,

$$K_{dry} = \frac{K_{sat}(\frac{\phi_F}{\phi})^{1-\phi} - K_F}{\frac{\phi_F}{\phi}^{2-1} - \phi}$$

and

$$\mu_{sat} = \mu_{dry}$$

where, $\phi$, $K_F$ and $\mu_{dry}$ are porosity, fluids bulk modulus and dry frame shear modulus respectively.

Next, we apply fluid substitution using Gassmann’s equation (Smith, et al., 2003) with the new fluid being a uniform mixture of brine and CO₂. Table 2 shows the brine and supercritical CO₂ properties at reservoir conditions. The fluid mixture is assumed to be homogenous. Thus, Wood’s average is used to calculate the properties of the fluid mixture (Wood, 1955).

<table>
<thead>
<tr>
<th>Fluid</th>
<th>$K$ (GPa)</th>
<th>Density(kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brine</td>
<td>2.75</td>
<td>1030</td>
</tr>
<tr>
<td>CO₂*</td>
<td>0.07328</td>
<td>653</td>
</tr>
</tbody>
</table>

Table 2 Brine and CO₂ properties at reservoir conditions. * Supercritical CO₂, from (Daley, et al., 2008).

The dry frame properties used in this calculation result in an average velocity decrease of about 500 m/s (Figure 3), which is less than the observed velocity decrease in the VSP (discussed later). To explore this issue, we used several values...
Thus, layers with velocities and density taken for $K_g$ (60 to 180 GPa) assuming one constitute while keeping all other parameters similar to the mixed mineralogy case. The vertical bar shows uncertainty in velocity estimated from the time-lapse VSP given the thickness and travel-time changes.

The uncertainties in our modelling are difficult to quantify, since $K_g$ is hard to constrain. In order to choose an appropriate $K_g$, we preform forward modelling and examine the response in the time delays of the first arrivals.

### VSP MODELLING

We aim to model the time-lapse VSP response near the injection well. Therefore, we assume the reservoir to be about 8.8 m thick, which is comparable to the crosswell results of Doughty, et al. (2008). For simplicity, we ignore the reservoir dip and perform the modelling for a horizontally layered medium. This means that geometry related uncertainties will be present, but for near-offset shots, we should get an adequate approximation of the seismic response.

We perform 1.5D elastic forward modelling using the OASES software package (Schmidt and Tung, 1986). The modelling is run for thin flat layers with velocities and density taken from the well logs (Figure 2) for the interval of interest. For the reservoir properties after injection, we use rock physics models with a range of $K_g$ values. In all modelling runs, a uniform saturation of 30% CO₂ is utilized over the interval of interest. The reservoir section is modelled with 0.1 m depth steps while for the rest of the model 0.6 m step is used to reduce the computation time. To create the synthetic VSP dataset, the reflectivity sequence produced by OASES is convolved with a 50 Hz Ricker source wavelet.

The first arrivals of the downgoing waves are extracted for both pre-injection and post-injection modelling results. Figure 4 shows that the first breaks time delays for the modelling results with grain composition of 20% feldspar and varying quartz and clay content is 0.8 ms, while for models using $K_g$ of 60, 100 and 140 GPa the time delays are 1.00, 1.2 and 1.3 ms, respectively for the offset of 125 m. The seismic modelling also illustrates that the time delays increase with increasing offset away from the receiver well (not shown).

### COMPARISON TO VSP DATA

To obtain robust results, for the first arrival time delay analysis we selected only the shots with good repeatability and no static related shifts between pre-injection and post-injection VSP data. Figure 5 shows the first arrival time delays for four near-offset shot locations at a number of azimuths. This provides the advantage of mapping the CO₂ effect on the area around the injection well with high resolution and gives us the opportunity to constrain the rock physics model.

The seismic traces were resampled to 0.1 ms and the first arrivals are picked manually. The downgoing waves for receivers just below the reservoir travel through the CO₂ plume around the injection well. Thus, their first breaks for waves travelling through the CO₂ plume experience a time delay that is different from the pre-injection survey. The peak difference in travel-time delays at depth of 1545 m is for the receiver that is about 8.8 m below the top of the reservoir, and gives a 1.3 ms delay. Given the thickness of about 8.8 m, this translates to a reduction in velocity of more than 750 m/s which is in agreement with the results of Zhou, et al. (2008).

The travel-time delays increase for larger offsets given the same azimuth, which is probably due to the increase in the path the seismic waves travel through the plume due to the change of the incident angle. This can be observed in the forward modelling at large offsets. The time delays decrease for deeper receivers possibly indicating the change in plume thickness or saturation profile away from the injection well.

The VSP first break time delays are higher than in the modelling with a constant 20% feldspar concentration and for any proportions of clay and quartz. However, given the uncertainty of 0.2 ms in VSP first arrival picks (about 80 m/s average over an 8.8 m interval) the modelling is within the margin of error of the VSP time delays for $K_g$ between 80 to 180 GPa in the rock physics model with CO₂ saturation of 30% over the whole interval. This large $K_g$ range does not appear realistic.
DISCUSSION

Integration of geophysical measurements has proven of great value for the Frio CO₂ injection pilot as it provided an understanding of the reservoir changes caused by CO₂ injection. The VSP data have validated the pre-injection well log measured velocities, thus justified their use with inverse Gassmann’s equation to estimate the dry frame properties.

In our analysis, the large reduction in \( v_p \) cannot be explained by a thicker CO₂ plume as the receiver that presented the largest delay time is about 8.8 m below the top of the reservoir, thus a thicker CO₂ plume would be unrealistic. Further, as shown by the velocity-saturation relation (Figure 3), having higher saturations will not increase the time delays to match with the VSP results as even with a full CO₂ saturation the velocity reduction is lower than that needed for such a time delay. This suggests that the friable nature of the reservoir sand can be a source of uncertainty in our modelling. Moreover, the chemical changes reported by Kharaka, et al. (2006) can be the cause of a large change in the rock frame properties after injection which we did not take into account in our modelling. This is supported by the shear wave reduction observed by Daley, et al. (2008) in the immediate vicinity of the injection well. Thus, these complex interactions of CO₂ with the reservoir rock is a parameter not to be ignored, as it could be the cause of such large velocity changes.

This work shows that VSP can be a powerful tool in constraining a velocity-saturation relation even with high uncertainty in the parameters of the rock physics model. In the absence of post-injection log velocities, VSP provided an estimate of the velocity change of about 750 m/s (1.3 ms delay) with an uncertainty of 80 m/s (0.2 ms delay). Our work will extend further to look into amplitude changes of both upgoing and downgoing waves to support the observed first arrivals time delays and mapping of the CO₂ plume.

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REFERENCES


