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

Mohammed Al Hosni
Curtin University
GPO Box U1987,
Perth, WA 6845
M.alhosni@postgrad.curtin.edu.au

Eva Caspari
Curtin University
GPO Box U1987,
Perth, WA 6845
Eva.caspari@postgrad.curtin.edu.au

Roman Pevzner
Curtin University, CSIRO
GPO Box U1987,
Perth, WA 6845
R.Pevzner@curtin.edu.au

Thomas M. Daley
LBNL
1 Cyclotron Road
Berkeley, CA 94720, US
tmdaley@lbl.gov

Boris Gurevich
Curtin University, CSIRO
GPO Box U1987,
Perth, WA 6845
B.Gurevich@curtin.edu.au

SUMMARY

Quantitative interpretation of time-lapse seismic data is an ongoing challenge. Understanding the velocity-saturation relations and changes caused by CO_2 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 CO_2 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 CO_2. 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: CO_2, 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 CO_2 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 CO_2 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 CO_2 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), (Doughty, 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.

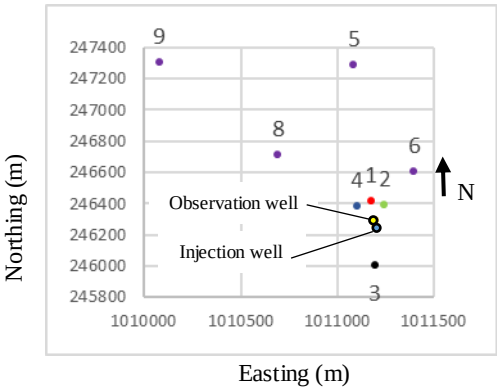

Figure 1. Frio VSP Geometry. Shots are numbered and wells are indicated. Shots 1-4 are in close proximity to the injection well with less than 300 m offset. The receivers are in the injection well. Modified from (Daley, et al.,2008)

Work reported by Kharaka, et al. (2006) has shown that CO_2 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 CO_2 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 CO_2 injection. Further, we are able to analyse both downgoing (including those travelling through the CO_2 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 CO_2 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 CO_2 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 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 upscaling 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 grains properties, whereas fluid-properties, pressure and porosity are constrained by core measurements and well logs.

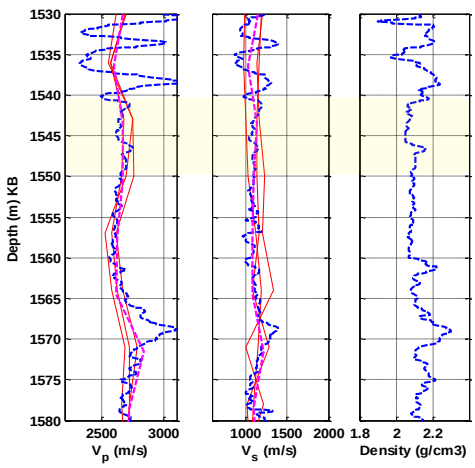

Figure 2. Baseline V_p, V_s and density logs in the injection well with the interval of interest shaded. Dashed magenta is the upscaled measurement by Backus averaging and the red lines are the interval velocities from VSP shots.

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_g and μ_g respectively, are calculated using the arithmetic average of the Hashin-Shtrikman bounds (Hashin and Shtrikman,1963).

Constitute	Density(kg/m^3)	K (GPa)	μ (GPa)
Quartz	2650	37	45
Feldspar (Plagioclase)	2630	75.6	25.6
Clay (Highly variable)	2260	25	9

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,

$$K_{dry} = \frac{K_{sat}\left(\frac{\phi K_g}{K_{fl}} + 1 - \phi\right) - K_g}{\frac{\phi K_g}{K_{fl}} + \frac{K_{sat}}{K_g} - 1 - \phi} \quad (1)$$

and

$$\mu_{sat} = \mu_{dry}, \quad (2)$$

where, ϕ, K_{fl} and μ_{dry} are porosity, fluids bulk modulus and dry frame shear modulus respectively.

Next, we apply fluid substitution using Gasmann's equation (Smith, et al.,2003) with the new fluid being a uniform mixture of brine and CO_2. Table 2 shows the brine and supercritical CO_2 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).

Fluid	K(GPa)	Density(kg/m^3)
Brine	2.75	1030
CO_2*	0.07328	653

Table 2 Brine and CO_2 properties at reservoir conditions. * Supercritical CO_2, 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

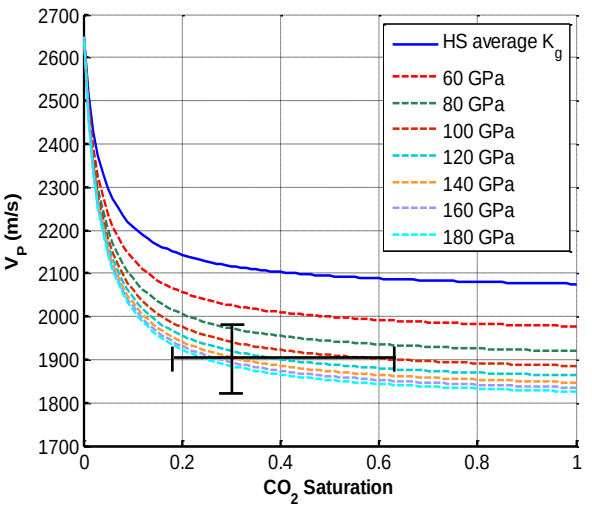

Figure 3. Velocity-saturation relation (VSR) for K_{dry} obtained by inverting well log velocities with Gassmann equation using different values of K_g. Solid line corresponds to K_g obtained by Hashin-Shtrikman average assuming mixed mineralogy (20% feldspar, 80% quartz). Other lines are for the values of K_g shown in the legend. The horizontal bar shows the range of saturations from saturation tool logs (Doughty, et al.,2008). The vertical bar shows uncertainty in velocity estimated from the time-lapse VSP given the thickness and travel-time changes.

for K_g (60 to 180 GPa) assuming one constitute while keeping all other parameters similar to the mixed mineralogy case. Figure 3 shows the velocity-saturation relation for increasing K_g. The dry frame bulk modulus (not shown) decreases with increasing K_g, thus the rock frame becomes more sensitive to fluid 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 Tango,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% CO_2 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).

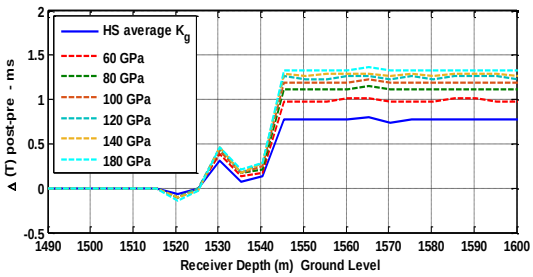

Figure 4. Time delays of first arrivals of the direct wave extracted from synthetic VSP seismogram for 30% CO_2 saturation over 8.8 m interval for an offset of 125 m. Each series is for a different K_g as shown in Figure 3.

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 CO_2 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 CO_2 plume around the injection well. Thus, their first breaks for waves travelling through the CO_2 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 CO_2 saturation of 30% over the whole interval. This large K_g range does not appear realistic.

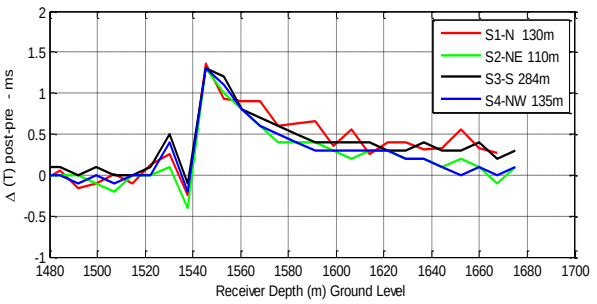

Figure 5. VSP first breaks time delays for shots 1-4 (see Figure 1) at different azimuths around the injection well. A maximum delay is observed at receiver depth 1545 m, which is approximately 8.8 m below the top of the reservoir. The uncertainty is approximately 0.2 ms estimated from the variation before the reservoir interval.

DISCUSSION

Integration of geophysical measurements has proven of great value for the Frio CO_2 injection pilot as it provided an understanding of the reservoir changes caused by CO_2 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 CO_2 plume as the receiver that presented the largest delay time is about 8.8 m below the top of the reservoir, thus a thicker CO_2 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 CO_2 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 CO_2 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 CO_2 plume.

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