Fluid substitution and seismic modelling in a sandstone aquifer

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ABSTRACT

Fluid substitution and seismic modelling were applied in order to evaluate the Paskapoo Formation as a potential CO₂ geological storage unit. The first stage of this project deals with the application of the Gassmann substitution model using well data and evaluation of property variations due to CO₂ saturation changes. Seismic modelling was undertaken in the area of interest simulating pre, during and post CO₂ injection scenarios. From Gassmann calculations it was found that the P-wave velocity drops between 0 to 20% CO₂ saturation and starts a subtle rise at 30% whereas the S-wave velocity increases directly proportional to CO₂ saturation. The P-wave velocity decreases approximately 7%, the S-wave velocity increases 0.8 %, Vₚ/Vₛ decreases an average value of 8% and the basal reflector presents a time delay of 1.6 msec. From seismic modelling it was found that the injection zone can be delineated in the CDP stack section through an amplitude change the top reflector and a time delay for the basal reflector. The reflectivity coefficient was evaluated using the Shuey approximation and qualitative observations of the sections, showing a decrease in the reflectivity with increasing CO₂ saturation, with a major drop in the first 10% and a further amplitude decrease with offset (higher angles). These parameters allow us to estimate the conditions that would help to interpret the real data in further phases of this study.

INTRODUCTION

The inevitable and fast increase of the greenhouse gases concentrations and hypnotized global warming, constitute one of society’s major concerns presently. The excess of CO₂ in the atmosphere is considered by many to be the principal cause of the problem, affecting the natural equilibrium. CO₂ sequestration in geological sites represents a viable solution or at least a way of mitigation. The idea of this method is to capture CO₂ produced by anthropogenic or natural point sources and inject it into a porous layer surrounded by non porous layers to trap the gas (Hovorka, 2008).

The main objective of this project is to evaluate Paskapoo Formation as a potential test CO₂ geological storage site. A fluid substitution model was performed using well information to estimate the effects and changes due to CO₂ injection. Synthetic seismograms were generated for each CO₂ saturation value. Gassmann equations were applied in order to evaluate changes in the P-wave and the S-wave velocity. Finally a 2D seismic model of the area was created with the respective density and velocity parameters obtained from well information. The zone of injection is defined inside the model. Six (6) CDP stack sections were created: 0%, 20%, 40%, 60%, 80% and 100% CO₂ saturation, changing parameters for each saturation stage. This model provides some ideas about the seismic respond depending on the CO₂ saturation and the evolution of the injection process.
AREA OF STUDY

The study site is located near the Rocky Mountains Foothills, Southwest of Calgary (Fig. 1). Close to this site, CREWES has undertaken several useful research projects in order to characterize this zone using multi-component seismic survey and vertical seismic profile (Lawton et al., 2008).

Figure 1: Priddis location (red dot) (Bachu et al., 2000)

GEOLOGICAL BACKGROUND

The study area is located at the eastern edge of the Rocky Mountain foothills in the triangle zone. This zone is between Jumping Pound and Wildcat Hills, Alberta (Slotboom et al., 1996). It is characterized by a blind thrust in the leading edge of the Rocky Mountain fold and thrust belt. In this zone the strata has wedged into the foreland succession with a blind frontal tip (Slotboom et al., 1996). The geometry of the area is defined by an amorphous flat base, beds and faults dipping toward the hinterland on the western side and some slight foreland dips on the eastern side, forming a triangle zone (Slotboom et al., 1996). Triangle zones are characterized by faults with opposite slip directions. They are related to a common lower detachment, so this faults and the detachment represent the triangle zone (Slotboom et al., 1996).
Stratigraphic units

Three tectonostratigraphic units form the triangle zone in this area: Precambrian crystalline basement, Palaeozoic carbonate group and Mesozoic and Early Tertiary age clastic group (Slotboom et al., 1996). Figure 2 displays the stratigraphic column. Mesozoic stratigraphic sequences present the main deformations associated with the triangle zone formation. This section is composed by inter-bedded sandstone, siltstone, shales and coals from the foreland molasse strata. These sediments were uplifted due to a series of compressional episodes that shortened and thickened the sediments in the western margin of the craton during formation of the Canadian Cordillera (Stockmal et al., 1996).

Turonian (Cardium Formation) through Paleocene (Porcupine Hills Formation) exposed strata correspond with foreland siliciclastic basin that goes from marine to nonmarine and some fresh water limestone (Stockmal et al., 1996). The sequence of sediments is formed by: marine to nonmarine Milk River Formation and marine Pakowki Formation, nonmarine Belly River Group. St. Mary River Formation and Willow Creek Formation present a thickening due to its considerable deformation related to the upper detachment of the triangle zone.

Paskapoo Formation

The Paskapoo Formation represents the sequence of interest in this study. It is a Tertiary Formation (Fig.2) composed of mudstone, siltstone and sandstone, with subordinate limestone and coal. The sandstone grades to conglomerate in places, and bentonite beds are also present. The strata represent a foreland deposit of a siltstone- and mudstone-dominated fluvial system (Grasby et al., 2008).

This Formation constitutes an important ground water reservoir target having some qualities that make that possible as high-porosity coarse-grained sandstone channels (Grasby et al., 2008). The basal Haynes Member and western portion of the Paskapoo Formation have higher sandstone volumes than other portions of the system (Grasby et al., 2008).

The Paskapoo Formation represents the youngest bed rock deposits in the Western Canada Sedimentary Basin having from 0 to 800m of thickness with a thinner section in the eastern part (see Figure 2) (Grasby et al., 2008). The deposits are distributed in an asymmetric foreland basin developed between the deforming mountain front and the adjacent craton due to the western thrusting of the Rocky Mountains (Grasby et al., 2008). The main source of sediments was the Palaeozoic-Mesozoic emerging mountains; compose by greenish sandy siltstone and mudstone, with light grey, thick-bedded sandstone deposited in nonmarine environments (Grasby et al., 2008). A plain zone where the strata are dipping westward, forming a homoclinal wedge into Alberta syncline, is called Paskapoo Sandstone, which has the most representative sandstone channels. Outside this sandy zone, the formation is composed for more than 50% of siltstone and mudstone (Grasby et al., 2008).
FLUID SUBSTITUTION AND GASSMANN EQUATION

Fluid substitution modeling is an important tool in reservoir characterization. In this case, fluid substitution equations were used to predict and to evaluate CO₂ injection in a specific area having well log information such as density and sonic.

Gassmann’s equation is one of the theories in fluid substitution modelling (Smith et al., 2003). Gassmann presents three major assumptions: the rock is homogeneous and isotropic, the pore space is completely connected and the fluids must be moveable. While many of the proposed models requires several and complicated inputs, Gassmann relations reflects the changes in P-wave and S-wave velocity due to saturation changes with simple inputs. Density and P-wave velocity logs are initial inputs and the constant parameters during substitution are matrix bulk modulus (Kₒ), frame or dry rock bulk modulus (K*), porosity (φ) and rock shear modulus (G) (Smith et al., 2003). The changes in fluid saturation will modify the fluid content and therefore, the bulk density (ρb) and fluid bulk modulus (Kfl) (Smith et al., 2003). Gassmann establishes empirical formulations that relate the saturated rock bulk modulus (Kₚₛₐₜ) with porosity, dry rock bulk modulus, mineral matrix bulk modulus and pore filling fluid bulk modulus (Smith et al., 2003). The rock bulk modulus is calculated using the following expression:

$$K_{sat} = K \frac{(1-\phi)}{\phi} \frac{K*}{K_0} \left(\Phi_{fl} \frac{1-\phi}{\phi} \frac{K*}{K_0} \right)$$ (1)

In order to resolve this formula it has to be accomplished a series of steps. Prior to apply Gassmann equation it is necessary define rock parameters such as bulk modulus, shear modulus and bulk density. Bulk modulus (K) is the ratio between stress increment ($\delta\varepsilon$) and volume strain ($\delta\sigma$=ΔV/V):

$$K = \frac{\delta\varepsilon}{\delta\sigma}$$ (2)

while shear modulus (G) is the ratio between shear strain and stress (Smith et al., 2003).
Bulk modulus (K) and shear modulus (G) can be related to compression velocity or P-wave velocity ($V_p$), shear velocity or S-wave velocity ($V_s$), and bulk density ($\rho_b$) all of them in saturated state, using these two equations:

$$K = \rho_b \left( V_p^2 - \frac{4}{3} V_s^2 \right) \quad (3)$$

$$G = \rho_b V_s^2 \quad (4)$$

Since the shear modulus is insensitive to fluid changes, it will remain constant during the substitution (Smith et al., 2003). To calculate the bulk density ($\rho_b$) is used the following expression:

$$\rho_b = \rho_0 (1 - \phi) + \rho_f \phi \quad (5)$$

where $\rho_0$ is matrix density, $\rho_f$ is fluid density and $\phi$ is porosity. Bulk density is going to change depending on the fluid saturation during the substitution.

The first step in Gassmann’s substitution is to define porosity values from well log data or to calculate them from density log values or any other log that could give this information (Smith et al., 2003). Rearranging equation 5 is possible to get porosity having density:

$$\phi = \frac{\rho_0 - \rho_b}{\rho_0 - \rho_f} \quad (6)$$

In order to substitute fluids it is necessary to establish their properties. In this case, the two fluids in discussion are water (or brine) and CO$_2$. Density and bulk modulus values could be obtained from laboratory measurements but in most of the cases some empirical relations are use such as Batzle and Wang (1992) equations. They obtain the density and bulk modulus knowing temperature, pressure, gravity of the fluid (ºAPI in oil) and concentration (ppm in brine). With this input values a good approximation of fluid properties can be made at certain conditions. Some suggest that Batzle and Wang equations as well Gassmann relations, are created thinking in a gas-oil-water scenario, and they might not represent the reality of a CO$_2$ fluid substitution (e.g. Xu, 2006). The resulting fluid bulk modulus ($K_n$) after mixing two or more fluids, it is given by the expression:

$$K_{f1} = \left[ \sum_{i=1}^{n} \frac{s_i}{K_i} \right]^{-1} \quad (7)$$

where $s_i$ is the saturation and $K_i$ is the bulk modulus of each fluid. This expression can be simplified in the following equation in the case of water and CO$_2$ mix:

$$K_{f1} = \left[ \frac{S_w}{K_w} + \frac{1 - S_w}{K_c} \right]^{-1} \quad (8)$$

where $S_w$ is water saturation, $S_c$ is CO$_2$ saturation, $K_w$ is water bulk modulus an $K_c$ is CO$_2$ bulk modulus.

Applying the same reasoning explained before, the fluid density ($\rho_f$) is given by:
\[ \rho_{fl} = \sum_{i=1}^{n} S_i \rho_i \]  
(9)

\[ \rho_{fl} = S_w \rho_w + (1 - S_w) \rho_c \]  
(10)

where \( \rho_i \) represent the density of each fluid, \( \rho_c \) is CO2 density and \( \rho_w \) water density.

Fluid bulk modulus and fluid density are going to reflect the fluid substitution changes and therefore, they are going to affect the model and define the variations.

To establish matrix characteristics, one needs to determine the matrix bulk modulus (\( K_o \)). These values are tabulated for main mineral components such as quartz and calcite among others. Most of the time, matrix is composed by different kind of minerals, and in case that fractional content information is available, the bulk modulus can be calculated using Voigt-Reuss-Hill (VRH) equation. This equation represents the average of the average, where is possible to obtain the bulk modulus (\( K_{vrh} \)) using Voigt and Reuss bulk modulus respectively (\( K_{voigt} \) and \( K_{reuss} \)) (Smith et al., 2003):

\[ K_{vrh} = \frac{1}{2} \left[ K_{(voigt)} + K_{(reuss)} \right] \]  
(11)

Reuss equation is the average of the harmonic mean (it represents the low band), and for the mixture of two components can be expressed as:

\[ K_{(reuss)} = \left[ \frac{F_1}{K_1} + \frac{F_2}{K_2} \right]^{-1} \]  
(12)

On the other hand Voigt equation is the average of the arithmetic mean (it represents the upper band):

\[ K_{(voigt)} = [F_1 K_1 + F_2 K_2] \]  
(13)

\( K_1, K_2 \) is the bulk modulus of each mineral and \( F_1, F_2 \) is the fraction of mineral in the rock (Smith et al., 2003).

Another method used to calculate the matrix bulk modulus is Hashin and Shtrikman (1963) which assume a homogeneous mix of minerals and has narrower upper bound than Voigt but keep the lower bound of Reuss. Hashin-Shtrikman bounds can be obtained with the following equation:

\[ M_{HS}^{\pm} = K_{HS}^{\pm} + \frac{4}{3G_{HS}^{\pm}} \]  
(14)

where \( M_{HS}^{\pm} \) is the P-wave modulus and:

\[ K_{HS}^{\pm} = K_1 + \frac{\phi}{(K_2 - K_1)^{-1} + (1 - \phi)(K_1 - \frac{5}{3} G_1)^{-1}} \]  
(15)

\[ G_{HS}^{\pm} = G_1 + \frac{\phi}{(G_2 - G_1)^{-1} + \frac{2(1 - \phi)(K_1 - 2G_1)}{5G_1(K_1 - \frac{5}{3} G_1)}} \]  
(16)

\( K_1, G_1 \) and \( K_2, G_2 \) are the bulk modulus and shear modulus of each mineral. The relation between Vogit, Reuss and Hashin-Shtirikman curves can be seen in Figure 3.
To define frame properties or dry rock bulk modulus ($K^*$), equation 1 is rearranged:

$$K^* = \frac{K_{sat}\left(\frac{\varphi K_0 + 1 - \varphi}{K_{fl}}\right) - K_o}{\frac{\varphi K_0 + K_{sat} - 1 - \varphi}{K_{fl}}}$$  (17)

Bulk modulus ($K_{sat}$) for the saturated rock obtained from equation 3, and the rest of the elements were obtained in previous steps (Smith et al., 2003). This property is calculated for a saturated rock and remains constant in fluid substitution. Shear modulus, matrix bulk modulus and porosity remain constant as well. Once that we have $K^*$ is possible calculate the rock bulk modulus ($K_{sat}$), using equation 3, for any water/CO$_2$ saturation values recalculating each time $K_{fl}$, $\rho_{fl}$, and $\rho_b$ (Smith et al., 2003).

![Figure 3](image-url)  

**Figure 3:** Curves of Reuss, Voigt and Hashin-Shtrickman, showing bulk modulus variation with the porosity.

The final step consists of P-wave ($V_p$) and S-wave velocity ($V_s$) calculation using rock bulk modulus values ($K_{sat}$) for different CO$_2$ saturation, using the following equations:

$$V_p = \sqrt{\frac{K_{sat} + \frac{4G}{3}}{\rho_b}}$$  (18)

$$V_s = \sqrt{\frac{G}{\rho_b}}$$  (19)

The shear modulus ($G$) calculated from equation 4 and the bulk density ($\rho_b$) recalculated from each saturation value using equation 5 (Smith et al., 2003).

The effects of fluid substitution in a certain formation or stratigraphic section could be evaluated by the changes suffered in P-wave velocity and S-wave velocity during the injection.
METHODOLOGY

Synthetic Seismogram Generation and Fluid Substitution Evaluation

Fluid substitution modelling was applied using the MILLAR 12-33-21-2W5 well log data. This is a well from Husky Oil and the data was recorded the presented data on June 19, 1980 (see figure 4). Hampson-Russell PRO4D software was used to evaluate the data.

Figure 4 shows the logs provided by the borehole measurements. Track 1 is the gamma ray, track 2 is the density and track 3 is the P-wave velocity. Other logs were available but they don’t play an important role in fluid substitution.

From the Gamma Ray log it is possible to identify or at least estimate our objective. In this case, will be a “clean” sandstone portion of Paskapoo Formation. From previous geological information, it is known that this stratigraphical section corresponds with Tertiary sediments overlaying the Edmonton Formation. Identifying the Edmonton Fm Top, is inferred that the zone is located above it. In the GR log is possible to appreciate a low GR portion with shaly beds on top and base delimiting it. This zone goes from 380m to 425 m depth (see figure 5).

Once the objective was defined, the log data available was verified. Density log is recorded from 400 m, so the upper part was estimated using average values. That will be the only manipulation over real data. In further studies, lack of information could be solved with more complete log data.

Another aspect that can be appreciated is the increase of the GR in the lower zone of the section (425-440m), related with the decrease in the density log and in the P-wave velocity, that could be inferred as a coal layer.
From the density log, a porosity log was created using equation 4. Matrix density will be given by theoretical sandstone density value $\rho = 2650 \text{ Kg/m}^3$ and as fluid density fresh water value $\rho = 1000 \text{ Kg/m}^3$. From the P-wave velocity log it is possible to calculate the S-wave velocity using the empirical relation:

$$V_s = \frac{V_p}{1.9} \quad (20)$$

where 1.9 is taken as a average value of $V_p/V_s$ ratio in clastic sediments.

With all the elements, CO$_2$ substitution was performed. First, complete water saturation condition is set. The first synthetic trace represents the 100% water saturation or 0% CO$_2$ saturation. The subsequent traces are going to increase from 10 to 10 percent CO$_2$ saturations till 100% stage. It is now possible to evaluate property changes due to CO$_2$ substitution, specifically: velocity, time delay and amplitude of the wavelet.

**Gassmann Fluid Substitution**

Gassmann equations were used in order to estimate the changes in the P-wave velocity and the S-wave velocity after fluid substitution. Having density and sonic log values in the section identified as Paskapoo, an average value for both were obtained, which will represent the input in fluid substitution. The S-wave velocity at 100% water saturation is calculated using equation 20.
In order to solve the Gassmann equation (see equation 1), it was necessary to follow the steps described previously.

1) Calculate porosity value from equation 4 using the bulk density for 100% water saturation.

2) Define fluid properties: bulk modulus and density. As it was mentioned, these values depend on pressure and temperature and can be calculated with Batzle-Wang equations (Smith et al., 2003). Due to the lack of precise information the temperature \( T \) was estimated using the geothermal gradient \( G_t \)

\[
T(410m) = G_t(410m) + T(surface) \quad (21)
\]

and the pressure \( P \) was calculated using the hydrostatic pressure gradient \( H_p \):

\[
P = H_p h \quad (22)
\]

where \( H_p = 9.792 \text{kPa/m} \) and the chosen depth \( h \) is 410m.

The Geothermal Gradient considered is 27 degrees C/km in Alberta (Hitchon, 1984) and estimating a surface temperature of 15 degrees C, the approximated temperature in the middle of the sand is 25.8 degrees C. For the pressure, the column above the objective \( h \) will be 410m having a pressure of 4.015MPa.

With these values and Batzle-Wang calculations it is possible to obtain the CO\(_2\) bulk modulus \( K_c = 0.02 \text{ GPa} \) and density \( \rho_c = 146.4 \text{ kg/m}^3 \). The expected phase of CO\(_2\) in a shallow formation would be gas, as we can see in the graph of Piri et al., 2005 (Fig. 6). The estimated water bulk modulus will be \( K_w = 2.33 \text{ GPa} \), and fresh water density \( \rho_w = 1000 \text{ kg/m}^3 \) due to the lack of information about specific salinity of the area, nevertheless, studies such as the one presented by Grasby (2008) analyse the chemical composition of aquifers in Paskapoo formation, and in the south west Alberta it can be appreciated a higher concentration of calcium (~20mg/L).

Figure 6: Temperature and pressure phase diagram for pure carbon dioxide (Piri et al, 2005).
Having the individual characteristics of each fluid, $K_f$ and $\rho_f$ can be calculated using formulas 8 and 10 respectively, at different CO2 saturation states.

3) Define matrix properties: $K_0$ matrix and $\rho_0$ matrix. In this case we consider that the matrix is composed by perfect sandstone (quartz), so the $K$ and $\rho$ values are theoretical values of this mineral and they are not affected by pressure or temperature conditions. Since $K_0=37$ GPa and $\rho_0=2650$ kg/m$^3$. According to lithological and stratigraphical characteristics, Paskapoo Formation contains clay and limestone.

4) Calculate bulk density by equation 5 with each new fluid density.

5) Calculate frame bulk modulus using equation 17 and introducing some of the previously mentioned values for 100% water saturation. $K_{sat}$ is calculated with equation 3. $K^*$ value remain constant and is not affected by the substitution.

6) Calculate the rock bulk modulus ($K_{sat}$) with equation 1. This element and bulk density ($\rho_b$) is going to define the P-wave velocity further values. $K_{sat}$ will vary according to the resultant $K_f$.

7) Determine P-wave velocity and S-wave velocity values with equations 18 and 19, calculating previously the shear modulus $G$ by equation 4. The bulk density and the rock bulk modulus were recalculated with each CO2 saturation values giving us eleven situations and eleven P-wave velocity and S-wave velocity values in each of them.

Seismic Modelling

Geological model

A 2D simple geological model of flat layers was created after estimating the P-wave velocity, the S-wave velocity and density parameters from the previous steps. The software utilized with this propose is NORSAR 2D. The interfaces between layers were estimated using the information provided by the well log dataset. The initial model parameters represent conditions prior to any CO2 injection scenario with 100% water saturation inside Paskapoo Formation. The model has an extension of 5 km and an injection zone of 1km located in the center of the model. This model attempts to characterize the changes in seismic data during various stages of CO2 injection (20%, 40%, 60%, 80% and 100% saturation). At the edges of the injection area, a 200 m transition zone was established; the parameters gradually range from the given specific CO2 saturation percentage to 0 % CO2.

Ray Tracing and Synthetic Seismogram Generation

Subsequent to generate the different models (before, during and after CO2 injection), it was necessary to obtain the seismic section (shot gather). The seismic survey parameters were: 120 channels, 10 meters between receivers (shot centered) and 40 meter spacing between shots. This geometry extended across the 5 km region. To perform ray-tracing was used the common shot ray-tracer with P-P reflections. After that it was possible to generate synthetic seismogram using a zero-phase Ricker wavelet with a frequency of 70 Hz. This frequency provided the resolution requirements in the area of interest:
where \( V \) is the P-wave velocity in the layer of interest, \( f \) is the frequency and \( \lambda \) is the wave length. Calculating with the corresponding values:

\[
\begin{align*}
\lambda &= \frac{V}{f} \\
&= \frac{4216.7 \text{ m}}{70 \text{ s}^{-1}} \\
&= 60.24 \text{ m}
\end{align*}
\]

Resolution \( \sim \frac{\lambda}{4} = 15.06 \text{ m} \) (25)

it was found that the resolution is approximately 15 m and the thickness of the layer is 45 m.

A total of six seismic files were generated and stored as SEG-Y files: 0%, 20%, 40%, 60% and 80% and 100% CO₂. These sections represent the shot-gathers.

**Processing of the Seismic Sections**

In order to evaluate the model scenarios, it was necessary to generate the CDP gather and the CDP stack of the obtained shot gather sections. This process was performed using PROMAX software. The first step was the creation of the velocity model which is derived from the geological model with the correspondent P-wave velocity for each layer. For every case (before, during and after CO₂ injection), a model was generated with corresponding velocity changes in the area of interest. After that, Normal Move Out (NMO) was applied to the reflectors in order to get the CDP gather. The final section or CDP stack was obtained by stacking the traces.

**Comparison of the Different Sections**

Once that the final stacked sections for the different saturation stages were obtained, it was possible to compare them and to evaluate the modelling results. The main alterations in the seismic reflectors are time shift and amplitude changes compared with the initial model stage.

The time delay was measured in the basal reflector. First it was necessary to calculate the theoretical time delay using the following equation:

\[
\Delta T = T_2 - T_1 = 2H \left( \frac{1}{V_2} - \frac{1}{V_1} \right)
\]

where \( H \) is the thickness of the layer (45 m), \( V_2 \) is the P-wave velocity of the injection zone for the given saturation stage and \( V_1 \) is P-wave velocity for 0% CO₂. Second, the time delay should be obtained from the CDP stack section. The 0% CO₂ section is considered as the reference, and the time of the bottom reflector (at 425 m) was measured taking the reflector average time. The same procedure was applied for the rest of the sections. After getting all the values we should find the differences of each reflection times with the 0% CO₂ case. These results should be compared with the theoretical calculations of time delay.
Another important evidence of different CO₂ saturation values in the seismic sections is the amplitude variation. The difference between section with CO₂ and the initial no CO₂ condition, should be, qualitatively and quantitatively, appreciated performing the subtraction of the no CO₂ section minus: 20%, 40%, 60% and 80% and 100% CO₂, respectively. The interpolated amplitude value will be measured in the top reflector of the area of interest. This reflector is not affected by the low density coal layer below Paskapoo. The measured values should be compared with theoretical calculations of reflectivity.

In order to evaluate, theoretically, this amplitude changes, the Amplitude Vs Offset (AVO) analysis was applied. The method used was Shuey approximation which is less complex approximation to the Zoeppritz equation (Shuey, 1985). It calculates the reflection coefficient for diverse geological models and different angles of incidence (Shuey, 1985). This approximation is defined for two layers and before being expressed some variables have to be defined:

\[ V_{p1} \] is the P-wave velocity of layer 1 (layer above the injection zone)
\[ V_{p2} \] is the P-wave velocity of layer 2 (injection zone)
\[ V_{s1} \] is the S-wave velocity of layer 1 (layer above the injection zone),
\[ V_{s2} \] is the S-wave velocity of layer 2 (injection zone),
\[ \rho_1 \] is the density of the layer 1,
\[ \rho_2 \] is the density of the layer 2,
\[ V_p = \frac{V_{p1} + V_{p2}}{2} \] is the P-wave velocity,
\[ \Delta V_p = V_{p2} - V_{p1} \] is the P-wave variation,
\[ V_s = \frac{V_{s1} + V_{s2}}{2} \] is the S-wave velocity,
\[ \Delta V_s = V_{s2} - V_{s1} \] is the S-wave variation,
\[ \rho = \frac{\rho_1 + \rho_2}{2} \] is the density,
\[ \Delta \rho = \rho_2 - \rho_1 \] is the density variation,
\[ \sigma_1 = \frac{V_{p1}^2 - 2V_{s1}^2}{2(V_{p1}^2 - V_{s1}^2)} \] is the Poisson ratio in layer 1
\[ \sigma_2 = \frac{V_{p2}^2 - 2V_{s2}^2}{2(V_{p2}^2 - V_{s2}^2)} \] is the Poisson ratio in layer 2
\[ \sigma = \frac{\sigma_1 + \sigma_2}{2} \] is the Poisson ratio,
\[ \Delta \sigma = \sigma_2 - \sigma_1 \] is the Poisson ratio variation,
\[ A_o = B_o - 2(1 + B) \frac{1 - 2\sigma}{1 - \sigma} \], with \[ B_o = \frac{\Delta V_p/V_p}{\Delta \rho/\rho} \]

Finally Shuey’s approximation can be expressed as:

\[ R_i = R_o + \left( A_o R_o + \frac{\Delta \sigma}{(1 - \sigma)^2} \right) \sin^2 \theta_i + \frac{\Delta \sigma}{2V_p} \left( \tan^2 \theta_i - \sin^2 \theta_i \right) \] (27)

where:
R_i is the reflection coefficient for the incident angle \( \theta_i \) and can be expressed as \( R_{pp} \) (only includes P-P reflection).

R_o is the reflection coefficient at zero offset.

Shuey’s equation can be expressed as:

\[
R_{pp} = A + B \sin^2 \theta_i + C (\tan^2 \theta_i - \sin^2 \theta_i) \tag{28}
\]

where \( A \) is the reflection coefficient at zero offset, \( B \), called gradient and describes the small angle behaviour (<30 degrees) and \( C \) describes large angles (Brown et al., 2007). If the geometry of the model doesn’t cover more than 30 degrees the equation can be simplify:

\[
R_{pp} = A + B \sin^2 \theta_i \tag{29}
\]

Beside the Shuey calculation, Zoeppritz 2.0 CREWES calculator was used in order to estimate the AVO effect and compare with the Shuey’s results.

RESULT

**Gassmann Fluid Substitution**

After applying fluid substitution over 380-425m in MILLAR 12-33-21-2W5 well and after generating synthetic seismic traces for each CO\(_2\) saturation states, some alteration can be evaluated. Figure 7 shows GR (track1), porosity (track 2), density, P-wave velocity (track 3), S-wave velocity (track 4) and synthetic logs with 100% water saturation. In addition is displayed the synthetic seismogram at different CO\(_2\) saturation values, form 0 to 100 percent.

Figure 8 shows the synthetic seismogram with different saturation values. The variation between synthetic traces can be appreciated in the zone of fluid substitution (380-425m). Looking at the bsal reflector (425 m) a subtle time shift affects it from 0 to 100% CO\(_2\) saturation. The amplitude values changes across the substitution in the top reflector (380m) with CO\(_2\) increment (See Fig.9). Changes in the P-wave velocity correspond with the variations in traces (See Fig.10), there is an evident P-wave velocity reduction, highlighted at 390-400m. The main drop occurs from 0 to 20% CO\(_2\) saturation, but it can’t be recognized any major variation for higher saturation values.

Gassmann equations were developed using Microsoft Excel calculus sheet. Important results are the P-wave velocity, the S-wave velocity, the P-wave velocity change, the S-wave velocity change and \( Vp/Vs \) change, all of them for CO\(_2\) substitution from 0 to 100 percent saturation (See Table 1). The P-wave velocity values drop abruptly between 0 to 0.2 CO\(_2\) saturation, and starts to increase at 0.3 saturation, as shown in Figure 11. From equation 18, this is evident from the relation of P-wave velocity with \( K_{sat} \) and \( \rho \) bulk. With CO\(_2\) saturation increasing the rock bulk modulus (\( K_{sat} \)) decreases and therefore the P-wave velocity decreases too, but at the same time the bulk density (\( \rho \)) diminishes and due to its inverse relation with P-wave velocity will increase. From 0 to 0.2, the decrease in \( K_{sat} \) values is more representative than the decrease in \( \rho \) resulting in an overall decrease in the P-wave velocity, but from 0.3 CO\(_2\) saturation, the lower density values
cause a subtle increment in the P-wave velocity. The maximum P-wave velocity decrease is 7 %.

Figure 7: MILLAR 12-33-21-2W5 Logs: gamma ray (track 1), porosity (track 2), P-wave (track 3), density (track 3), S-wave (track 4), synthetic traces at different CO$_2$ saturation values, and synthetic trace at 100 % water saturation.
Figure 8: Synthetic seismogram at different saturation values. Zone of fluid substitution with blue parenthesis (380-425m). Time shift at 425 m with red line (basal reflector).

Figure 9: Synthetic traces, amplitude variation with increasing CO₂ saturation
Fluid substitution sandstone aquifer

Figure 10: Synthetic traces, velocity variation with increasing CO₂ saturation

![Synthetic traces, velocity variation with increasing CO₂ saturation](image)

Table 1: a) Gassmann fluid substitution results (380-425m). b) Input values.

<table>
<thead>
<tr>
<th>Water/Brine Saturation</th>
<th>CO₂ Saturation</th>
<th>Kf (Gpa)</th>
<th>Fluid Density (Kg/m³)</th>
<th>Bulk Density (Kg/m³)</th>
<th>Ksat (Gpa)</th>
<th>Vp (m/s)</th>
<th>Vs (m/s)</th>
<th>Vp change (%)</th>
<th>Vs change (%)</th>
<th>Vp/Vs change (%)</th>
<th>dt (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>2.330</td>
<td>1000.000</td>
<td>2509.250</td>
<td>26.075</td>
<td>4212.023</td>
<td>2216.854</td>
<td>0.000</td>
<td>0.000</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>0.9</td>
<td>0.1</td>
<td>0.187</td>
<td>914.650</td>
<td>2501.969</td>
<td>21.702</td>
<td>3904.561</td>
<td>2220.077</td>
<td>-7.300</td>
<td>0.145</td>
<td>-7.434</td>
<td>1.683</td>
</tr>
<tr>
<td>0.8</td>
<td>0.2</td>
<td>0.097</td>
<td>829.300</td>
<td>2494.688</td>
<td>21.518</td>
<td>3900.835</td>
<td>2223.315</td>
<td>-7.388</td>
<td>0.291</td>
<td>-7.657</td>
<td>1.705</td>
</tr>
<tr>
<td>0.7</td>
<td>0.3</td>
<td>0.065</td>
<td>743.950</td>
<td>2487.408</td>
<td>21.453</td>
<td>3903.185</td>
<td>2226.566</td>
<td>-7.332</td>
<td>0.438</td>
<td>-7.737</td>
<td>1.691</td>
</tr>
<tr>
<td>0.6</td>
<td>0.4</td>
<td>0.049</td>
<td>658.600</td>
<td>2480.127</td>
<td>21.420</td>
<td>3907.187</td>
<td>2229.832</td>
<td>-7.237</td>
<td>0.585</td>
<td>-7.777</td>
<td>1.667</td>
</tr>
<tr>
<td>0.5</td>
<td>0.5</td>
<td>0.040</td>
<td>573.250</td>
<td>2472.846</td>
<td>21.400</td>
<td>3911.886</td>
<td>2233.112</td>
<td>-7.125</td>
<td>0.733</td>
<td>-7.802</td>
<td>1.639</td>
</tr>
<tr>
<td>0.4</td>
<td>0.6</td>
<td>0.033</td>
<td>487.900</td>
<td>2465.566</td>
<td>21.386</td>
<td>3916.951</td>
<td>2236.407</td>
<td>-7.005</td>
<td>0.882</td>
<td>-7.819</td>
<td>1.610</td>
</tr>
<tr>
<td>0.3</td>
<td>0.7</td>
<td>0.028</td>
<td>402.550</td>
<td>2458.285</td>
<td>21.376</td>
<td>3922.239</td>
<td>2239.716</td>
<td>-6.880</td>
<td>1.031</td>
<td>-7.830</td>
<td>1.579</td>
</tr>
<tr>
<td>0.2</td>
<td>0.8</td>
<td>0.025</td>
<td>317.200</td>
<td>2451.005</td>
<td>21.369</td>
<td>3927.676</td>
<td>2243.040</td>
<td>-6.751</td>
<td>1.181</td>
<td>-7.839</td>
<td>1.547</td>
</tr>
<tr>
<td>0.1</td>
<td>0.9</td>
<td>0.022</td>
<td>231.850</td>
<td>2443.724</td>
<td>21.363</td>
<td>3933.223</td>
<td>2246.379</td>
<td>-6.619</td>
<td>1.339</td>
<td>-7.846</td>
<td>1.515</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0.020</td>
<td>146.500</td>
<td>2436.443</td>
<td>21.358</td>
<td>3938.855</td>
<td>2249.733</td>
<td>-6.485</td>
<td>1.483</td>
<td>-7.852</td>
<td>1.482</td>
</tr>
</tbody>
</table>

Table 1: a) Gassmann fluid substitution results (380-425m). b) Input values.
On the other hand, the S-wave velocity increase is directly proportional to CO₂ saturation (see table 1) as shown in Figure 12. From equation 19, it is possible to see that the S-wave velocity change depends only on bulk density variations since the shear modulus remains constant and it is not reflected by fluid substitution. However, the average increase of the S-wave velocity with respect to 100% water saturation is only 0.8%.

\[ \text{Figure 11: P-wave velocity change versus CO₂ saturation} \]

\[ \text{Figure 12: S-wave velocity change versus CO₂ saturation} \]

\[ \frac{V_p}{V_s} \] values decrease with CO₂ saturation due to the increase of \( V_s \) and a decrease in \( V_p \) (see Table 1) having a maximum decrease of 8%. Figure 13 shows a sharp drop from 0 to 0.1 CO₂ saturation, becoming more linear for higher values. An extra element included in this table is the time delay calculated using equation 26. As CO₂ saturation increases a time delay through the reservoir is produced; it takes more time to the P-wave travel the through the zone of interest. In this case the thickness of the interval (h) is 45 m. The average two-way delay time is 1.6 ms.
Fluid substitution sandstone aquifer

Seismic Modelling

A 2D geological model generated for the area is shown in Figure 14. It is made up a total of 8 layers form 0 to 1 km depth. Paskapoo Formation is the fourth (4th) layer, represented with dark blue and is from 380-425 m. The parameters estimated from well information for each of the layers are listed in Table 2. The first layer parameters are approximate for shallow conditions. Figure 15 represents the same geological model but after CO₂ injection. All the initial conditions remain constant changing the parameters in the zone of injection which is reflected as the green block in Figure 15. The two regions at each side are the transition zones. The parameters used in the injection area for the different saturation stages are summarized in Table 3.

Figure 13: P-wave velocity/S-wave velocity change versus CO₂ saturation

Figure 14: 2D Geological model of the area. Layer 4 (in blue) represents Paskapoo Formation.
Table 2: P-wave and density values for each layer in the geological model. Paskapoo Formation is the 4th layer (green label).

<table>
<thead>
<tr>
<th>Layer</th>
<th>Vp (m/s)</th>
<th>ρ (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1900</td>
<td>2300</td>
</tr>
<tr>
<td>2</td>
<td>2546</td>
<td>2250</td>
</tr>
<tr>
<td>3</td>
<td>3498</td>
<td>2390</td>
</tr>
<tr>
<td>4</td>
<td>4212</td>
<td>2509</td>
</tr>
<tr>
<td>5</td>
<td>3326</td>
<td>1875</td>
</tr>
<tr>
<td>6</td>
<td>3710</td>
<td>2429</td>
</tr>
<tr>
<td>7</td>
<td>4019</td>
<td>2398</td>
</tr>
<tr>
<td>8</td>
<td>3739</td>
<td>3738</td>
</tr>
</tbody>
</table>

Figure 15: 2D Geological Model with the area of saturation in green. Transition zones are at both sides (pink and purple blocks respectively).

Table 3: Density and P-wave velocity values in the injection zone for each saturation value.

<table>
<thead>
<tr>
<th>CO₂ Saturation (%)</th>
<th>ρ (kg/m³)</th>
<th>Vp (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2509</td>
<td>4212</td>
</tr>
<tr>
<td>20</td>
<td>2495</td>
<td>3901</td>
</tr>
<tr>
<td>40</td>
<td>2480</td>
<td>3907</td>
</tr>
<tr>
<td>60</td>
<td>2466</td>
<td>3917</td>
</tr>
<tr>
<td>80</td>
<td>2451</td>
<td>3928</td>
</tr>
<tr>
<td>100</td>
<td>2436</td>
<td>3939</td>
</tr>
</tbody>
</table>

Table 3: Density and P-wave velocity values in the injection zone for each saturation value.

Six CDP stack seismic sections were generated for the conditions: 0%, 20%, 40%, 60%, 80% and 100% CO₂ saturation. Figure 16 shows the 0% CO₂ saturation prior to...
injection stage (upper section) and the 100% CO₂ saturation or final injection stage (lower section). The reflector in the CDP stack sections represent the interfaces of the geological model but expressed in time domain, excluding the first superficial layer. The third reflector represents the top of Paskapoo Fm. and in the fully saturated stage is possible to see the changes in the reflection character.

**Figure 16:** a) CDP stack sections 0% CO₂ saturation (initial model). b) CDP stack sections 100% CO₂ saturation in the area of interest.
Evaluating the time shift in the zone of injection, different time delay values were found depending on the saturation. The theoretical values for time delay calculated with equation 26 are reflected in Table 4 with its respective tendency graph (Figure 17). On the other hand, in Table 5 we have the values for the time delay estimated from the CDP stack section and its graph as (Figure 18). The tendency of both curves is the same, it can be seen a sharp increase in the time delay for the 20% CO₂ saturation stage, but the delay start a subtle decrease from 40%. There is an approximated difference of 0.07 ms between the theoretical and the observed values (higher values for the theoretical case). This difference might be attributed to the effect of the coal layer below Paskapoo. Between these two layers there is a high amplitude contrast that make difficult to obtain an accurate position in time of the basal reflector. Time delay vs. CO₂ saturation curve has the opposite tendency than the P-wave velocity change vs. CO₂ saturation curve. When the P-wave drops the time delay rises and when the P-wave velocity starts its subtle rising, time delay diminishes.

<table>
<thead>
<tr>
<th>CO₂ Saturation (%)</th>
<th>dt (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>10</td>
<td>1.68</td>
</tr>
<tr>
<td>20</td>
<td>1.70</td>
</tr>
<tr>
<td>30</td>
<td>1.69</td>
</tr>
<tr>
<td>40</td>
<td>1.67</td>
</tr>
<tr>
<td>50</td>
<td>1.64</td>
</tr>
<tr>
<td>60</td>
<td>1.61</td>
</tr>
<tr>
<td>70</td>
<td>1.58</td>
</tr>
<tr>
<td>80</td>
<td>1.55</td>
</tr>
<tr>
<td>90</td>
<td>1.51</td>
</tr>
<tr>
<td>100</td>
<td>1.48</td>
</tr>
</tbody>
</table>

Table 4: CO₂ saturation values and theoretical calculated time delay (dt).

![Graph of theoretical time delay vs. CO₂ saturation](image-url)
Table 5: CO₂ saturation values and observed time delay (dt)

<table>
<thead>
<tr>
<th>CO₂ Saturation (%)</th>
<th>dt (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>1.04</td>
</tr>
<tr>
<td>40</td>
<td>1.02</td>
</tr>
<tr>
<td>60</td>
<td>0.94</td>
</tr>
<tr>
<td>80</td>
<td>0.89</td>
</tr>
<tr>
<td>100</td>
<td>0.82</td>
</tr>
</tbody>
</table>

The effect of the CO₂ injection can be appreciated by subtracting each of the CDP stack sections from the 0% CO₂ section. Figure 19 shows the difference between the 0% CO₂ section and the 100% CO₂ section. As is expected, the rest of the traces outside the area of interest were cancelled while the top and bottom reflectors of this region are highlighted due to the difference in amplitudes and travel times of the event from the base of the injection horizon.
Amplitude versus offset analysis

In order to evaluate the changes in amplitude versus offset (AVO) depending on the saturation percentage, Shuey’s approximation was applied. Taking equation 29; A, B and \( R_{pp} \) coefficients for the different CO\(_2\) saturation stages, were calculated (see Table 6). The gradient B and the \( R_{pp} \) coefficient for the different stages is calculated with 15 degrees of P-wave incidence as model case.

<table>
<thead>
<tr>
<th>CO(_2) Saturation</th>
<th>( A (R_0) )</th>
<th>B (( \theta = 15 ) degrees)</th>
<th>( R_{pp} ) (( \theta = 15 ) degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.117</td>
<td>-0.0121</td>
<td>0.105</td>
</tr>
<tr>
<td>0.1</td>
<td>0.078</td>
<td>-0.0142</td>
<td>0.064</td>
</tr>
<tr>
<td>0.2</td>
<td>0.076</td>
<td>-0.0142</td>
<td>0.062</td>
</tr>
<tr>
<td>0.3</td>
<td>0.075</td>
<td>-0.0141</td>
<td>0.061</td>
</tr>
<tr>
<td>0.4</td>
<td>0.074</td>
<td>-0.0141</td>
<td>0.060</td>
</tr>
<tr>
<td>0.5</td>
<td>0.073</td>
<td>-0.0141</td>
<td>0.059</td>
</tr>
<tr>
<td>0.6</td>
<td>0.072</td>
<td>-0.0140</td>
<td>0.058</td>
</tr>
<tr>
<td>0.7</td>
<td>0.071</td>
<td>-0.0140</td>
<td>0.057</td>
</tr>
<tr>
<td>0.8</td>
<td>0.071</td>
<td>-0.0139</td>
<td>0.057</td>
</tr>
<tr>
<td>0.9</td>
<td>0.070</td>
<td>-0.0139</td>
<td>0.056</td>
</tr>
<tr>
<td>1</td>
<td>0.069</td>
<td>-0.0138</td>
<td>0.055</td>
</tr>
</tbody>
</table>

Table 6: CO\(_2\) saturation stages with its correspondent A, B and \( R_{pp} \) values.

The values for the overlaying bed are: P-wave velocity of 3497 m/s (\( V_{p1} \)), S-wave velocity of 1665 m/s (\( V_{s1} \)) and a density of 2390 kg/m\(^3\) (\( \rho_1 \)).
In Figure 20 are represented the values of Table 6. The first graphs, A (zero offset reflectivity coefficient) vs. CO\textsubscript{2} saturation, shows that for higher concentrations of CO\textsubscript{2} the amplitude will decrease. Zero offset reflectivity has a quick drop from 0% to 10% CO\textsubscript{2} saturation having a subtle decrease in the subsequent stages. CO\textsubscript{2} will reduce the bulk density and therefore the reflectivity contrast. In this sense the amplitude is going to be reduced with the increment of CO\textsubscript{2} saturation.

The second graph, B (gradient) vs. CO\textsubscript{2} saturation, shown a different tendency, having the same significant decrease from 0% to 10%, but starts subtle rise after 20% CO\textsubscript{2} saturation similar V\textsubscript{p} vs. CO\textsubscript{2} saturation. Finally, the P-wave reflectivity coefficient (R\textsubscript{pp}) vs CO\textsubscript{2} saturation graph is similar to A vs. CO\textsubscript{2} saturation, where the reflectivity values and therefore, the resulting amplitude values, will decrease with the increment of CO\textsubscript{2} saturation, having the greater drop in the first 10%.

Beside the theoretical calculation, the amplitude was estimated form the CDP stack section. Table 7 shows the relative values for amplitude decrease with the increment of CO\textsubscript{2} saturation. In Figure 21 we have amplitude vs. CO\textsubscript{2} saturation, presenting the same tendency than the theoretical curve.
Table 7: Relative amplitude values measured from CDP stack sections with different CO₂ saturation conditions

<table>
<thead>
<tr>
<th>CO₂ Saturation (%)</th>
<th>Amplitude (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>20</td>
<td>64</td>
</tr>
<tr>
<td>40</td>
<td>62</td>
</tr>
<tr>
<td>60</td>
<td>61</td>
</tr>
<tr>
<td>80</td>
<td>60</td>
</tr>
<tr>
<td>100</td>
<td>57</td>
</tr>
</tbody>
</table>

Figure 21: Amplitude vs. CO₂ saturation (measured from CDP stack section).

After evaluating the changes in reflectivity due to CO₂ saturation, the final $R_{pp}$ was calculated with different angles of incidence to evaluate the changes of reflectivity with offset. Shuey’s approximation (equation 29) was applied for three CO₂ saturation stages: 0%, 20% and 60%, taking a maximum angle of 25 degrees which is close to the incident angle for the maximum offset in this geometry.

Table 8: $R_{pp}$ coefficient values at different CO₂ saturation stages (0%, 20% and 60%) and its changes with the angle of incidence.

<table>
<thead>
<tr>
<th>Angle (Degrees)</th>
<th>$R_{pp}(0% \text{ CO}_2)$</th>
<th>$R_{pp}(20% \text{ CO}_2)$</th>
<th>$R_{pp}(60% \text{ CO}_2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.117</td>
<td>0.076</td>
<td>0.072</td>
</tr>
<tr>
<td>5</td>
<td>0.115</td>
<td>0.074</td>
<td>0.071</td>
</tr>
<tr>
<td>15</td>
<td>0.105</td>
<td>0.062</td>
<td>0.058</td>
</tr>
<tr>
<td>25</td>
<td>0.085</td>
<td>0.038</td>
<td>0.035</td>
</tr>
</tbody>
</table>
In Table 8 shows the $R_{pp}$ values at the different stages (0%, 20% and 60%) and with different incidence angles. The graph presented in Figure 22 shows the curves at each saturation stage. The reflectivity diminishes with the increment in the incident angle. All the curves have the same tendency, but with the CO$_2$ increment the reflectivity values decrease. The major drop occurs for 0% to 20%.

**CONCLUSIONS**

- Paskapoo Formation has suitable qualities for a test CO$_2$ geological storage site; it has considerable section of clean sandstone and being a shallow objective will reduce monitoring complexities and cost.

- Gassmann theory is a practical and useful tool in fluid substitution models. Direct evaluation and synthetic seismogram variation reflects the effects of CO$_2$ saturation. Applying this principle over a 380-425 m section it is possible to evaluate some changes. In the synthetic traces a time shift and amplitude variation is detectable in the area of interest. P-wave velocity drops quickly from 0 to 0.2 CO$_2$ saturation, becoming more uniform at higher saturations.

- Applying Gassmann fluid substitution, the following was observed: average P-wave velocity decrease is 7%, average S-wave velocity increase is 0.8%, average $V_p/V_s$ decrease 8% and two-way time delay trough the reservoir is 1.6 ms. The $V_s$ increase is directly proportional to the CO$_2$ saturation. The decrease of $V_p$ and density will represent a decrease in the impedance and therefore in the reflectivity contrast.

- Seismic modelling helped to simulate the conditions in the region of interest and the seismic changes during the different stages of CO$_2$ injection (0%, 20%, 40%, 60%, 80% and 100% CO$_2$ saturation). These variations can be seen in the injection zone inside the Paskapoo Formation. After performing the difference between traces the residual CDP stack section obtained highlights the injection zone.
• Evaluating the time shift from the CDP stack sections, a delay was found in the basal reflector for 20% CO₂ saturation condition (1.04 ms), but it started to diminish with the saturation increment. The observed values are coherent with the theoretical calculations. The time delay vs. CO₂ Saturation has the opposite tendency than the Vp change vs. CO₂ Saturation curve. The observed value for time delay is approximated 0.07 ms less than the expected value. This range of error could be a product of the reflection effect of the coal layer below the Paskapoo Formation.

• The amplitude will decrease with increasing CO₂ saturation, having a major drop at 20% CO₂ saturation, according what it can be observe from CDP stack sections. The overlaying layer present lower velocity and density than Paskapoo Formation, so the increase in CO₂ saturation will diminish the bulk density in the Formation, reducing the reflectivity contrast. Theoretical and observed data confirm this result.

• From Shuey’s approximation, it was found that the P-wave reflectivity coefficient decreases with the CO₂ saturation increment. The major drop will occur at the first 20% saturation, and it will have a slight decrease for the next stages. Evaluating the changes in reflectivity due to incident angle, it was found that for larger angles, the reflectivity decreases.

ACKNOWLEDGMENT

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