FLUID SUBSTITUTION AND SEISMIC MODELLING IN A SANDSTONE AQUIFER

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Don Lawton
Outline

- Objectives
- Area of Study and Stratigraphy
- Fluid Substitution
- Data and Methodology
- Results and Conclusions
Objectives

- To evaluate the Paskapoo Formation as a potential CO₂ geological storage site.
- To apply fluid substitution and seismic modelling in order to identify and analyze the effects of CO₂ on rock properties and seismic patterns.
Wellbore Data: MILLAR 12-33-21-2W5

Rocky Mountains
Foothills, 20 kilometres
Southwest of Calgary

Area of Study

(Bachu et al., 2000)
**Stratigraphy**

**Paskapoo Fm:**
- Composed of mudstone, siltstone and sandstone, with subordinate limestone and coal.

**Foreland Deposits**
- Important ground water reservoir target
- High porosity coarse-grained sandstone channels

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<table>
<thead>
<tr>
<th>ERA</th>
<th>PERIOD</th>
<th>FORMATION OR GROUP</th>
<th>LITHO.</th>
<th>AVERAGE SEISMIC VELOCITIES (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tertiary (TERT)</td>
<td></td>
<td>Paskapoo</td>
<td></td>
<td>2200–2700</td>
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<tr>
<td>Cretaceous</td>
<td>Upper</td>
<td>Edmonton (EDMN)</td>
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<td></td>
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<td>Bearpaw Shale</td>
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<td></td>
<td>Lower</td>
<td>Belly River (BLRV)</td>
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<td>3800–4100</td>
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<td>Wapiabi</td>
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<td>Alberta Group</td>
<td>Cardium (CRDM)</td>
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<td>3900–4150</td>
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<td>Blackstone</td>
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<td>Lower</td>
<td>Blairmore (BMGP)</td>
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<td>4200–4400</td>
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<td>Kootenay</td>
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<td>4100–4300</td>
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<td>Fernie</td>
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<td>Jurassic</td>
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<td>Mississippian (MSSP)</td>
<td>Rundle Group</td>
<td>Mount Head Turner Valley</td>
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<td>Banff</td>
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<td>Kaskasia</td>
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<tr>
<td>Devonian (DEVN)</td>
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<td>Palliser</td>
<td></td>
<td>5500–6000</td>
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<td></td>
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<td>Fairholme</td>
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*Lawton et al., 1996*
Fluid Substitution

Gassmann equation

\[ K = \frac{\delta \varepsilon}{\delta \sigma} \]

\[ K_{\text{sat}} = \text{Saturated Rock Bulk Modulus} \]

\[ K_0 = \text{Matrix Bulk Modulus} \]

\[ \rho_0 = \text{Matrix Density} \]

\[ K_{100\text{sat}} = \text{Rock Bulk Modulus 100\% water sat} \]

\[ K^* = \text{Dry Rock Bulk Modulus} \]

\[ G = \text{Shear Modulus} \]

\[ \rho_b = \text{Bulk Density} \]

\[ \phi = \text{Porosity} \]

\[ \rho_{\text{fl}} = \text{Fluid Density} \]

\[ K_{\text{fl}} = \text{Fluid Bulk Modulus} \]

\[ K_{\text{sat}} = K^* \left( 1 - \frac{K^*}{K_0} \right)^2 \left( 1 - \frac{\phi}{K_{\text{fl}}} \right) + \frac{1 - \phi}{K_0} - \frac{K^*}{K_0^2} \]
Fluid Substitution

Gassmann equation

\[ V_s = \sqrt{\frac{G}{\varphi}} \]

**Constants during substitution:**
\[ \varphi, G, \rho_0, K_0, K* \]

**Variables during substitution:**
\[ K_{fl}, \rho_{fl}, \rho_b, \]

\[ K_{sat} = K* \left( \frac{1 - \frac{K*}{K_0}}{\frac{\varphi}{K_{fl}} + \frac{1 - \varphi}{K_0} - \frac{K*}{K_0^2}} \right) \]

\[ \sigma_p = \sqrt{\frac{K_{sat} + \frac{4G}{3}}{\rho_b}} \]
Wellbore data: MILLAR 12-33-21-2W5

Target: 380-425m

Coal
Methodology

Fluid substitution using Gassmann’s equation and synthetic seismogram generation.

Seismic Modelling:
- 2D geological model
- Ray-tracing and synthetic seismogram generation
- Processing of the seismic sections
- Comparison between different seismic sections
- Recognition of differences in seismic pattern and AVO analysis
Logs and synthetic traces

<table>
<thead>
<tr>
<th>GR (API)</th>
<th>Φ (%)</th>
<th>p (gr/cc)</th>
<th>Vp (m/s)</th>
<th>Vs (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>0%</td>
<td>100%</td>
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</table>

380(m) 425(m)
Synthetic Traces. CO$_2$ Saturation

Results

CO$_2$ sat %

Injection zone

Basal Reflector

Depth (m)
Results

Amplitude variations

Velocity variations

Injection zone

380 m

425 m

380 m

4800 m/s

3600 m/s
Results

$V_P$ and $V_S$ changes

![Graphs showing changes in $V_P$, $V_S$, and $V_p/V_s$ vs. CO$_2$ Saturation]
Geological model

Initial model

Model with CO₂ Injection zone
Seismic modelling

CDP stack: Initial model

CDP stack: After CO₂ injection

Time (ms)
300
Results

Difference between sections

<table>
<thead>
<tr>
<th>SHOT</th>
<th>25</th>
<th>50</th>
<th>75</th>
<th>100</th>
<th>125</th>
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</thead>
<tbody>
<tr>
<td>CHAN</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>

Time (ms)

300
Results

Time delay (basal reflector) vs. CO₂ saturation

Theoretical calculation:

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

Measured from the section
Results

Amplitude (top reflector) vs. CO$_2$ saturation

Theoretical calculation:

$$R_{ij} = \frac{(\rho_j V_j - \rho_i V_i)}{((\rho_j V_j + \rho_i V_i))}$$

Measured from the section
AVO: Shuey’s approximation

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

\[ R_{pp} = \text{P-wave Reflectivity} \]

\( A = \text{First Coefficient, normal Incidence Reflectivity} \)

\( B = \text{Second Coefficient, small angle (<30 degrees)} \)

\( C = \text{Third Coefficient, larger angle (>30 degrees)} \)

\( \Theta = \text{Angle of Incidence} \)

\[ R_{pp} = A + B\sin^2\theta_i \]
Having an angle of Incidence, $\theta = 15$ degrees

$A$ and $B$ values for $\theta = 15$ degree:

- $A$ decreases with CO$_2$ Saturation.
- $B$ decreases sharply and then levels off with CO$_2$ Saturation.

$R_{pp}$ also decreases with CO$_2$ Saturation.
AVO: Shuey’s approximation

AVA (Amplitude Vs. Angle)

<table>
<thead>
<tr>
<th>Angle (Degrees)</th>
<th>Rpp(0% CO₂)</th>
<th>Rpp(20% CO₂)</th>
<th>Rpp(60% CO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.117</td>
<td>0.0759</td>
<td>0.0721</td>
</tr>
<tr>
<td>5</td>
<td>0.115</td>
<td>0.0743</td>
<td>0.0706</td>
</tr>
<tr>
<td>15</td>
<td>0.105</td>
<td>0.0618</td>
<td>0.0581</td>
</tr>
<tr>
<td>25</td>
<td>0.085</td>
<td>0.0382</td>
<td>0.0348</td>
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</tbody>
</table>

R_{pp} Vs Angle

- Rpp 0% CO₂
- Rpp 20% CO₂
- Rpp 60% CO₂
Recent Progress

Field acquisition

May, 2010: 3D 3C Seismic Survey
(15 receivers lines and 7 source lines)

August, 2010: 2D Seismic Survey
(One 2.5 km Line)
Recent Progress

Extended geological model

Distance (km)

0.0  1.0  2.0  3.0  4.0  5.0  6.0  7.0  8.0

0.0  0.2  0.7  1.2

1 km
Conclusions

• Paskapoo Formation has suitable qualities for a test CO\textsubscript{2} geological storage site.

• Gassmann theory is a practical and useful tool in fluid substitution models.

• There is a recognizable difference in rock properties and seismic response due to CO\textsubscript{2}:

  1) P-wave velocity drops \(~7\%\) from 0\% to 20\% CO\textsubscript{2} saturation
2) S-wave velocity increase is directly proportional to CO$_2$ saturation (average $V_s$ increase 0.8 %).

3) $V_p / V_s$ shows a decrease of 8%

4) Time delay of the bottom reflector is $\sim 1.6$ ms

5) AVO gradient will decrease with CO$_2$ saturation, particularly between 0% and 20 % CO$_2$ saturation.
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