SEISMIC SPECTRAL MONITORING OF CO\textsubscript{2} IN A GEOLOGICAL RESERVOIR

Julián L. Gómez and Claudia L. Ravazzoli

CONICET and Departamento de Geofísica Aplicada, Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, Paseo del Bosque s/n, La Plata, Argentina, jgomez@fcaglp.unlp.edu.ar, http://www.fcaglp.unlp.edu.ar/~jgomez

Keywords: Two-phase flow, spectral attributes, seismic reflectivity, CO\textsubscript{2}

Abstract. Peak frequency is a spectral seismic attribute widely used for reservoir thickness estimation and hydrocarbon detection. In this work we apply this attribute in the context of the geological storage of carbon dioxide (CO\textsubscript{2}) and analyze its reliability as a thickness estimator for the gas accumulation. To model the vertical distribution of CO\textsubscript{2}, we solve the Buckley-Leverett equation with discontinuous flux function. A matrix reflectivity algorithm then computes, in the frequency domain, the seismic reflectivity. We find that the peak frequency variability due to CO\textsubscript{2} saturation does not alter significantly its correlation with the accumulation thickness. We then extend the applicability of the spectral attribute by examining its time-lapse response to the evolution of the injected CO\textsubscript{2} volume within a reservoir. We find that a description of the CO\textsubscript{2}-brine contact as well as the evaluation of the reservoir’s caprock sealing capacity can be obtained from this implementation. Peak-frequency time-lapse signatures when the CO\textsubscript{2} forms an up-going front, evolves into a growing accumulation and leaks into the caprock are identified.
1 INTRODUCTION

The geological storage of industrial carbon dioxide (CO$_2$) has the potential to provide a viable short-term mitigation of its atmospheric loading and subsequent greenhouse effect. In this context, the seismic characterization of the injected CO$_2$ in a reservoir is of prime importance for volume capacity evaluation and long-term site performance. The seismic spectral attribute peak-frequency or tuning frequency has been widely utilized for thickness estimation in conventional hydrocarbon reservoirs (Marfurt and Kirlin, 2001; Puryear and Castagna, 2008). Recently Williams and Chadwick (2012) have utilized the peak frequency with notable results to map thin CO$_2$ accumulations at the Sleipner CO$_2$ sequestration site.

The purpose of this study is to analyze the performance of the peak frequency for thickness estimation of a CO$_2$ accumulation and to test its potential as a time-lapse monitoring tool. We show that the peak frequency attribute is a robust indicator for CO$_2$ accumulation thickness.

We find that its variability due to the CO$_2$ overall saturation does not alter significantly its correlation with layer thickness. We then extend the range of applicability of the peak frequency and examine its changes in time as a tool for tracking the CO$_2$ flow and for leakage detection.

The CO$_2$ reservoir considered in this article is modeled after the Sleipner site at the North Sea, Norway. Since 1996, millions of tonnes of CO$_2$ have been injected at the Utsira formation, a large permeable high-porosity sandy aquifer located at a depth from 700 to 1000 m. The upward migration of the injected supercritical CO$_2$ due to buoyancy effects amounts to about 250 m and seems to have been stopped by the caprock situated at the top of the formation (Chadwick et al., 2005).

2 PEAK FREQUENCY AND LAYER THICKNESS

To derive the relationship between peak frequency and layer thickness we consider the analytical expression for the seismic reflectivity for an elastic and acoustic media due to a layer of thickness $h$ between two halfspaces. The layer reflectivity is given by Liu and Schmitt (2003)

$$R_L(f, \theta_1) = \frac{i(Z_2^3 - Z_1Z_3) \sin(k_{22}h) + (Z_3 - Z_1)Z_2 \cos(k_{22}h)}{i(Z_2^3 + Z_1Z_3) \sin(k_{22}h) + (Z_3 + Z_1)Z_2 \cos(k_{22}h)},$$

where $i = \sqrt{-1}$, $f$ is the frequency and $k_{22} = |k_2| \cos \theta_2$, the vertical component of the wavenumber vector, of modulus $|k_2|$. $Z_j = V_j\rho_j/\cos \theta_j$ is the seismic impedance, $V_j$ the P-wave seismic velocity, $\rho_j$ is bulk density and $\theta_j$ the reflection angle in media $j = 1, 2, 3$, related to each other by Snell’s law.

As it can be seen from Equation 1 the layer P-wave reflectivity is complex, periodic and frequency dependent since $k_{22}h = \frac{2\pi f V_2}{\lambda}$. The periodicity of $R_{pp}$ is controlled by the layer thickness $h$, the layer velocity $V_2$ and the incidence angle $\theta_1$.

The layer reflectivity modulus $|R_L|$ displays minima or notches of (Liu and Schmitt, 2003)

$$|R_L(f, \theta_1)| = \left| \frac{Z_3 - Z_1}{Z_3 + Z_1} \right|,$$

when

$$k_{22}h = \frac{2\pi h}{\lambda} \cos \theta_2 = m\pi, \quad m \in \mathbb{N}. \quad (3)$$

Of our particular interest is to rewrite the condition given by Equation 3 in term of the frequency. Since $\lambda = V_2/f$, the frequencies where the reflectivity notches occur are given by

$$f_m^m = m \frac{V_2}{2h \cos \theta_2}. \quad (4)$$
From the periodicity of the trigonometric functions, the peak frequencies where $|R_{pp}|$ shows maxima are given by

$$f_{P}^{m+1} = \left( \frac{1 + 2m}{2} \right) \frac{V_2}{2h \cos \theta_2}.$$  \hspace{1cm} (5)

At normal incidence ($\theta_1 = 0$), the first peak frequency ($m = 0$) occurs at

$$f_p = \frac{V_2}{4h}.$$  \hspace{1cm} (6)

In terms of the two-way time at normal incidence, $\Delta T = \frac{2h}{V_2}$, it follows that

$$f_p = \frac{1}{2\Delta T},$$  \hspace{1cm} (7)

what constitutes an useful relationship for the estimation of temporal thicknesses from peak frequencies (Williams and Chadwick (2012)). Figure 1 shows $|R_L(f, h)|$ at normal incidence for a fully saturated CO$_2$ layer of increasing $h$ using the parameters of Table 1 and 2, as well as a Gassmann fluid substitution to calculate the seismic impact of the CO$_2$ saturation. The trends of the maxima are clearly visible.

![Figure 1: Modulus of the P-wave reflectivity $|R_L(f, h)|$ at normal incidence. The layer has $S_g = 100 \%$.](image)

3 SEISMIC ATTENUATION

After the injection, the CO$_2$ is most likely to be distributed irregularly at different scales within the in-situ brine, these spatial heterogeneities may give rise to mesoscopic seismic attenuation and dispersion phenomena. These effects are represented in this work by implementing a White’s periodic model. Quintal et al. (2011) have shown that the mesoscopic model proposed
by White et al. (1975) gives a reasonable account for attenuation and velocity dispersion in finite media with random heterogeneities in fluid content. White’s representative rock volume is composed of a fully CO$_2$ saturated lamina of thickness $l_g$ and a fully saturated brine lamina of thickness $l_b$, being $l = l_g + l_b$ the length of White’s sample (Figure 2). The CO$_2$ saturation of the lamination is then $S_g = \frac{l_g}{l}$. To account for the lack of specific knowledge on the in-situ saturation of the CO$_2$ accumulation, for a given CO$_2$ saturation $S_g$ between [10%, 90%], we generate a sequence of $N$ random saturations

$$S_j = S_g + \epsilon_j \Delta S$$

(8)

between $[S_g - \Delta S, S_g + \Delta S]$, where $\epsilon_j$ is a uniform random number between $[-1, 1]$ and $j = 1, \ldots, N$. In this way, the bulk density for each of White’s samples is calculated by

$$\rho_j = \phi (S_j \rho_g + (1 - S_j) \rho_b) + (1 - \phi) \rho_m,$$

(9)

where $\phi$ is the sandstone porosity, $\rho_g$ and $\rho_b$ are the CO$_2$ and brine densities respectively listed in Table 2.

Since the CO$_2$ saturation is given in terms of $S_g = l_g/l$, according to the given $S_j$, we calculate the thicknesses of the CO$_2$ and brine laminae by $l_g = lS_j$ and $l_b = l - l_g$ respectively. In our tests, we consider $l = 0.5$ m and $\Delta S = 10\%$.

For every $S_j$ we calculate, at each frequency $f$, the corresponding White’s complex plane wave modulus $M_j(f, S_j)$ and average the results to obtain $\bar{M}(f, \bar{S}_g)$, where

$$\bar{S}_g = \frac{1}{N} \sum_{j=1}^{N} S_j,$$

(10)

is the overall CO$_2$ saturation. For the following tests we used $N = 100$. A histogram for the case $\bar{S}_g = 90\%$ is shown in Figure 3. Given the average plane-wave modulus, and average bulk density $\bar{\rho}(\bar{S}_g) = \frac{1}{N} \sum_{j=1}^{N} \rho_j$, following Carcione (2007), the complex P-wave velocity is

$$V(f, \bar{S}_g) = \sqrt{\frac{\bar{M}}{\bar{\rho}}},$$

(11)

the P-wave phase velocity is calculated as

$$V^p(f, \bar{S}_g) = \left( \text{Re} \left\{ \frac{1}{V} \right\} \right)^{-1},$$

(12)

and the quality factor is

$$Q(f, \bar{S}_g) = \frac{\text{Re}\{\bar{M}\}}{\text{Im}\{\bar{M}\}}.$$

(13)
4 CO₂ FLOW

The vertical distribution of the CO₂ saturation in the reservoir is modeled by the 1D Buckley-Leverett equation. Since for the considered reservoir the capillarity effects are not important (Gómez and Ravazzoli, 2012), the flow of the injected gas is modeled by means of the 1D buoyancy driven Buckley-Leverett equation without capillarity and constant porosity:

\[
\phi \frac{\partial}{\partial t} S_g(t, z) + \frac{\partial}{\partial z} F(S_g, z) = 0, \tag{14}
\]

where \( S_g(t, z) \) is the CO₂ saturation, \( t \) is time, \( z \) is the vertical direction and \( \phi \) porosity. \( F(S_g, z) \) is the global flux function,

\[
F(S_g, z) = \frac{1}{\mu_b} k_{rb} K(z) f(S_g)(\rho_b - \rho_g)g. \tag{15}
\]

\( \mu_b \) and \( k_{rb} \) are the viscosity and relative permeability of brine, \( K \) the absolute permeability, \( g \) the gravity field modulus, \( \rho_b \) and \( \rho_g \) the brine and CO₂ density respectively. \( f(S_g) \) is the fractional flux function,

\[
f(S_g) = \frac{k_{rg}}{k_{rg} + \mu_b k_{rb}}, \tag{16}
\]

being \( k_{rg} \) and \( \mu_g \) the viscosity and relative permeability of CO₂.

The relative permeabilities are computed by the Brooks-Corey expressions (Brooks and Corey, 1966),

\[
k_{rb}(S_g) = (1 - S_{eg})^{2+\lambda \lambda}\]
\[
k_{rg}(S_g) = S_{eg}^2 \left[ 1 - (1 - S_{eg})^{2+\lambda \lambda} \right] \tag{17}
\]

where \( \lambda \) is the pore size distribution index and

\[
S_{eg} = \frac{S_g - S_{rg}}{1 - S_{rg} - S_{rb}} \tag{18}
\]

is the effective gas saturation. \( S_{rb} \) and \( S_{rg} \) denote the residual brine and CO₂ saturation respectively.

Figure 3: Histogram for the random CO₂ saturations \( S_j \) considered to make the overall value of \( S_g = 90\% \). 100 random saturations where considered between 80\% and 100\%.
The initial condition taken is \( S_g = 0 \). At the base of the computational domain \( z = -20 \) m the saturation will be held at 0.28\% for all \( t \), this means that the CO\(_2\) is assumed to be injected continually from the bottom of the computational domain. The value of 0.28\% is close to the value that makes \( F \) a maximum; which is the highest saturation permitted to travel in the domain. The condition at the base of the domain implies then that the CO\(_2\) will enter the target reservoir \( (z = 0 \) m) as a shock of nearly constant saturation.

To numerically implement the Buckley-Leverett law we use the conditionally stable finite-difference relaxation method proposed by Seaïd (2006). The main advantage of this method is the simplicity of the resulting scheme that accurately solves the Buckley-Leverett law in the presence of permeability discontinuities. This method has been written as a FORTRAN90 subroutine and tested against the results of Hayek et al. (2009) and Seaïd (2006). The relaxation scheme parameters applied are analogous of those in Gómez and Ravazzoli (2012). We refer to this publication for more details on the derivation of the Buckley-Leverett equation and its implementation.

<table>
<thead>
<tr>
<th>Lithology</th>
<th>( V_p ) [m/s]</th>
<th>( V_s ) [m/s]</th>
<th>( \rho ) [kg/m(^3)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shale</td>
<td>2270</td>
<td>850</td>
<td>2100</td>
</tr>
<tr>
<td>Sandstone</td>
<td>2050</td>
<td>620</td>
<td>2050</td>
</tr>
</tbody>
</table>

Table 1: Seismic velocities and density of the Sleipner sandstone and shale at the 100\% brine saturated pre-injection state, taken from Williams and Chadwick (2012).

5 SEISMIC REFLECTIVITY OF THE CO\(_2\) FLOW

Once the vertical distribution of the carbon dioxide flux has been simulated, the reservoir’s P-wave reflectivity response at normal incidence is obtained using a matrix reflectivity method for layered media. The matrix reflectivity method is an stable recursion that, starting from the bottom of the reservoir, adds one layer at a time and computes its reflectivity. Once the top of the reservoir is reached, the method gives the frequency and angle dependent complex reflection and transmission coefficients of compressional P and vertical shear waves SV. The heart of this algorithm is based solely on the continuity of particle displacements and stress at the interfaces between the successive layers that compose the reservoir (Pride et al., 2002).

At normal incidence, the reflectivity algorithm takes the simple scalar form (Mavko et al., 2011),

\[
\hat{R}^{(k)} = R^{(k)} + \frac{1}{1 + R^{(k)} E^{(k)} \hat{R}^{(k+1)} E^{(k)}} T^{(k)} \tag{19}
\]

\[
\hat{T}^{(k)} = \frac{\hat{T}^{(k+1)} E^{(k)} }{1 + R^{(k)} E^{(k)} \hat{R}^{(k+1)} E^{(k)}} T^{(k)} \tag{20}
\]

where \( \hat{R}^{(k)} \) and \( \hat{T}^{(k)} \) are the generalized reflection and transmission coefficients up to layer \( k = 1, \ldots, n + 1 \), where \( n \) is the number of layers considered. The reflection and transmission coefficients for scaled displacements of each layer \( k \) are

\[
R^{(k)} = \frac{\rho_{k-1} V_{k-1} - \rho_k V_k}{\rho_{k-1} V_{k-1} + \rho_k V_k}, \tag{21}
\]

\[
T^{(k)} = \frac{2 \sqrt{\rho_{k-1} V_{k-1} \rho_k V_k}}{\rho_{k-1} V_{k-1} + \rho_k V_k}, \tag{22}
\]
<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity of sand, $\phi$</td>
<td>0.37</td>
<td>[]</td>
</tr>
<tr>
<td>Permeability of sand, $K_1$</td>
<td>$1 \times 10^{-12}$</td>
<td>[m$^2$]</td>
</tr>
<tr>
<td>Permeability of shale, $K_2$</td>
<td>$5 \times 10^{-14}$</td>
<td>[m$^2$]</td>
</tr>
<tr>
<td>Matrix bulk modulus of sand, $K_m$</td>
<td>36.9</td>
<td>[GPa]</td>
</tr>
<tr>
<td>Matrix bulk modulus of shale, $K_m$</td>
<td>22.72</td>
<td>[GPa]</td>
</tr>
<tr>
<td>Density of brine, $\rho_b$</td>
<td>1040.0</td>
<td>[kg/m$^3$]</td>
</tr>
<tr>
<td>Density of CO$_2$, $\rho_g$</td>
<td>690.0</td>
<td>[kg/m$^3$]</td>
</tr>
<tr>
<td>Viscosity of brine, $\mu_b$</td>
<td>$0.25 \times 10^{-3}$</td>
<td>[Pa s]</td>
</tr>
<tr>
<td>Viscosity of CO$_2$, $\mu_g$</td>
<td>$4.38 \times 10^{-5}$</td>
<td>[Pa s]</td>
</tr>
<tr>
<td>Bulk modulus of brine, $K_b$</td>
<td>2.305</td>
<td>[GPa]</td>
</tr>
<tr>
<td>Bulk modulus of CO$_2$, $K_g$</td>
<td>0.088</td>
<td>[GPa]</td>
</tr>
<tr>
<td>Residual saturation of brine, $S_{rb}$</td>
<td>0.20</td>
<td>[ ]</td>
</tr>
<tr>
<td>Residual saturation of CO$<em>2$, $S</em>{rg}$</td>
<td>0.05</td>
<td>[ ]</td>
</tr>
<tr>
<td>Pore size distribution index, $\lambda$</td>
<td>2</td>
<td>[ ]</td>
</tr>
</tbody>
</table>

Table 2: Main parameters for the reservoir. Data has been collected from Audigane et al. (2007); Chadwick et al. (2004); Hayek et al. (2009); Mouche et al. (2010) and Williams and Chadwick (2012).

$E^k = \exp(2\pi i f h_k/V_k)$ is the phase shift operator and $i$ the imaginary unit. $V_k$ is the P-wave velocity, $\rho_k$ the density and $h_k$ the thickness of layer $k$. The recursion begins at the base of the layering by setting $R^{(n+1)} = \hat{R}^{(n+1)} = 0$ and $T^{(n+1)} = \hat{T}^{(n+1)} = 1$. From the algorithm we obtain the sequence:

$$\hat{R}^{(n+1)}, \hat{R}^{(n)}, \hat{R}^{(n-1)}, \ldots, \hat{R}^{(1)};$$

being $R_{pp}(f) \equiv \hat{R}^{(1)}$ the generalized reflection coefficient of the layered medium. By means of the correspondence principle (Ben-Menahen and Singh, 1981) we can extend this algorithm for a layered medium with velocity dispersion and attenuation. This algorithm was also written in FORTRAN90 and interacts with the saturation profile given by the Buckley-Leverett subroutine by means of a driver script written in bash.

6 PEAK FREQUENCY AND CO$_2$ SATURATION

The main parameters that characterize the modeled CO$_2$ accumulation, and have a substantial impact in the seismic reflectivity, are the layer thickness $h$ and overall gas saturation $S_g$. Some spectral attributes, such as spectral gradient (Sulistyoati et al., 2011) and average frequency (Barnes et al., 2004), can not individualize the layer thickness effects from the CO$_2$ saturation on the reflectivity. For this reason, we investigate in this section how independent is the thickness estimation through $f_p$ from the CO$_2$ saturation of the accumulation. The reservoir considered in this section is a poroelastic medium that consists of a CO$_2$ saturated layer between two halfspaces (Figure 4). The upper halfspace (medium 1), represents the Nørdland shale caprock. The embedded layer of thickness $h$ (medium 2), is a Utsira sandstone partially saturated by immiscible CO$_2$ and brine. The CO$_2$ is at a supercritical state, behaving as a low-viscosity fluid. The bottom halfspace of the model (medium 3), consists of a Utsira sandstone fully saturated with brine. Seismic velocities and densities for the shale caprock and the fully brine saturated sandstone are shown in Table 1 and the physical properties of the reservoir fluids are listed in Table 2. In Figure 5a we plot the amplitude of the normal-incidence reflection coefficient for an accumulation of $h = 30$ m. This frequency-dependent reflectivity exhibits the effects of velocity dispersion (Figure 5b) and attenuation (5c) due to wave-induced fluid flow. A lowering
Caprock

Sandstone, \( \bar{S}_g \) Sandstone, \( \bar{S}_g = 0 \)

Figure 4: One CO\(_2\) saturated layer between halfspaces to evaluate peak frequency in a CO\(_2\) storage reservoir.

Figure 5: (a) Amplitude of the normal-incidence reflection coefficient of the layer, \( |R_L| \), when layer thickness is \( h = 30 \) m. The CO\(_2\) overall saturation is \( \bar{S}_g = 50\% \). (b) P-wave phase velocity and (c) attenuation from White’s model.

of \( |R_L| \) amplitudes at high seismic frequencies, due to attenuation can be seen. At the zero frequency limit the layer reflectivity becomes the reflection coefficient between the halfspaces. The character of the normal-incidence reflectivity for White’s model is shown in figure 6. As we can see, the trend of the peak frequency with layer thickness holds in the case of a non elastic medium. We assess next how robust is this relationship to changes in CO\(_2\) saturation. Figure 7 shows the layer thickness versus peak frequency curve for overall CO\(_2\) saturations between 10\% and 90\%. The case when \( S_g = 0 \) is not taken into account because it is the baseline case, where no CO\(_2\) is yet present in the targeted reservoir. As we can see, the standard deviation in thickness estimation, given by the error bars, is acceptable. The sensitivity due to the varying overall CO\(_2\) content starts to increases when \( h \) becomes small. For layers of \( h < 4 \) m, the standard deviation can be of over 20 Hz but the peak frequency is already beyond the seismic range \( f < 120 \) Hz. For \( h > 4 \) m the deviation is lower than 5 Hz. We conclude from this test that peak frequency is a viable estimator for layer thickness regardless of the overall CO\(_2\) saturation content and the viscoelastic effects. This because the CO\(_2\) saturation mainly modifies the \( |R_L| \) amplitude but not the position of its notches and maxima.

In the next section we will show how a time-lapse computation of peak frequency can be used to trace the evolution of the CO\(_2\) flow in a reservoir.
7 TIME-LAPSE PEAK FREQUENCY

Since the CO$_2$ accumulation thickness is given by the position of the CO$_2$-brine fluid contact, it is to expect that a time-lapse calculation of peak frequency should be able to track this fluid/fluid contact through time. Whether or not the CO$_2$ layer can be imaged explicitly by the seismic method, this could be used as a practical tool to interpret the CO$_2$ flow in a reservoir.

Based on Sleipner’s topmost CO$_2$ accumulation, we consider a 20 m thick brine saturated Utsira sandstone overlain by a halfspace playing the role of the Nørdland shale caprock. At the base of the computational domain, 10 m below the target reservoir base, we consider a constant CO$_2$ saturation of 28 %. The CO$_2$ will enter the targeted sandstone reservoir at $z = 0$ as a saturation front. At the top of the domain we apply the condition of no CO$_2$ flow, $F = 0$, where $F$ is the global flux function. As the reservoir is modeled as an assemblage of two lithological units, the highly permeable Utsira sandstone and the low-permeable shale caprock, the absolute permeability function takes the form

$$K(z) = \begin{cases} K_1, & \text{if } 0 \leq z \leq 20 \text{ m;} \\ K_2 < K_1, & \text{if } z > 20 \text{ m.} \end{cases}$$ (24)

We discretized the reservoir as a stack of $n$ plane layers, of thickness $h$ equal to the size of White’s representative volume, i.e. $h = l$, with $l = 0.5$ m. The effect of the vertical distribution of CO$_2$ saturation in the P-wave velocity $V_P$ for any layer in the reservoir is given by White’s formula, using the methodology described in section 3. The only difference is that this time we use for each layer the CO$_2$ saturation $S_g(t, z)$ given directly by the Buckley-Leverett equation, instead of an overall time-independent mean $\bar{S}_g$. Once all the velocities and densities of the layered model are adjusted to the vertical saturation profile, the normal-incidence P-wave reflectivity $R_{pp}$ for the stack of layers is obtained the reflectivity algorithm. The number of layers that comprises the reservoir varies from $n = 40$ for the sealed caprock case to $n = 60$ for the leaking caprock case.
In the following tests we consider two geologic storage situations, one where no upward migration into the caprock exists (sealed caprock), and another where leakage takes place into the shale (unsealed caprock). The parameters of the reservoir and fluids are given in Table 2. In the context of the CO\(_2\) geological storage and monitoring it would be interesting to assess the difference between these two cases by means of a simple method as the peak frequency evolution proposed in this work. For the two reservoir models analyzed we calculate the curve of peak frequency in time. The results indicate that time-lapse peak frequency changes can describe the evolution of the CO\(_2\) distribution and also evaluate reservoir integrity.

### 7.1 Sealed caprock

Figure 8 displays the vertical distribution of CO\(_2\) and the associated seismic reflectivity at different times. The solution \(S(t, z)\) is calculated using a time discretization of \(t_{s} = 1\) day at height intervals of \(\Delta z = 0.5\) m. Figures 8a to 8c show the evolution of the vertical CO\(_2\) distribution at three different times. Figures 8d to 8f display the amplitude spectra of the reflectivities. Figure 8a shows the advancing CO\(_2\) front at \(t_{s} = 4\) in Figure 8b, at \(t_{s} = 24\), the CO\(_2\) has accumulated below the caprock, giving rise to a down-going front. Finally in 8c the vertical profile of CO\(_2\) starts to become constant with height at \(t_{s} = 84\). As expected, the reflectivity at this point (Figure 8f) is rather independent of frequency. Figure 9 displays the time-lapse curve of the first peak frequency of \(|R_{PP}|\). Three stages are clearly visible. (a) The CO\(_2\) front is traveling upwards to reach the caprock. The peak frequency increases because the zone where \(S_g = 0\) diminishes with time. The effect on the reflectivity is of a thinning fully saturated brine layer between a caprock and a CO\(_2\) saturated sandstone. As the brine layer becomes thinner, the notches in the reflectivity move toward higher frequencies. This is the only stage where an increase in peak frequency with time is observed. (b) The CO\(_2\) starts to accumulate under the caprock. As the CO\(_2\) accumulation thickens, the peak frequency decreases in agreement with Equation 6. The transition between this stage and the previous one occurs when the ascending fluid/fluid contact reaches the base of the caprock. The curves in these stages are not exactly symmetrical due to the fact that in the previous stage there is a fully saturated brine zone whereas in this one CO\(_2\) is present in all the reservoir. (c) After the fluid/fluid contact at the base of the accumulation leaves the target reservoir \((z < 0)\), the CO\(_2\) saturation will increase.
to reach the maximum value of $1 - S_{rb}$ (where $S_{rb}$ is the residual brine saturation) and $S_g(t, z)$ will tend to a constant value for all $z$. We have seen in the first section that peak frequency is rather independent of CO$_2$ saturation, so the reflectivity will become rather constant with time. In this test, where no upward migration of CO$_2$ exists into the caprock, peak frequency becomes stable at a frequency related to a thickness of 20 m, as can be seen in the peak frequency versus thickness plot of Figure 6.

We have seen that when the CO$_2$ distribution stabilizes, the peak frequency becomes constant in time. In the next section, we will show that this time-lapse trend in peak frequency is modified if the CO$_2$ migrates vertically into the caprock. In this situation, the peak frequency attribute would also be able to identify an unfavorable leakage scenario.

### 7.2 Unsealed caprock

We consider now a situation where CO$_2$ has the potential to leak into the caprock and eventually originate a secondary accumulation. We consider for this purpose a model where the reservoir sandstone, of permeability $K_1$ is overlain by a 10 m Nørland shale with permeability $K_2$ given in Table 2. To account for the mesoscopic effects in the caprock due to the CO$_2$, we apply the White formulation to the shale, with a porosity of $\phi = 0.25$ from Carcione and Picotti (2006).

Figure 10 presents the CO$_2$ distribution and the P-wave reflectivity amplitude at three different stages. In Figures 10a and 10d, when $t_{ts} = 6$, the CO$_2$ front propagates upwards. In Figures 10b and 10e, at $t_{ts} = 19$, the reflected shock propagates downwards. In Figures 10c and 10f, when $t_{ts} = 94$, the distribution starts to become constant with high and a shock travels in the caprock. We show in Figure 11 how the time-lapse peak frequency curve varies when upward migration of CO$_2$ into the caprock occurs. As we can see, in stage (a) a CO$_2$ front goes towards the caprock, and in (b) a CO$_2$ accumulation develops. The differences with the sealed caprock (Figure 9) arises once the CO$_2$ reaches the caprock base at $z = 20$ m. At stage (c) the peak frequency displays a monotonic decrease in time due to the upward migration of CO$_2$ into the shale, as opposed to the constant trend of the sealed case. The length over time of the decreasing
trend, is related to the value of the permeability on the shale. Lower caprock permeabilities will present longer peak frequency decrease trends than higher permeabilities. Eventually, this trend will reach frequencies very close to zero. At this moment, in stage (d), the first peak frequency adopts the trend of the 2nd peak frequency, which becomes stable once the CO\(_2\) accumulates in the shale below \(z = 30\) m. Similar to the sealed caprock case, the peak frequency will stabilize at stage (e), but this time at a higher frequency than a priori expected for a sandstone reservoir of 20 m.

The results indicate that a reservoir with CO\(_2\) leakage presents, as main characteristics, a sustained decrease in the time-lapse peak frequency and a stabilization to a higher-than-expected frequency.

8 CONCLUSIONS

It has been shown in this paper that peak frequency is a robust spectral attribute for estimating layer thickness in a CO\(_2\) storage aquifer. We have seen that its sensitivity to CO\(_2\) saturation does not affect considerably the character of the attribute. We have also shown that a time-lapse computation of this attribute, has the potential to delineate and characterize the vertical distribution of the injected CO\(_2\). In this way, peak frequency signatures for the stages when the CO\(_2\) forms an up-going front, a growing accumulation or an upward leakage into a caprock can be identified. The peak frequency analysis presented in this work is not limited to saturation profiles derived from the Buckley-Leverett equation and can be extended to arbitrary saturation profiles.

It is worthwhile to point out that the analysis of the peak frequency attribute with real seismic data would require: (i) a high-resolution time-lapse seismic data to reach the peak frequencies related to thin layers; (ii) spectral balancing to remove the effect of the seismic source on the amplitude spectra of the seismic traces; (iii) isolation of a window containing the seismic reflections associated to CO\(_2\)-brine contacts; (iv) determination of peak frequencies and their time-lapse variations through an appropriate time-frequency decomposition on the selected seismic window.

A 2D distribution of the CO\(_2\) in the Sleipner reservoir should not display, due to the high homogeneity of the rocks, much different vertical profiles than the considered in this work.
This means that the results and conclusions will hold in that situation. The 1D representation developed in this manuscript provides then of a basis for generalizations to higher dimensions.

We expect that the theoretical time-lapse results of this work may contribute as a practical tool to guide in the seismic interpretation of field data.

9 ACKNOWLEDGMENTS

This work was partially supported by CONICET (Argentina) PIP 112-200801-00952 and Programa de Incentivos, Universidad Nacional de La Plata (UNLP).

REFERENCES


Chadwick R.A., Arts R., and Eiken O. 4D seismic quantification of a growing CO$_2$ plume at Sleipner, North Sea. Petroleum Geology: North-West Europe and Global Perspectives-
White J.E., Mikhaylova N.G., and Lyakhovitskiy F.M. Low-frequency seismic waves in fluid-