

THEORETICAL AVA ANALYSIS FOR GEOLOGICAL CO₂ SEQUESTRATION

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Resumen

La inyección de dióxido de carbono (CO₂) en formaciones geológicas es una práctica empleada en países desarrollados (Alemania, Canadá y Noruega entre otros) para mitigar la emisión a la atmósfera de gases de invernadero. Esta práctica requiere de un continuo monitoreo con el fin de verificar las condiciones de este gas y su distribución en el subsuelo. El fuerte contraste entre las propiedades físicas de los fluidos naturales del reservorio y las del CO₂, permite la utilización de los métodos sísmicos como herramientas para el control del CO₂ luego de la inyección. Dichos métodos permiten vincular magnitudes observables con las propiedades físicas de las rocas así como el tipo de fluido poral y sus condiciones in situ.

En este trabajo se propone un modelo de Biot-Gassmann para calcular los coeficientes de reflexión teóricos para ondas P en función del ángulo de incidencia (AVA) para offsets cercanos y en el rango de las frecuencias sísmicas. Se considera en particular el caso de una onda P plana incidente en la interfase entre una capa sello de lutita y un estrato de arenisca *Utsira*, del campo de inyección Sleipner (Noruega, Mar del Norte) saturada por una mezcla de agua de formación y de CO₂ en estado supercrítico.

En una primera instancia se observa el comportamiento del coeficiente de reflexión de las ondas P en función de distintos niveles de saturación del dióxido de carbono, así como para diferentes estados termodinámicos (subcríticos y supercríticos).

En una segunda etapa se analiza la sensibilidad de los coeficientes de regresión de AVA ante diferentes estados de saturación. A partir de este análisis se concluye que el parámetro *intercept* muestra un decaimiento monótono a medida que aumenta la saturación de CO₂. El parámetro *gradiente* decrece también fuertemente para bajas saturaciones y exhibe cambios de tendencia a saturaciones intermedias. El tercer parámetro también muestra variaciones apreciables en el rango de saturaciones 0-30%.

Los resultados obtenidos sugieren la posibilidad de emplear la información sísmica de reflexión para la discriminación el estado del CO₂ en las acumulaciones horizontales formadas dentro de la arenisca.

Por último cabe remarcar que este estudio se encuadra dentro del proyecto de cooperación multinacional CO₂ReMoVe (FP6) financiado por la Unión Europea, que nuclea organizaciones tanto industriales como de investigación y de servicio, tendientes al logro de los objetivos establecidos en el Protocolo de Kioto como también a la generación y diseminación del conocimiento sobre estos temas.

Abstract

The geological sequestration of carbon dioxide (CO₂) in depleted hydrocarbon reservoirs or deep saline aquifers is a practice used in developed countries to mitigate greenhouse gas emissions to the atmosphere. As it is well known, these procedures require careful monitoring to verify the gas conditions and its distribution in the subsurface. In this sense, the

marked contrast between the physical properties of natural reservoir fluids and those of carbon dioxide allows the utilization of seismic methods as a tool to monitor its space-temporal distribution after the injection. For CO₂ monitoring purposes it is necessary to search for appropriate seismic indicators, a problem directly related to the use of multiphase rock physics models linking observable magnitudes such as velocities, amplitudes and reflection coefficients of seismic waves to the petrophysical properties, composition and state of the rock as well as pore-fluid type and in situ physical conditions.

With this motivation, we use a Biot-Gassmann formulation to compute the theoretical P-wave amplitude reflection coefficients versus angle of incidence (AVA) for near offset angles and a frequency within the seismic range (50Hz), when a planar P wave strikes the interface between a shale layer (seal) and the Utsira sandstone (from Sleipner field, North Sea), saturated by a mixture of brine and CO₂ at supercritical conditions (where CO₂ behaves as gas with the density of a fluid).

We analyzed the sensitivity of the AVA coefficients to different states of saturation. From this analysis we conclude that the intercept parameter shows a monotonic decreasing behavior, with very strong variations with respect to the pre-injection state for low saturations, showing slower changes for high saturations. The gradient parameter also decays strongly for low CO₂ saturations, showing changes of trend for saturations in the intermediate range. The third parameter also shows appreciable variations particularly for saturations in the range 0-30%.

We also found appreciable differences between the reflection coefficients in the subcritical and supercritical states, which suggest the possibility of using seismic reflection data to discriminate the state of the CO₂ in the horizontal accumulations within the Utsira sandstone.

The present study is being conducted within the framework of *CO2ReMoVe (FP6)* project, an international consortium financed by the European Union aiming to the accomplishment of the objectives established in the Kyoto agreement as well as the generation and dissemination of knowledge related to transportation, injection, storage and behavior of CO₂.

Introduction

The sequestration and geological storage of CO₂ constitutes a significant and feasible option to mitigate and stabilize CO₂ emission in the atmosphere, contributing to the achievement of Kyoto targets. As is well known, geological storage of carbon dioxide must be carefully monitored to prevent this greenhouse gas from seeping to the biosphere.

Since October 1996, million of tonnes of CO₂ are separated from natural gas and re-injected into a shallow saline aquifer, the *Utsira* formation at Sleipner field (Norway). This formation consists of a high porosity unconsolidated sandstone with several thin intra-reservoir shale layers of structural geometry yet not completely known. These shale intervals act as temporary seals causing accumulations of high CO₂ saturations beneath them which are clearly observed in the time lapse seismic sections presented by Arts et al. (2004, 2007). While these standard methods allow to monitor the presence or absence of CO₂ they are limited to quantify the saturation and state of this fluid within the reservoir. As a way to overcome this constrain, Brown et al. (2007) suggests an AVO based method to monitor both presence and degree of CO₂ saturation. He shows that variations in the best-fitting AVO parameters, A (*intercept*), B (*gradient*) and C given by Mavko et al. (1998), before and after CO₂ injection may be seismically noticeable. This encouraged us to perform a parametric analysis of the P wave reflection coefficient and the corresponding AVO parameters for different CO₂ saturations, pore pressures and reservoir temperatures.

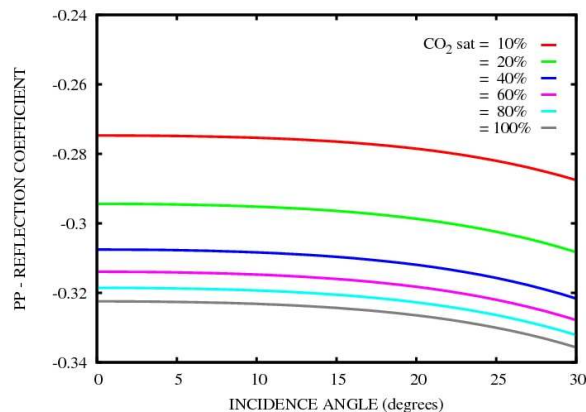


Figure 1: P-wave amplitude reflection coefficient at incident angles in the near offset range and different degrees of CO₂ saturation, on the planar interface between a shale and the Utsira sandstone. For the pre-injection state in the offset range considered R_{pp} varies between -0.0573 to -0.038.

Amplitude versus angle analysis

Variations in the reflection coefficients vs. angle of incidence (AVA) are commonly used in reservoir geophysics to infer different properties of the solid and fluid constituents of the saturated rocks (Mavko et al., 1998). In this work, we investigate if they can be usefully applied to the characterization of horizontal CO₂ accumulations, a problem of particular relevance for monitoring lateral migrations across permeable layers. Using a Biot-Gassmann formulation (Biot, 1956) and following the ideas in Dutta & Odé (1983) and Santos et al. (1992), we compute the set of theoretical amplitude reflection and transmission coefficients versus angle of incidence. We consider a 50 Hz plane P-wave striking the horizontal interface between a brine saturated shale layer and the Utsira sandstone saturated by a mixture of brine and CO₂ at supercritical conditions.

The model is calibrated for the pre-injection case (full brine saturation), taking into account the P and S sonic wave velocities and the density log value given by Arts et al. (2004), and using inverse Gassmann's relations (Mavko et al. 1998). For the sandstone we consider the following parameters: porosity 37%, permeability 1.6 Darcy, solid grain bulk modulus 36.9 GPa, frame bulk and shear moduli 1.845 GPa and 0.857 GPa and grain density 2.65 gr/cm³. The corresponding properties of the shale layer are: porosity 25%, permeability 0.001 Darcy, solid grain bulk modulus 20 GPa, frame bulk and shear moduli 3.11 GPa and 1.528 GPa and grain density 2.45 gr/cm³. The physical properties of CO₂ (density and bulk modulus) for variable temperature and pressure conditions are computed using Duan et al. (1992) equation of state, while the viscosity is approximated with Sutherland's formula. To obtain the density, bulk modulus and viscosity of brine for given pressure and temperature we used Batzle & Wang (1992) empirical equations for salinity of 50000 ppm (Carcione et al. 2006). For the present analysis we restrict our attention to the PP reflection coefficient (denoted as R_{pp}) and assumed a long term CO₂ injection so that it is reasonable to consider the gas as uniformly distributed within the pore space of the rock, forming a layer of thickness large compared to the wavelengths involved. Figure 1 shows the behavior of R_{pp} as a function of incidence angle for fixed pore pressure $P = 10$ MPa and temperature $T = 36$ °C at different degrees of CO₂ saturation. These R_{pp} curves display a class III anomaly behavior according to standard AVA classification (Castagna et al. 1998) and they are in agreement with those

recently published by Ghaderi & Landro (2009).

In the near offset domain or below the critical angle, we assumed the R_{pp} reflection coefficient as being approximated as (Mavko et al., 1998):

$$R_{pp}(\theta) \sim A + B \sin^2\theta + C (\tan^2\theta - \sin^2\theta).$$

This enables us to perform a parametric analysis on the A , B and C coefficients to study their sensitivity at different saturations levels by implementing a standard fitting procedure on the results shown in Figure 1. The coefficients so obtained are plotted in Figure 2. From this analysis we found that the intercept parameter A , related to the normal incidence reflection coefficient, shows a monotonic decreasing behavior with significant variations in the CO_2 saturation range 0 to 30% (about 10% from 10 to 30% of CO_2 saturation), showing lower relative changes at higher saturations.

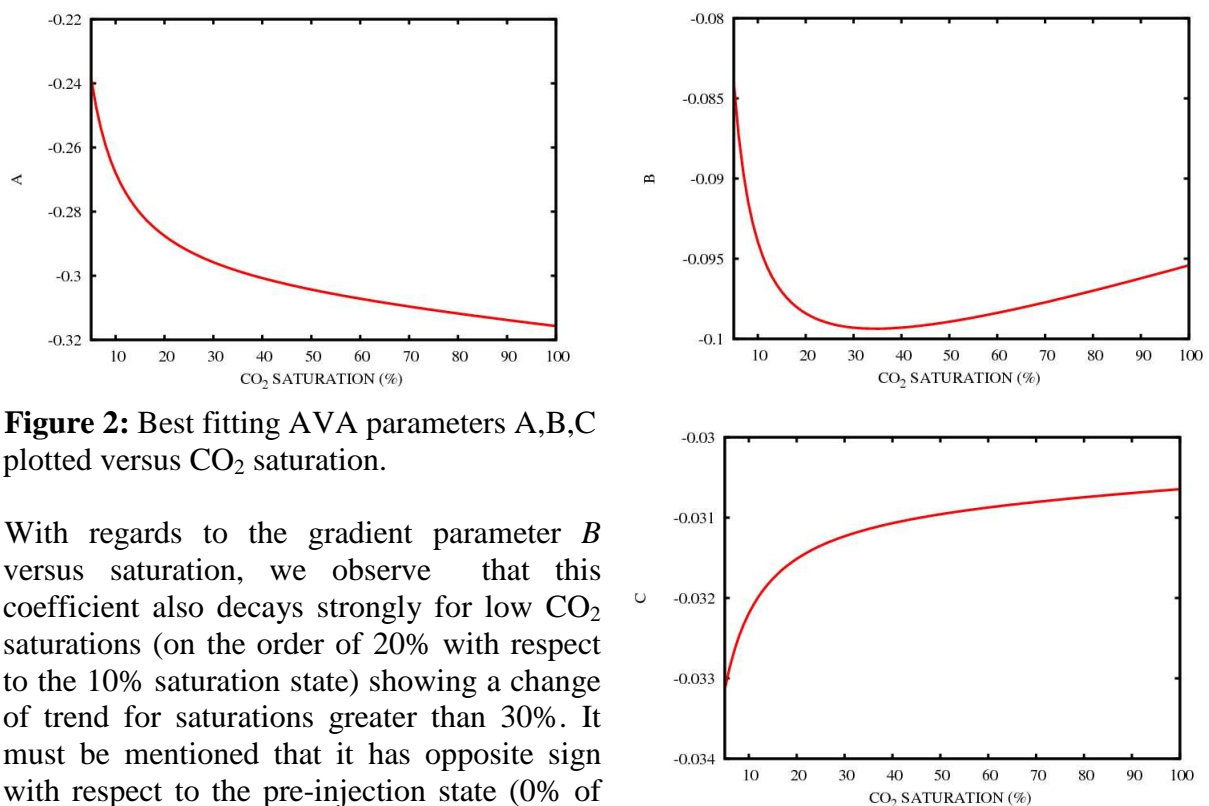


Figure 2: Best fitting AVA parameters A, B, C plotted versus CO_2 saturation.

With regards to the gradient parameter B versus saturation, we observe that this coefficient also decays strongly for low CO_2 saturations (on the order of 20% with respect to the 10% saturation state) showing a change of trend for saturations greater than 30%. It must be mentioned that it has opposite sign with respect to the pre-injection state (0% of CO_2 saturation). Concerning the C parameter, it also shows marked variations between 0 to 30%.

However, for practical purposes and monitoring applications, it must be remarked that a careful analysis about the resolution of the seismic data would be essential to assess the significance of the relative changes observed in the parameters, which in some cases may be under the conventional seismic resolution. This subject should be further investigated with synthetic data.

Due to the uncertainty in the measurements of the formation temperature and to analyze the influence of this thermodynamic variable in the reflection coefficients, we computed R_{pp} versus angle for three fixed supercritical temperatures (32, 36 and 40°C) at $P = 10$ MPa, for fixed CO_2 saturations of 10 and 60% (Figure 3 left). For these states we observe a marked change in the reflection coefficient vs. angle close to 5% for 10% saturation and 2% for 60%

CO₂ saturation respectively. In both saturation states the reflection coefficient increases in absolute value with increasing temperature, although the changes are more pronounced for low saturations.

Finally, we analyze the sensitivity of the reflection coefficient to different pressure states, above and below the critical value. We computed R_{pp} versus angle for three fixed pore pressures $P = 6$ MPa (subcritical gas state), 10 and 14 MPa (supercritical) for a fixed reservoir temperature $T = 36^\circ\text{C}$ and CO₂ saturation of 10% and 60%. The corresponding curves are shown in Figure 3 right. We found appreciable differences between the reflection coefficients in these states with a noticeable decrease in absolute value with increasing pressure. This effect is more important at a 10% CO₂ saturation level (with a relative change of 10% as opposed to only 1% for a 60% CO₂ saturation). This suggests the possibility of using seismic data for the discrimination of the state of the CO₂ in the different accumulations within the Utsira formation, which seems possible even using normal incidence data only. These results may be particularly important in the detection of potential CO₂ depressurization zones within the reservoir from time lapse seismic data.

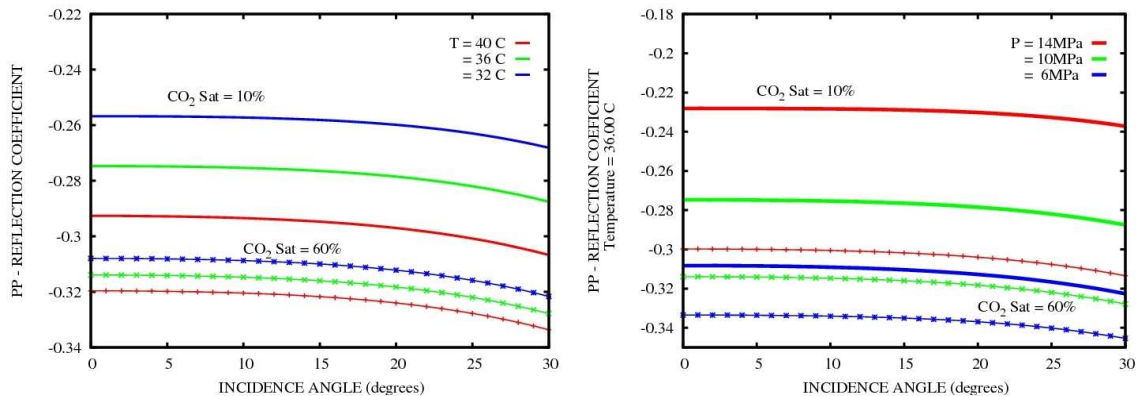


Figure 3: Left: P-wave reflection coefficient for incident angles in the near offset range, for three fixed temperatures and two saturation levels (10 and 60%) at the interface between a shale and Utsira sandstone. Right: the same but considering three different pressures (6, 10 and 14 MPa) and the same CO₂ saturation schemes.

Discussion, conclusions and future work

We analyzed the behaviour of R_{pp} vs. angle of incidence at the top of a horizontal CO₂ accumulation within the Utsira formation at Sleipner field (Norway). In particular for the case of fixed formation temperature and poral pressure, we predicted the variations of the AVA parameters A , B , C with CO₂ saturation. From this analysis we conclude that the intercept parameter A shows a monotonic decreasing behavior, with very strong variations with respect to the pre-injection state for low saturations, showing slower changes at higher saturations. The gradient parameter B also decays strongly for low CO₂ saturations even showing changes of trend for saturations in the intermediate range. Concerning the C parameter, it shows noticeable variations for CO₂ saturations between 0 to 30%.

Next we studied the behavior of R_{pp} vs. angle for different temperatures in the supercritical region. For these states we observe a marked change in the reflection coefficient vs. angle, on the order of 5%. We also analyzed the sensitivity of the reflection coefficients to different pressure states, above and below the critical pressure. We found appreciable differences between the reflection coefficient in both states, of around 10 % for low CO₂ saturations. As a conclusion we can affirm that these results suggest the possibility of using seismic reflection

data to characterize the CO₂ state in the horizontal accumulations within the Utsira formation. The determination of saturation from AVA coefficients seems also feasible (particularly for saturations lower than 30%) but with some limitations due to increasing uncertainty at higher saturation levels. This leads us to consider another attributes, such as elastic impedance, to deal with this subject. In all cases precaution must be taken with regards to seismic resolution and processing procedures in order to obtain meaningful estimations of the AVA coefficients. It must be pointed out that since the analysis was carried out for the case of the Sleipner field, in which the CO₂ accumulations take the form of thin horizontal layers, a modelling approach taking into account the effect of layer thickness should be implemented. In addition, variations in AVA coefficients derived from implementing other equations of state for carbon dioxide and solubility effects would be necessary. These topics will be the subject of forthcoming works.

Acknowledgments

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