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Seismic Reflectivity in Carbon Dioxide Accumulations: A Review

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Introduction

It is widely recognized that the continuous increase in the concentration of carbon dioxide (CO₂) in our atmosphere is a major cause of global climate change [1]. Consequently, in accordance with the objectives of the Kyoto Protocol, many carbon dioxide capture and storage projects are being developed worldwide to reduce and stabilize the emission of this greenhouse gas into the atmosphere. The geological storage of CO₂ in many cases becomes a feasible option to accomplish this goal, giving rise to the science of *carbon sequestration*, a challenging task for governments, scientists and engineers [2].

The main targets for geological disposal of CO₂ are depleted hydrocarbon reservoirs and deep saline aquifers. While the latter are more numerous, their characterization requires detailed studies because they are typically not explored for prospecting. The geological sequestration of carbon dioxide requires careful prior study and subsequent monitoring to prevent this gas from leaking to the surface. In general, the significant contrast between the physical properties of natural reservoir fluids and those of carbon dioxide allows the utilization of time lapse seismic methods to monitor the evolution of the injected CO₂ volume.

While it is accepted that time lapse surveys are able to monitor the presence or absence of CO₂ within a geological formation, their ability to quantify the saturation, state and volume of this fluid within the reservoir still needs research efforts from the geophysical community. This makes it necessary to search for reliable seismic indicators. Theoretical and numerical modeling provides, in this sense, a tool to explore useful correlations between the seismic response and relevant parameters of the CO₂ repository.

The significance of the *seismic reflectivity* has long been recognized by many authors, resulting in the publication of numerous works for different constitutive models and applications. In close connection with this, the analysis of seismic amplitude variation with angle, hereafter called *AVA* is frequently used in reservoir geophysics to obtain information about the rocks and pore fluids. The behavior of the reservoir reflectivity for different overall CO₂ saturations, distribution types, layer thicknesses, frequencies and CO₂ physical states

controls the amplitude of seismic wave reflections and strongly conditions the detectability of the injected CO₂ volume, as reported by [3],[4] and [5] among others.

With this idea, using rock physics models, in this chapter we focus on the theoretical analysis of the properties and variations of the seismic reflectivity and related parameters in a porous rock partially saturated with CO₂ and brine. In our tests we model the seismic effects of different CO₂ accumulations formed below impermeable seals.

We calibrate our models using information on the Utsira formation, a shallow saline aquifer in the Sleipner field (offshore Norway). Millions of tonnes of CO₂ have been separated since October 1996 from natural gas and re-injected into the aquifer, consisting of a highly porous and unconsolidated sandstone, with several thin intra-reservoir shale layers. These shale intervals act as temporary seals causing accumulations of CO₂ beneath them [6],[7], whose saturations increase with time. A 50-100 m thick high velocity layer overlies the sand, forming the reservoir caprock, known as the Nørland formation. It is mainly composed of shales, siltstones and mudstones [8]. Another high-velocity shale layer of about 5 m thick is located about 10 m below the top of the sand.

As pointed out by [9] the *topmost* CO₂ layer is of special interest for monitoring the Sleipner injection site, since its growth reveals the total upward flux and its changes over time. Thus, the analysis of the reflectivity associated with this kind of CO₂ accumulation is an important topic in CO₂ sequestration problems. The present book chapter focuses on this subject and is structured in three main sections considering different aspects of the problem.

First, in Section 1 we present a description of the models and rock physics tools used in the subsequent sections. Next, in Section 2 we model the compressional P-wave reflection coefficient at the interface between a caprock and a permeable porous layer partially saturated by a mixture of brine and CO₂ under liquid, supercritical and gaseous conditions. For this analysis we consider a simple model consisting of two halfspaces, combining a fluid substitution procedure and a Gassmann-Hill formulation to take into account variable spatial distributions of the fluids. We perform a sensitivity analysis of the standard AVA coefficients (intercept, gradient and curvature) in the near offset range, to investigate their correlations with CO₂ saturation and its thermodynamic state within the geologic formation. Also, we analyze the effect of modeling the CO₂ by means of simple and complex equations of state.

The two-halfspace representation considered in Section 2 is valid when the accumulation thicknesses are larger than the involved seismic wavelengths. When this assumption is not valid, the interference between the multiple waves reflected at the different boundaries give rise to strong frequency dependence, *reflectivity dispersion* and *tuning* effects which must be taken into account. To do this, in Section 3 we compute the *generalized* P-wave reflection coefficients by means of a reflectivity method. This leads us to the study of frequency dependent AVA and *amplitude vs. frequency AVF*, which are topics of great interest due to the increasing use of spectral decomposition techniques on seismic data. This also allows us to analyze the pattern of maxima in the reflectivity amplitude and their associated *peak frequencies*, which are strongly related to the thickness of the CO₂ layer.

Seismic monitoring of geological CO₂ injection sites is mostly based on the seismic reflections coming from high saturation CO₂ accumulations. This is due to their large seismic amplitudes and good signal to noise ratio. However, low-saturation zones with dispersed CO₂, or *saturation transition zones* may have an important role in the propagation of

waves within the reservoir, giving rise to amplitude and phase changes of the seismic signals. Transition zones have been studied by different authors in the geophysical literature considering linear velocity trends with depth and constant density [10], [11]. Therefore, using the parameters of the Sleipner field, in Section 3.3 we model the reflectivity response of a CO₂ transition layer, defined by a given linear vertical CO₂ saturation profile, which results in a non-linear velocity trend with depth.

In general, emphasis is placed on establishing correlations between the seismic reflectivity and related attributes (intercept, gradient, curvature, peak frequencies) and the overall CO₂ saturation, its physical state and thickness of the accumulation. These results are intended to help in the understanding of the expectable variations in a seismic time lapse study. They can be extended to other CO₂ repositories with proper calibration of the rock and fluid properties.

Many of the results and procedures presented in this chapter are a revision and extension of those published by us in [4], [12], [13], [14] and [15].

1. Theoretical framework and assumptions

In this section we summarize the modeling tools used later for the applications. First we explain the procedure for the calculation of the elastic properties of the partially saturated rocks for variable CO₂ saturation. Next we describe the laws for the computation of the physical properties of the CO₂ and brine for the different temperature and pressure states. Finally, we outline the reflectivity method for the computation of the generalized seismic reflectivity of the layered model

1.1. Elastic properties of CO₂ bearing rocks

To begin with the description of the model we consider that after the injection, a volume of carbon dioxide occupies part of the pore volume of a geologic reservoir which at the pre-injection state was fully saturated with brine. For simplicity we assume that CO₂ displaces, without dissolution, part of the *in-situ* brine giving rise to a two-phase fluid saturation. From now on the corresponding saturations of free CO₂ and brine are denoted as S_g and S_{br} , respectively, so that $S_{br} + S_g = 1$.

For the study of partially saturated rocks it is necessary to compute the bulk density and elastic coefficients (bulk and shear modulus) of the fluid saturated medium. The bulk density ρ is given by

$$\rho = (1 - \phi)\rho_s + \phi (S_{br} \rho_{br} + S_g \rho_g), \quad (1)$$

where ϕ is the rock porosity, ρ_s is the mineral grain density and ρ_g, ρ_{br} are CO₂ and brine densities, respectively.

The formulation and solution of the energy and amplitude splitting problem when a monochromatic plane compressional wave strikes obliquely at a plane interface between two porous saturated media has been discussed by various authors, such as [16], [17] and [18]. In those papers the mechanical behavior of the porous rock was described using the classic constitutive relations and equations of motion of Biot [19],[20]. In the following sections our aim is to study the reflection of elastic waves and related parameters, for frequencies f

within the common seismic range $f \leq 120\text{Hz}$. When a low frequency seismic wave propagates through a fluid saturated rock, due to fluid viscosity the solid and the fluid move in phase, so the medium behaves as an *effective* medium.

One of the most significant models to estimate the effective bulk modulus and the seismic velocity of a porous fluid saturated rock is to use Gassmann's relations [21] which can be written in the form:

$$K^G = K_s \left(\frac{K_m + Q}{K_s + Q} \right), \quad \text{with } Q = \frac{K_f(K_s - K_m)}{\phi(K_s - K_f)}. \quad (2)$$

In this equation the mechanical behavior of the fluid saturated porous medium is assumed to be elastic and isotropic. The coefficients K_m , K_s and K_f are the bulk modulus of the dry matrix, the mineral grains and the pore fluid, respectively. The physical properties of the two-phase brine-CO₂ fluid are computed using an *effective fluid* whose density is given by their weighted average and its compressibility by the isostress Reuss average of individual fluid bulk moduli [22]:

$$\frac{1}{K_f} = \frac{S_{br}}{K_{br}} + \frac{S_g}{K_g}, \quad (3)$$

where K_{br} and K_g are the bulk moduli of brine and CO₂. In these equations, it is assumed that the mixture of CO₂ and brine at the pore scale can be treated as a viscous single phase effective fluid. However, as pointed out in [23], this approach is strictly valid only when the pore fluids are uniformly mixed at very small scales so that the different wave-induced pressure increments in each fluid have time to diffuse and equilibrate during a seismic period. This critical distance is the so-called *diffusion length*. The presence of fluid heterogeneities over scales greater than this length (in which wave induced pore pressure gradients cannot equilibrate quickly), gives rise to a *patchy saturation*. It has been shown that for low frequencies such as those used in seismic exploration the effective modulus of a rock with patches of brine and CO₂ of arbitrary geometry is given by [24],[23]

$$\frac{1}{(K^P + \frac{4}{3}\mu)} = \frac{S_{br}}{K_{br}^G + \frac{4}{3}\mu} + \frac{S_g}{K_g^G + \frac{4}{3}\mu}; \quad (4)$$

where K_{br}^G and K_g^G are the Gassmann's moduli (2) of the rock fully saturated with brine and CO₂. The coefficient μ denotes the shear modulus of the rock, equal to that of the rock matrix, since the rigidity of a rock does not change due to the saturant fluid.

The existence of heterogeneous fluid distribution may give rise to mesoscopic wave attenuation and velocity dispersion phenomena in the seismic frequency range. There are many studies about numerical modeling of these effects, e.g. [25],[26],[27], showing that they are strongly dependent on the shapes and characteristic lengths of the patches. Given that these parameters are rarely known, to avoid dealing with this uncertainty, in our analysis we assume elastic layers where no attenuation-dispersion phenomena, associated with the patchy fluid distribution take place. However, these effects can be included in our formulation using appropriate viscoelastic models in the frequency domain. Because of the

classic *correspondence principle*, this implies the replacement of the real constant elastic moduli by complex frequency dependent moduli [20].

The patchy (Hill) and uniform (Gassmann) fluid distributions are respectively upper and lower bounds for the seismic wave velocities [23]. Taking into account the uncertainties in the knowledge of the *in-situ* CO₂ - brine distribution, in our models we assume that for each saturation it is reasonable to compute the average between both velocities.

It is important to mention the assumption of no chemical interactions between the pore fluids and the frame, which allows us to employ the fluid substitution procedure to consider that the pore space is saturated by brine and CO₂ in variable proportions. Also, since the amount of CO₂ dissolved in brine is a negligible fraction [28],[29], we do not take this effect into account. Nevertheless, when CO₂ is injected in oil reservoirs this effect can not be neglected and should be included in the physical models, as shown in [4] and [28].

As pointed out in [8], no systematic variations in fluid pressure are observed in the Sleipner field. Thus, variations of rock elastic properties with effective pressure (related to the difference between confining and pore pressure), are not taken into account in the model. However, using appropriate effective pressure laws these effects can be included in the computations, as explained in [18].

1.2. Physical properties of carbon dioxide and brine

Depending on the *in-situ* pressure and temperature conditions the CO₂ can exist in the subsurface in different phases. We recall that the *critical point* for CO₂ occurs at a temperature $T_c = 31.1$ °C and a pressure $P_c = 7.39$ MPa. For temperatures higher than T_c and pressures higher than P_c the carbon dioxide is in a *supercritical* state, where it is compressible like a gas but with the density of a liquid. This characteristic of CO₂ is particularly relevant for its underground storage since supercritical CO₂ can fill the available pore volume with minimum buoyancy effects [30]. Temperatures and pressures near the critical point commonly occur in applications involving CO₂, such as enhanced oil recovery techniques and sequestration projects [31]. However, as pointed out by [30], the depth at which CO₂ supercritical conditions are present is highly variable and strongly dependent on surface temperature and geothermal gradients, even within a single basin. In addition, the pressure regime of the basin (normal or abnormal), is also very important and is related to its geologic history, existence of sealing faults, permeability barriers and the occurrence of overpressure generation mechanisms [32].

For the examples, the density and bulk moduli of brine for given *in-situ* temperature and pressure conditions are computed using the semi-empirical relations proposed by Batzle and Wang (BW) [29]. For the computations we consider a typical brine salinity of 50000 ppm. The corresponding properties of CO₂ can be computed using some of the many equations of state (EoS) developed for real gases such as the two-parameter van der Waals (vW) equation [35] and the Peng and Robinson (PR) equation [34], or some more specific one such as Duan, Moller and Weare (DMW) [33], which involves fifteen parameters. To our knowledge, there is no full agreement in the geophysical literature about which EoS is the most appropriate to represent CO₂ properties under the thermodynamic conditions found in geologic reservoirs. Therefore, we use different models to analyze the effect of the EoS in the seismic magnitudes of interest. With that purpose we selected three different temperature

Physical state EoS	CO ₂ DMW	CO ₂ PR	CO ₂ vW	Brine BW
<i>Gaseous</i>				
$T = 40^\circ \text{ C}$	$K_g = 0.0049$	$K_g = 0.0089$	$K_g = 0.0050$	$K_{br} = 2.5986 \text{ GPa}$
$P = 6 \text{ MPa}$	$\rho_g = 149.8$	$\rho_g = 153.2$	$\rho_g = 142.1$	$\rho_{br} = 1028.7 \text{ kg/m}^3$
<i>Supercritical</i>				
$T = 36^\circ \text{ C}$	$K_g = 0.037245$	$K_g = 0.026120$	$K_g = 0.01999$	$K_{br} = 2.6234 \text{ GPa}$
$P = 10 \text{ MPa}$	$\rho_g = 637.6$	$\rho_g = 706.4$	$\rho_g = 490.7$	$\rho_{br} = 1030.4 \text{ kg/m}^3$
<i>Liquid</i>				
$T = 20^\circ \text{ C}$	$K_g = 0.0931$	$K_g = 0.1376$	$K_g = 0.0464$	$K_{br} = 2.5009 \text{ GPa}$
$P = 10 \text{ MPa}$	$\rho_g = 853.5$	$\rho_g = 833.1$	$\rho_g = 565.2$	$\rho_{br} = 1036.07 \text{ kg/m}^3$

Table 1. Physical properties of CO₂ and brine under different thermodynamic conditions. The density and bulk moduli of CO₂ are obtained using three equations of state: DMW [33], PR [34] and vW [35]. The CO₂ bulk moduli estimations are corrected for adiabatic conditions. The properties of brine are computed using BW laws [29] for a salinity of 50000 ppm.

and pressure (T, P) values: (40°C , 6 MPa) corresponding to gaseous state, (36°C , 10 MPa) corresponding to supercritical state and (20°C , 10 MPa) corresponding to liquid state. The resulting estimations are shown in Table 1 and will be used in the following sections. The temperature and pressure of the supercritical state are in agreement with the conditions reported in [8] for Utsira sandstone.

It must be pointed out that the different CO₂ bulk moduli estimations in Table 1, to be used for the computations, were corrected to represent adiabatic conditions. The reason is that the fluid compression due to the passage of a wave is fast, so that the process is not isothermal [29], [37].

1.3. Calibration of the rock physics model

To calibrate our elastic model for the Utsira sandstone, we used the measured bulk density and the compressional and shear wave velocities in the preinjection state (i.e. under full brine saturation), given in [8] and [38]: $\rho_b = 2050 \text{ kg/m}^3$, $V_p = 2050 \text{ m/s}$ and $V_s = 640 \text{ m/s}$. Using the parameters given for the pore water $\rho_{br} = 1040 \text{ kg/m}^3$, $K_{br} = 2.305 \text{ GPa}$ and the average sandstone porosity $\phi = 0.37$, the mineral grain density results in $\rho_s = 2643 \text{ kg/m}^3$. We also performed a Gassmann-inverse calculation to obtain: $K_m = 2.569 \text{ GPa}$ and $\mu = 0.84 \text{ GPa}$. For the shale layers we obtained the elastic parameters using the reported values: $V_p = 2270 \text{ m/s}$, $V_s = 850 \text{ m/s}$ and $\rho_b = 2100 \text{ kg/m}^3$.

1.4. The generalized reflectivity of a layered medium

The computation of the reflection and transmission coefficients of elastic waves propagating through layered media is a subject of interest in different fields such as seismology, seismic prospecting and underwater acoustics. The first numerical procedures date back to the pioneering works of Thomson [39] and Haskell [40], who proposed matrix methods that transfer stresses and displacements through successive layers. Since then, different approaches and applications have been presented.

In this work we perform an implementation of the *reflectivity method* [41], [42], which is based on the continuity of particle displacements and stress components at the interfaces between sets of plane layers embedded between two halfspaces. This method builds up the reflection

and transmission matrices iteratively by starting at the top of a lower bounding halfspace and adding one layer per iteration until the total stack response is constructed. This procedure is intuitively simple and exact [43], taking into account all internal reverberations. The recursion algorithm is

$$\begin{aligned}\mathcal{R}_{j-1} &= R_{j-1}^d + T_{j-1}^u \bar{\mathcal{R}}_j (I - R_{j-1}^u \bar{\mathcal{R}}_j)^{-1} T_{j-1}^d, \\ \mathcal{T}_{j-1} &= \bar{\mathcal{T}}_j (I - R_{j-1}^u \bar{\mathcal{R}}_j)^{-1} T_{j-1}^d; \\ \bar{\mathcal{R}}_j &= E_j \mathcal{R}_j E_j, \\ \bar{\mathcal{T}}_j &= \mathcal{T}_j E_j,\end{aligned}\tag{5}$$

were \mathcal{R}_j and \mathcal{T}_j are the total-reflection and total-transmission matrices of interface j . $R_j^{u,d}$ and $T_j^{u,d}$ are the upward and downward layer reflection and transmission matrices respectively. These matrices depend on the bulk density, P- and SV-wave seismic velocities and ray angles from interface j . E_j is the layer phase-shift diagonal matrix and $(I - R_{j-1}^u \bar{\mathcal{R}}_j)^{-1}$ is known as the reverberation operator [44], with I being the identity matrix.

The recursion starts at the base of the layering $j = n$ with $\mathcal{R}_n = R_n^d = 0$ and $\mathcal{T}_n = T_n^d = I$ and continues to $j = 1$. When the top of the layering is reached, the generalized P-wave reflection coefficient for scaled displacements is obtained from $R_{pp}(f, \theta) = \mathcal{R}_{0[1,1]}$. This coefficient is a complex function of frequency f and incidence angle θ .

For a complete description of the matrices involved in this scheme the reader is referred to [44].

2. AVA analysis at the top of a CO₂ accumulation

In this section we model the seismic compressional wave reflection coefficient and related AVA parameters at the interface between Utsira sandstone, partially saturated by mixtures of CO₂ and brine, overlain by a shale caprock, with the properties described in Section 1.3.

Following the classic approach, for the present applications both media are considered as elastic halfspaces, an assumption valid for layers of thicknesses larger than the wavelengths of the incident waves. Under these conditions the reflection coefficient are real and frequency independent. In this particular configuration, our reflectivity method reproduces the classic results of Zoeppritz [45] for two halfspaces.

In the near offset domain $\theta < 60^\circ$ or below the critical angle, we can assume that the R_{pp} reflection coefficient as a function of the incidence angle θ can be approximated using the expression of Shuey [46]:

$$R_{pp}(\theta) \approx A + B \sin^2 \theta + C (\tan^2 \theta - \sin^2 \theta); \tag{6}$$

where A , B and C are known as the *AVA coefficients*. A is called the *intercept*, B the *gradient* and C the *curvature* [47],[48]. The intercept is equal to the normal incidence reflection coefficient and is controlled by the contrast in acoustic impedance between both media. The gradient is related to the contrast in density and in compressional P and shear SV wave



Figure 1. Compressional elastic wave velocity for variable CO₂ saturation S_g obtained using Gassmann-Hill average under different thermodynamic conditions.

