Using Simulator-to-Seismic 3D Modelling to evaluate a monitoring strategy for CO2 storage in shallow-water siliciclastic reservoirs

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Summary

Disused oil and gas reservoirs and saline aquifers are promising candidates for Carbon Dioxide (CO_2) storage, which is key for reducing emissions to the atmosphere. Ensuring safe storage of CO_2 requires a thorough assessment of leakage risks and cap rock efficiency, along with continuous monitoring of stress field changes through seismic data. In Brazil, shallow-water, sandstone-rich aquifers near industrial hubs present strong potential for Carbon Capture and Storage (CCS). The Ponta Aguda deep saline formation, located in the Santos Basin, represents a gigaton-scale storage resource that could support CO_2 storage hubs in the country's most industrialized region. However, challenges remain in reservoir geomechanics and high-resolution seismic monitoring due to environmental legislation restrictions, complicating predictive modeling efforts. To address these challenges, this study employs simulator-to-seismic modeling, integrating static and dynamic reservoir properties. Fluid substitution was applied to model the elastic properties of CO_2-saturated rocks, and a Petro-elastic Model (PEM) was designed to capture pressure and saturation effects. A 3D convolution modeling approach using point-spread functions (PSFs) was then implemented to enhance seismic resolution while accounting for acquisition geometry and overburden effects. This methodology aims to optimize monitoring strategies, reduce uncertainty, and ensure the long-term environmental safety of CO_2 storage projects.

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Introduction

Disused oil and gas (O&G) reservoirs and saline aquifers are potential Carbon Dioxide (CO2) storage sites. According to Lichtschlag et al. (2021), subsurface geological formations may reduce 13% of CO2 emissions, an effort needed to mitigate the greenhouse effect, meeting the Paris Agreement´s terms. However, the quantitative assessment of leakage risks associated with the sealing cap rocks efficiency is mandatory for safely stored CO2 volumes without environmental damage. Furthermore, monitoring the effects of reservoir fluid injection through active and passive seismic data as the stress field changes is pivotal in managing risks.

Brazil's shallow-water, sandstone-rich aquifers near industrial hubs present strong potential for Carbon Capture and Storage (CCS). The Ponta Aguda deep saline formation, located in the shallow waters of the Santos Basin, is a potential gigaton-scale storage resource capable of supporting the development of CO2 storage hubs in the southeast of Brazil, the most industrialized region of the country (Erdtmann et al., 2024). However, known gaps related to reservoir geomechanics and monitoring still exist for developing this CO2 storage site, which became more difficult to predict given the complexity of acquiring high-resolution seismic data in shallow water environments due to environmental legislation restrictions. To tackle this problem, assess uncertainty, and establish a framework for long-term monitoring in a shallow-water scenario, this study focuses on seismic modeling as a key tool to define the optimal monitoring strategy to mitigate environmental damage due to CO2 injection. We employed simulator-to-seismic modeling, integrating static and dynamic properties from reservoir simulations. Fluid substitution was applied to model the elastic properties of rocks saturated with CO, and a Petro-elastic model (PEM) was designed to capture both the saturation and pressure signatures. Then, we employed a 3D convolution modeling approach via point-spread functions (PSFs) to enhance seismic resolution while accounting for acquisition geometry, frequency limitations, incidence angles, and overburden propagation.

Geological Setting

The Ponta Aguda Formation is a 2,000 – 3,000-meter-thick sedimentary section composed of fluvio-deltaic to shallow marine deposits overlain by the Marambaia Formation, a regional shaly caprock (Moreira et al., 2007). Deposited from the Campanian to Eocene in a continental platform this Cenozoic reservoir could be classified in the concept of Ringrose et al. (2019) as a "Class A" saline aquifer, which represents the best choice for initial deployment of CO_2 geologic storage projects. The stratigraphic-structural framework of the Santos Basin is correlated to the evolution of the South Atlantic Ocean (Moreira et al., 2007). For the purpose of CCS site screening, the modelled interval comprises the Aptian salt, deposited during the SAG phase of the basin, the Albian siliciclastic-carbonate platform, and the siliciclastic sequence of transgressive-regressive cycles deposited during the drift stage, from the Late Cretaceous to Recent (Figure 1).

Materials and Methods

To evaluate the CO_2 storage capacity of the aquifer, a dataset comprising 40 wells and 3D seismic data was used to construct a refined geological model covering an area of 20 x 20 km. The modelled section includes Aptian salt, the Albian siliciclastic-carbonate platform, and siliciclastic deposits formed through transgressive-regressive cycles from the Late Cretaceous to the present (Figure 1). The simulation based on this geological model applied incremental injections of 200 million tons of CO2, constrained by a maximum pressure threshold of 1.25 times the initial reservoir pressure, to assess pressure front propagation and reservoir connectivity. Reservoir heterogeneity was analyzed using the Lorenz Coefficient to identify variations in permeability and flow characteristics.
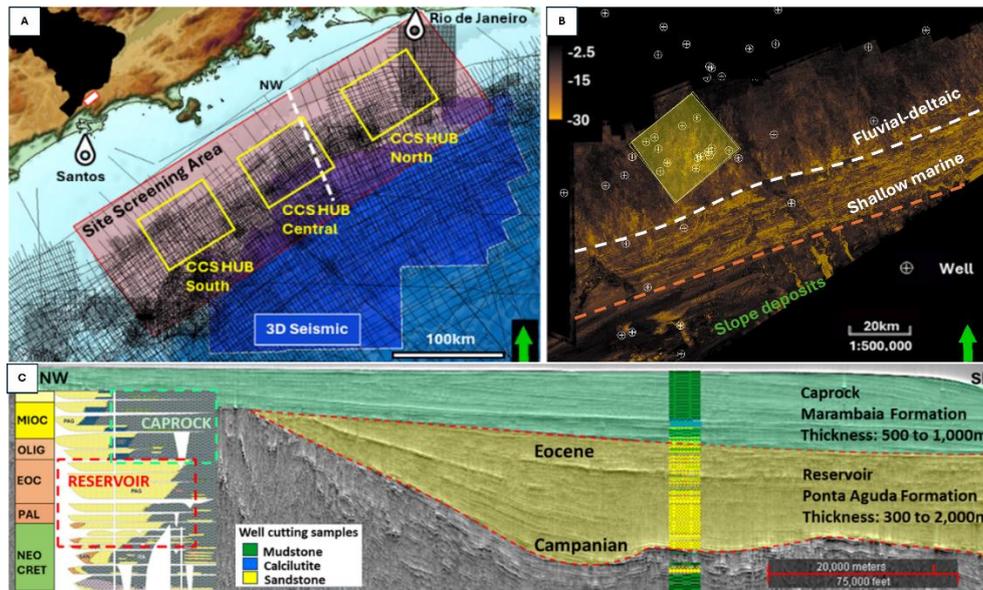
Figure 1 A) *Localization of the site screening area and the seismic data in the shallow waters of the Santos Basin. B) Seismic amplitude extraction in a window of 100 ms near the top of the Ponta Aguda Formation. The yellow polygon highlights the studied area. C) 2D NW-SE seismic section (in-depth, white dashed line in A) showing the thickness of the Ponta Aguda Formation (reservoir) and the Marambaia Formation (caprock). The stratigraphic chart was adapted from Moreira et al (2007).*

Elastic properties of rocks are influenced by factors such as fluid saturation, porosity, and pressure variations (Mavko et al., 2009). Once acquisition and processing effects are compensated, changes in elastic properties translate into variations in seismic signal amplitude. We employed simulator-to-seismic modelling, integrating static and dynamic properties from reservoir simulations at specific time steps. Pressure and saturation data were extracted from the 3D compositional simulation model at five-year intervals, and Petro-elastic model (PEM) parameters were computed at each time step to model elastic parameters using calibrated well-log data and Gassmann (1951) fluid substitution model to account for pore-pressure effects and to estimate saturated compressional velocities and densities. The Greenberg and Castagna (1962) relationship was applied to calculate the shear velocities.

We then employed a 3D convolution modelling approach with space-varying PSFs to simulate target-oriented 3D PreStack Depth Migrated (PSDM) images, as proposed by Lecomte (2008). This method allows to incorporate effects from wave propagation through the overburden, acquisition geometry, illumination heterogeneity and lateral resolution, which are usually neglected by traditional 1D time convolution (Lecomte et al, 2016). Furthermore, the computation of the PSFs is decoupled from the detailed reservoir models. This means that, once the PSFs are computed, they can be separately convolved with each 3D reflectivity volume from all different reservoir scenarios, which makes the methodology ideal for time-lapse studies.

Using a regional interval velocity model and a Ricker pulse with a peak frequency of 30 Hz as a wavelet, we simulated a dense towed-streamer acquisition, with a shooting direction approximately orthogonal to the main faults. This geometry is based on successful examples of CCS monitoring (e.g. Furre et al, 2024), and is a starting point for optimizing survey design and the overall seismic monitoring strategy.

Results

Figure 2 illustrates the PEM and the seismic modelling results for three different injections scenarios: 2036 (five years after the beginning of injection), 2065, and 2105 (when injection is planned to end). Properties shown are the saturation of CO_2, the change in acoustic impedance, and the 4D seismic amplitude difference, all in a representative NW-SE section and projected into the top of Paleocene

horizon. For the seismic amplitude maps, we display average amplitudes computed inside a window centered at the Top of Paleocene horizon, as instantaneous amplitudes could be contaminated with lateral lobes. We observe a strong correlation between CO2 saturation and the predicted changes in acoustic impedance. The modelled 4D anomalies, indicated by the negative (red) tops, correctly portray predicted gas fronts at the reservoir.
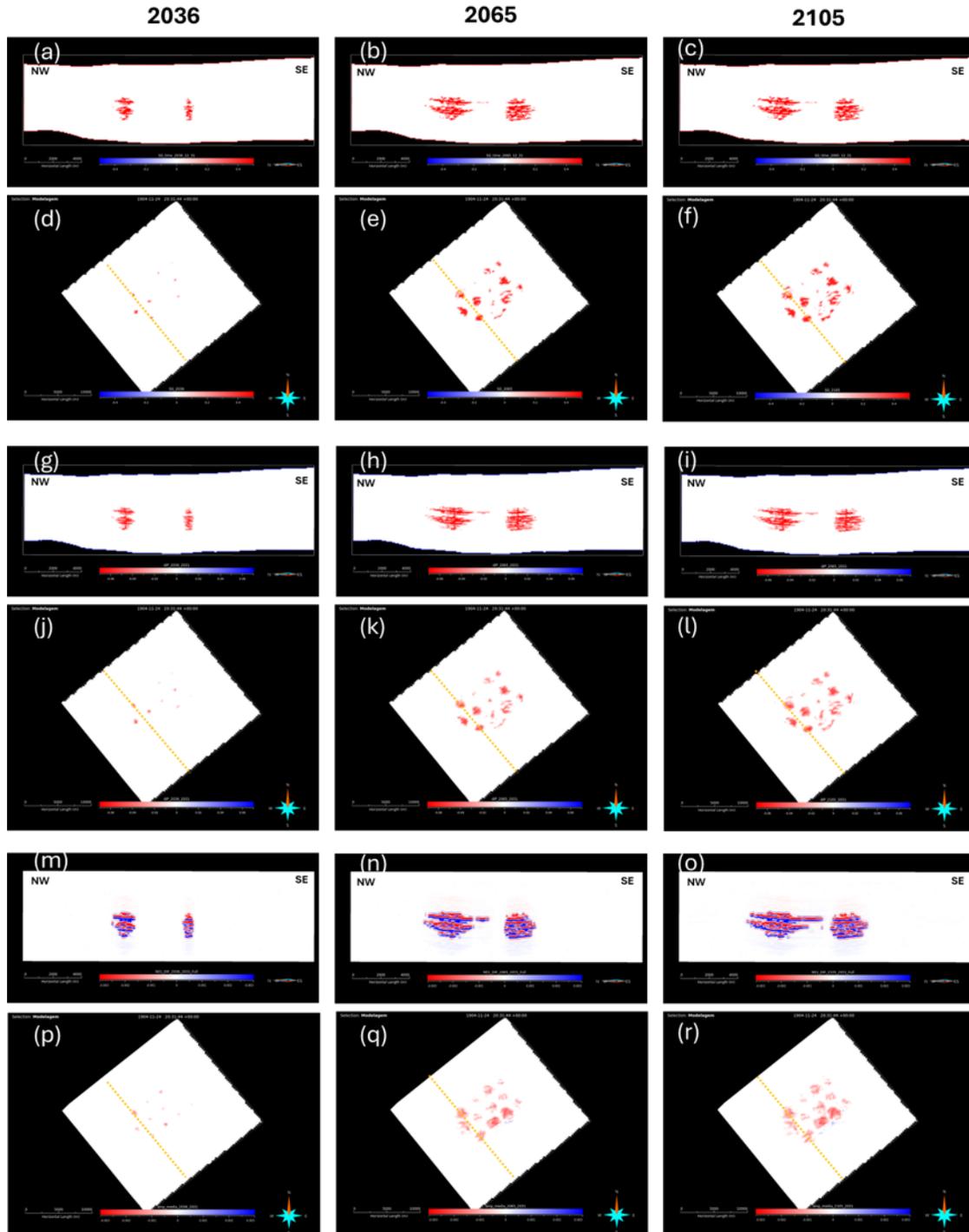

Figure 2 *Results modelled for years 2036 (left), 2065 (middle) and 2105 (right). From (a) to (f): CO2 saturations. From (g) to (l): changes in acoustic impedance compared to the beginning of injection (2031). From (m) to (r): 4D seismic amplitude differences compared to the beginning of injection (2031). The yellow dashed lines represent the location of the NW-SE sections. Maps were calculated on the top of Paleocene horizon. Modelled area corresponds to the yellow polygon shown in Figure 1B.*

Conclusions

The compositional simulator modelled injections between january 2031 (start of the Baseline acquisition) and January 2105 (final Monitor acquisition), with simulated CO_2 injectors started operating in December of 2031 in the saline acquifer. The higher the CO2 saturation, the lower the gas density and higher the acoustic impedance contrast to the saline water. We observe the areas around the injectors presenting strong 4D seismic responses due to the increase in CO_2 content, controlled by the NE-SW main faults, which reduce the transmissibility of the model.

Observations indicate that saturation changes due to injection lead to impedance variations exceeding the threshold for a detectable 4D signal. The predicted impedance change due to CO2 injection is estimated to be up to 7.5%. This is particularly evident in saline reservoirs, where the contrast between water and a gas-CO2 mixture produces a strong 4D response. 3D modelling suggests that both pressure increases (pressure buildup) and saturation changes (water being replace by gas-CO_2) cause impedance reductions (softening). Modelled seismic 4D amplitudes, considering effects from survey geometry, resolution limits and propagation through the overburden, were able to correctly identify the CO2 plume. Despite operational, environmental and regulatory challenges, acquiring high-resolution time-lapse seismic data will be an essential tool for the monitoring of the CCS site.

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