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4D Assessment of CCUS Potential through Synthetic Seismic Generation Using Forward Models

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Abstract Summary

In response to the increasing global demand for policies and actions aimed at reducing CO_2 emissions, the oil and gas industry is intensifying efforts to identify and characterize viable areas for carbon dioxide (CO_2) storage. A key technique in this endeavor is 4D evaluation, which involves sophisticated monitoring and analysis of reservoir changes over time. This approach is particularly beneficial for assessing potential CO_2 storage sites as it provides crucial insights into fluid movement within the reservoir and the impact of gas on seismic expression. Forward stratigraphic modeling emerges as a powerful tool in 4D evaluation, especially in scenarios with limited available data. By enabling the creation of 4D physically based forward stratigraphic simulations, this modeling technique facilitates the development of geologically consistent subsurface models, thus helping to characterize potential CO_2 storage zones. Another critical component of the 4D evaluation process is synthetic seismic generation. Synthetic seismic data simulates the propagation of seismic waves through the reservoir, providing a representation of geological properties and fluid dynamics. This simulation aids in identifying changes in CO_2 distribution over time and assists in the validation and calibration of dynamic reservoir models. The integration of forward stratigraphic modeling results as input for synthetic seismic generation creates a robust workflow for 4D assessment of potential areas for Carbon Capture, Utilization, and Storage (CCUS). This workflow combines forward modeling with more consistent representations of facies properties and sedimentary internal architecture, as well as fluid dynamics according to facies changes and modeled porosity, and finally the seismic response of the impedance contrasts of the modeled sedimentary record and the impact generated by the difference in distribution and saturation of CO_2 by the simulation of injection and storage in the reservoir.

Introduction

In recent years, advancements in carbon storage techniques have emphasized the need for accurate characterization of reservoir behavior, particularly regarding CO_2 injection. In this study, the workflow proposed was used as a solution to better characterize a potential zone for storing CO_2 from Emborê Formation in the Campos Basin in Brazil (Figure 1), composed of thick layers of sandstone that have an average porosity of 0.25 and permeability of 1000mD, occurring mainly below 800m depth, and shale deposits, generally discontinuous, that can act as potential regional seals. The modeled volume is divided into two stratigraphic zones composed of a reservoir and a seal. The reservoir is a saline aquifer composed of Eocene deltaic sandstones and finer-grained siltstones. The seal zone is from Oligo-Miocene and provides the greatest potential for sealing in the area, directly overlying the Eocene saline aquifer, a CO_2 injection target that has approximately 1×10^9 m^3 of pore volume. Our dataset included a seismic cube, 7 wells with logs, and seismic surfaces representing the main events and progradation features. This study aims to assess changes in reservoirs over time following CO_2 injection by generating synthetic seismic data through forward modeling under various CO_2 saturation scenarios. Geological Process Modeling (GPM) is used to construct geological features based on processes such as erosion and sedimentation, resulting in stratigraphic bodies from different depositional systems like rivers, shorelines and progradation. Using GPM outputs, including facies and structural features, the porosity model was estimated more quickly and accurately using EMBER (Embedded Model Estimator) tool, which employs a Quantile Random Forest algorithm alongside traditional geostatistical methods, and it was important to identify optimal injection sites with porosities around 0.25. Petroelastic models were then developed through Reservoir Elastic Modeling (REM), which considers variations in facies fractions and correlates them with mineral compositions, yielding volumes of compressional and shear velocities and density. These parameters are essential for creating synthetic seismic data, which is achieved by convolving with a defined wavelet frequency. By integrating hard, conceptual, and synthetic seismic data, this study enhances the calibration of geological models against real seismic data and modeled responses, including impedance. Ultimately, it aids in predicting the 4D seismic response to CO_2 injection, representing a significant advancement in geosciences and supporting future operational decisions.

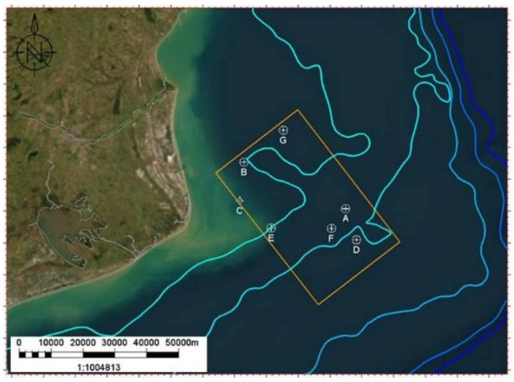

Figure 1: Study area (in orange), located in the Campos Basin, north coast of the state of Rio de Janeiro.

Method

The integrated workflow used to perform this study is shown in Figure 2, which also details the main output data. The GPM model was using processes of diffusion and steady flow, and by taking into account the sea-level variations, we were able to reproduce the delta plain, front delta and prodelta settings as well as the deltaic progradation. Local and regional traps/seals were also captured, highlighted by continuous layers composed of silt and clay. The porosity model was estimated based on GPM facies fractions as training feature and bias and porosity well log in EMBER method. This approach combines regressive decision trees with geostatistical methods such as kriging to incorporate stratigraphic data. According to Daly (2021), it estimates the conditional distribution for each grid cell, forming the basis for simulation.

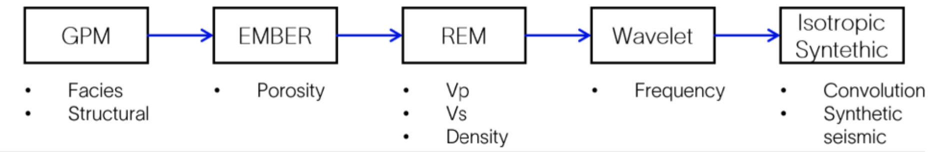

Figure 2: General workflow.

The Reservoir Elastic Modeling (REM) workflow is used to generate petroelastic models. This process considers the porosity model and variations in the facies fractions modeled in the GPM, which may be associated with the predominant minerals that make up the mineral mixture of the rock. In this work, the bulk and shear moduli of quartz were considered for the coarse and fine sand facies, and for silt, an intermediate value was given between quartz and the value calculated based on well data for the clay fraction. To simulate fluid movement over time, scenarios of CO_2 saturation were created during elastic modeling, that included no gas presence, the presence of gas after five years through a plume of smaller diameter, and its dispersion after fifteen years, where the diameter increased due to the volume of diluted gas. The reservoir modeling generates estimated volumes of elastic parameters derived from rock physics and fluid substitution equations (Voigt & Reuss average and Patchy respectively). These parameters serve as essential input data for generating synthetic seismic data, following convolution with a wavelet of defined dominant frequency. In this study, an analytical Butterworth wavelet with a peak frequency of 18 Hz was calculated. The synthetic seismics were generated through the Isotropic Synthetic seismic attribute, which performs the convolution of the wavelet with the elastic models of Vp, Vs, and density from Zoeppritz's law, considering the different saturation scenarios.

Results

Based on the GPM model, which showed good capacity to reproduce the thicknesses observed in the well data, as well as the distribution of facies in certain intervals and, mainly, the stacking pattern associated with depositional processes such as deltaic progradations, three synthetic seismic volumes were generated. These volumes vary in terms of saturation and the radius of influence of CO_2 in the reservoir, allowing the evaluation of the effects of these variables on the seismic response. The seismic volumes can be seen in Figure 3, where a crossline section and a time slice are shown in Figure 3a for the scenario in which there is 100% water saturation and therefore 0% injected CO_2 gas. In Figure 3b, the same crossline section and time slice are shown for the scenario after 5 years of CO_2 injection and finally in Figure 3c for the CO_2 injection scenario after 15 years.

Since a spherical gas plume was considered around the injection wells, the location of the gas influence is highlighted in the image by a dashed circle. In addition, it is worth noting that the gas saturation varies within the defined gas plume, therefore in the center of the plume the saturation is higher close to 100% (closer to the injection wells) and decreases towards the edges of the gas influence. This gas dispersion in the form of a plume was based on the dynamic simulation of the reservoir that represented this character at the chosen times of 5 and 15 years of injection. Observing figure 3, it is very difficult to perceive the differences in seismic amplitudes between the three scenarios. This behavior was already expected, since the same behavior is observed in real data.

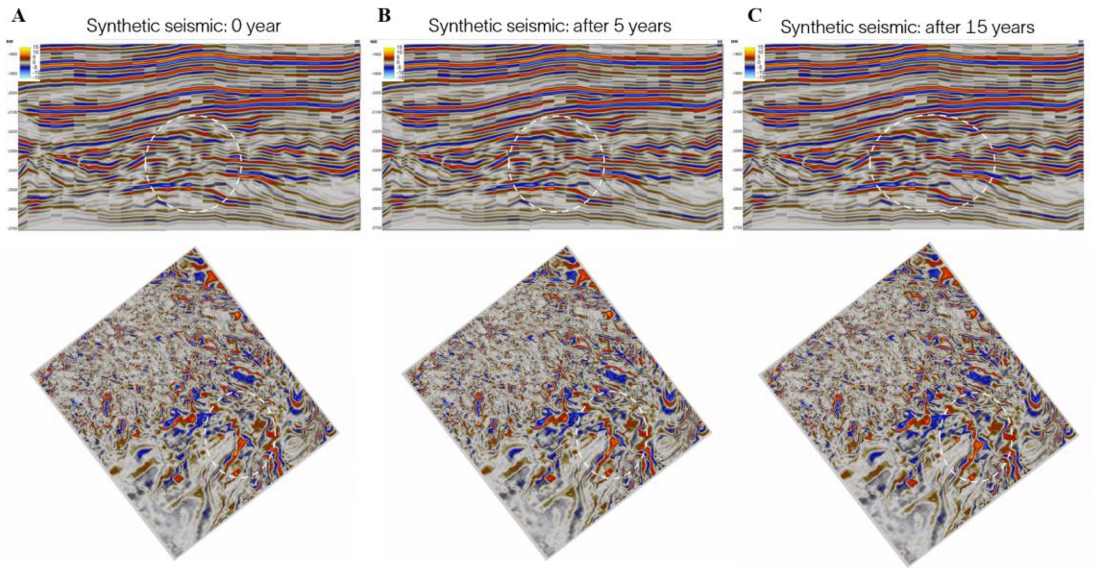

Figure 3: Qualitative comparison of synthetic seismic for 0, 5, and 15-year scenarios in section and timeslice.

In order to highlight the effect of gas on seismic amplitude, the residual between the scenarios was calculated. This shows how the seismic signal can be disturbed by the presence of gas over time (Figure 4). The radius of influence of the CO_2 plume is also highlighted.

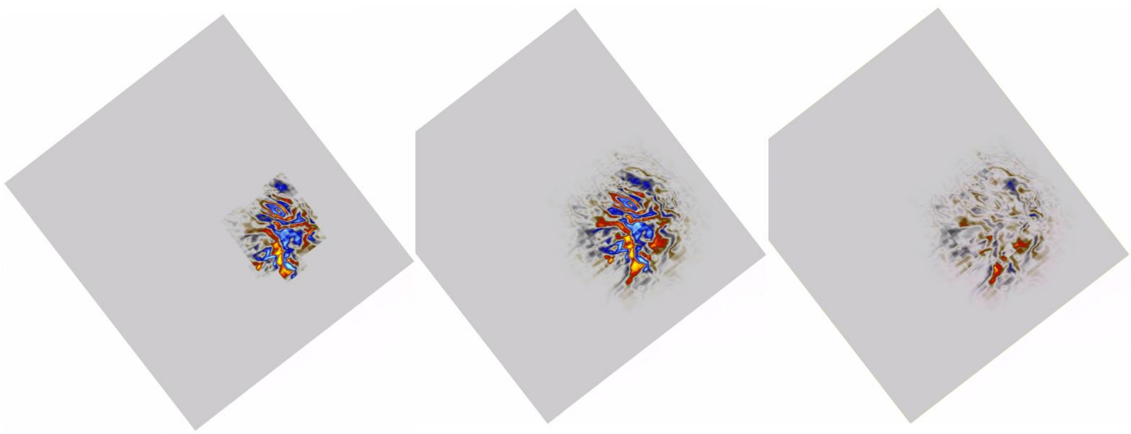

Figure 4: Residual volumes for scenarios after 5 years, 15 years, and between 15 and 5 years of CO2 injection.

Figure 4 will therefore highlight the difference in amplitude between the scenario after 5 years of injection and 0 year, the same residual volume is made between the effect after 15 years and 0 year, and finally the difference between the scenarios saturated in CO_2 was also calculated, that is, the impact occurring between 15 and 5 years of injection.

It is interesting to mention that the geological model created is of very high resolution, and the definition of the wavelet frequency peak used in this study was based on the frequency of the seismic data acquired in the area. The main intention of this is to be able to compare the synthetic data with the real seismic data in the future and to carry out studies on the details incorporated into the geological model from the GPM modeling, how this model can be adjusted to be more compatible with the real data, and also how the adjustments of the elastic parameters of each mineral fraction can be calibrated to get closer to what is observed in hard data.

Conclusions

This study demonstrated the effectiveness of an integrated workflow for the 4D evaluation of potential geological CO_2 storage sites, combining forward stratigraphic modeling, machine learning for porosity estimation, and synthetic seismic generation based on petroelastic parameters. Applied to the Emborê Formation, the workflow enabled the construction of geologically consistent models capable of simulating the evolution of CO_2saturation over time and its impact on seismic response. The analysis of residual volumes highlighted the subtle amplitude variations associated with the presence of CO_2, reflecting behavior observed in real seismic data and reinforcing the workflow's potential for calibrating geological models and predicting seismic responses in Carbon Capture, Utilization, and Storage (CCUS) projects. These results emphasize the importance of integrating the areas of geology, geophysics and reservoir engineering to develop more robust workflows, allowing a better understanding of 4D studies and thus obtaining a more accurate and predictive reservoir characterization.

References

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