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Quantification of reservoir heterogeneities and their impacts on CO2 plume geometry

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Summary

Site screening is the process of defining the place where a Carbon, Capture, and Storage (CCS) project could be developed. Applied in the early stages of evaluation, this process involves several critical variables that should be analyzed. For example, the distance of CO2 sources, injection forecasting, flow assurance, storage capacity, well injectivity, and the feasibility of monitoring methods. Once these major factors indicate a potential viable project, quantifying reservoir heterogeneities and their impacts on the geometry of CO2 plume is essential to develop optimized monitoring plans and select areas that are favorable for lower monitoring costs. This paper presents a methodology for quantifying heterogeneities in 3D reservoir models of a deep saline formation and correlated them with CO2 plume radius obtained from flow simulations. The variance of the geometric mean permeability, calculated according to the dimensions of geological elements, was used as a reservoir heterogeneity index that impacts CO2 plume behavior. Based on this analysis, it was possible to prioritize two subregions of 150 km² each as candidates for further detailed mapping within an area of nearly 4,000 km² in the shallow waters of the Santos Basin, Brazil.

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Introduction

Site screening is the process of defining the place where a Carbon, Capture, and Storage (CCS) project could be developed. Applied in the early stages of evaluation, this process involves several critical variables that should be analysed. For example, the distance of CO2 sources, injection forecasting, flow assurance, storage capacity, well injectivity, and the feasibility of monitoring methods are all important considerations. Evaluated under operational safety limits, these factors contribute to determining the best locations for developing a CCS project.

Once these major factors indicate a potential viable project, concerns about reservoirs' local variability controlling the plume migration begin to rise. This is due to the subsurface distribution of CO_2 impacting monitoring plans, including the method, survey size, and frequency of data acquisition. Therefore, quantifying reservoir heterogeneities and their impacts on the geometry of CO2 plume is essential to develop optimized monitoring plans and select areas that are favourable for lower monitoring costs.

This paper presents a methodology for quantifying heterogeneities in 3D reservoir models and correlated them with CO2 plume radius obtained from flow simulations. The main goal is to provide a procedure, based on geological elements, to identify areas with minimum and maximum plume radius to support further investigation decisions.

This methodology was applied to a data set from the shallow waters of the Santos Basin, Brazil. A deep saline formation in this area, composed of a thick sequence of fluvial-deltaic to shallow marine reservoirs and a regional caprock, was modelled for CCS site screening.

The variance of the geometric mean permeability, calculated according to the dimensions of geological elements, was used as a reservoir heterogeneity index that impacts CO2 plume behaviour. Based on this analysis, it was possible to prioritize two subregions of 150 km² each as candidates for further detailed mapping within an area of nearly 4,000 km².

Method and/or Theory

According to Ringrose and Bentley (2015), the best way to build reservoir models is to address specific questions and design models that are "fit-for-purpose." For CO2 storage models, the authors argue that evaluation requires a range of scales because injection affects not only the flow behaviour near the wellbore but also the geomechanical responses in larger areas. This concept of 'fit-for-purpose' and multiscale modelling guides the analysis of which hierarchical geological elements and their corresponding dimensions should be considered to represent the reservoir heterogeneities. Furthermore, after a 3D reservoir model is built, quantifying its heterogeneity is essential for predicting flow behaviour and, ultimately, prioritizing resource allocation.

To measure reservoir heterogeneity and its impacts on CO2 plume migration, it is preferable to analyse local variations in rock properties within the 3D grid rather than the entire model. To assess the extent to which a local characteristic represents the whole, Gommes (2016) proposed a quantitative measure of heterogeneity conditioned by a finite probe volume. This volume is systematically moved through the sample to measure the local average of a property at each point. As a result, the variance of this local average is an indicator of heterogeneity. By using probe volumes of various sizes, it is possible to quantitatively characterize the heterogeneity over a variety of length scales.

This method was applied to evaluate the variance of the geometric mean permeability within a variable-size rolling averaging window (denominated probe) as a measure of heterogeneity in a reservoir model from the Santos Basin, Brazil. The results were plotted against the CO2 plume radius from flow simulations, revealing geological elements correlated to probe size that control the distance of CO2 migration from the injection point. This information is critical to indicating which areas in the site screening process have the greatest potential for shorter migration distances.

The study area is located in the shallow waters of the Santos Basin, Brazil (Figure 1A). This southern portion of the country contains the largest industrial CO2 emitters, making site screening strategic for developing CCS projects in this region. To achieve this goal, a dataset of wells and 2D/3D seismic (Figures 1B, 1C and 1D) was used to model the Ponta Aguda Formation at depths between -1,000m and -2,500m.

According to Moreira et al. (2007), the reservoirs of this deep saline formation, with a 2,000 m thick sedimentary section, are composed of fluvio-deltaic to shallow marine deposits, covered by a regional caprock associated with shales from the Marambaia Formation.

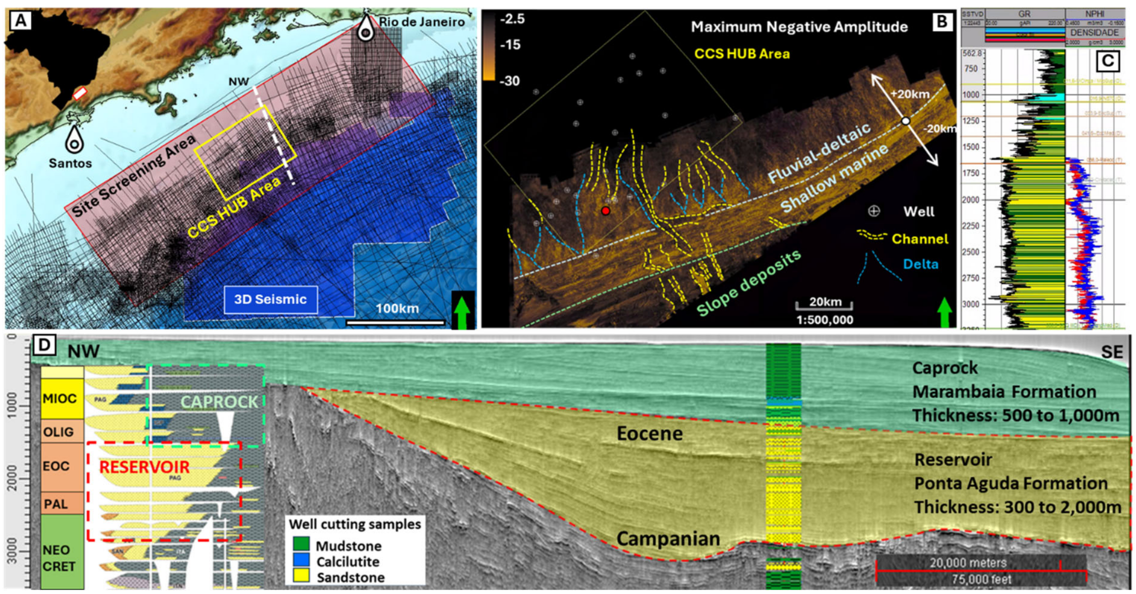


Figure 1 *A) Localization of the site screening area and the seismic data in the shallow waters of the Santos Basin. B) Seismic amplitude extraction in a window of 100 ms near the top of the Ponta Aguda Formation. The arrows show that the ancient coastline varied by 20 km seaward (-) and landward (+) developing transgressive-regressives cycles over time. C) Example of a well log (GR filled with cutting samples facies), NPHI, and RHOB, located inside the CCUS Hub area (red circle). D) 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 (2007).*

The model was built within the CCS HUB Area (Figure 1A), which was previously selected by considering factors such as the distance from CO2 sources, storage capacity, and well injectivity. Since this area is still large (approximately 4,000 km²), the main objective of the model was to define where further investigations, such as detailed mapping, should take place. For this purpose, the area was subdivided into smaller subregions (Figure 2A).

In this context, the scale of mapping was 1:500,000 within a 3rd-order sequence stratigraphy framework. The geological elements used in the model to guide the distribution of sandstones were 'channel,' 'delta,' and 'shallow marine' (Figure 1B). These major architectural elements controlled the internal distribution of rock properties and consequently the spatial variation of permeability (Figures 2C and 2D).

Regarding the 3D reservoir impacts of important factors (which is not presented in this paper), such as geostatistical algorithms, deterministic scenarios, and uncertainty analysis, among others, the CCS

HUB Area model with 8MM cells (250 x 250 x 6 m) was simulated with a total mass injection of 200 million tons of CO_2 within 12 wells in each subregion from A to H (Figure 2B). To evaluate the reservoir response as a whole, the injection interval was set at 600 m (Figures 2E and 2F).

In order to assess the variance of geometric mean permeability on various length scales, several probe dimensions (Figure 3A) were designed to quantify the level of heterogeneity in the model. The results presented in Figure 3B indicate that smaller probes exhibit higher variance, ranging from 7 to 9, reflecting that variations in permeability on this scale occur between neighbouring cells, similar to the nugget effect. As the probe volume increases, these values decrease to below 2, reflecting that at this observation window size, the reservoir becomes more homogeneous.

Neither of these values is useful for quantifying local heterogeneity that significantly impacts flow behaviour. This is evidenced in Figure 3C, where it is possible to note that Probes 21 and 3 present a low correlation between the CO_2 plume radius and the variance of each subregion.

However, Probe 4 shows the best correlation and could be used to classify regions with minimal CO_2 migration, such as subregions D and G. This is due to the fact that this probe size (1000 x 1000 x 12m) is more related to the dimensions of the geological elements considered a priori in the reservoir modelling.

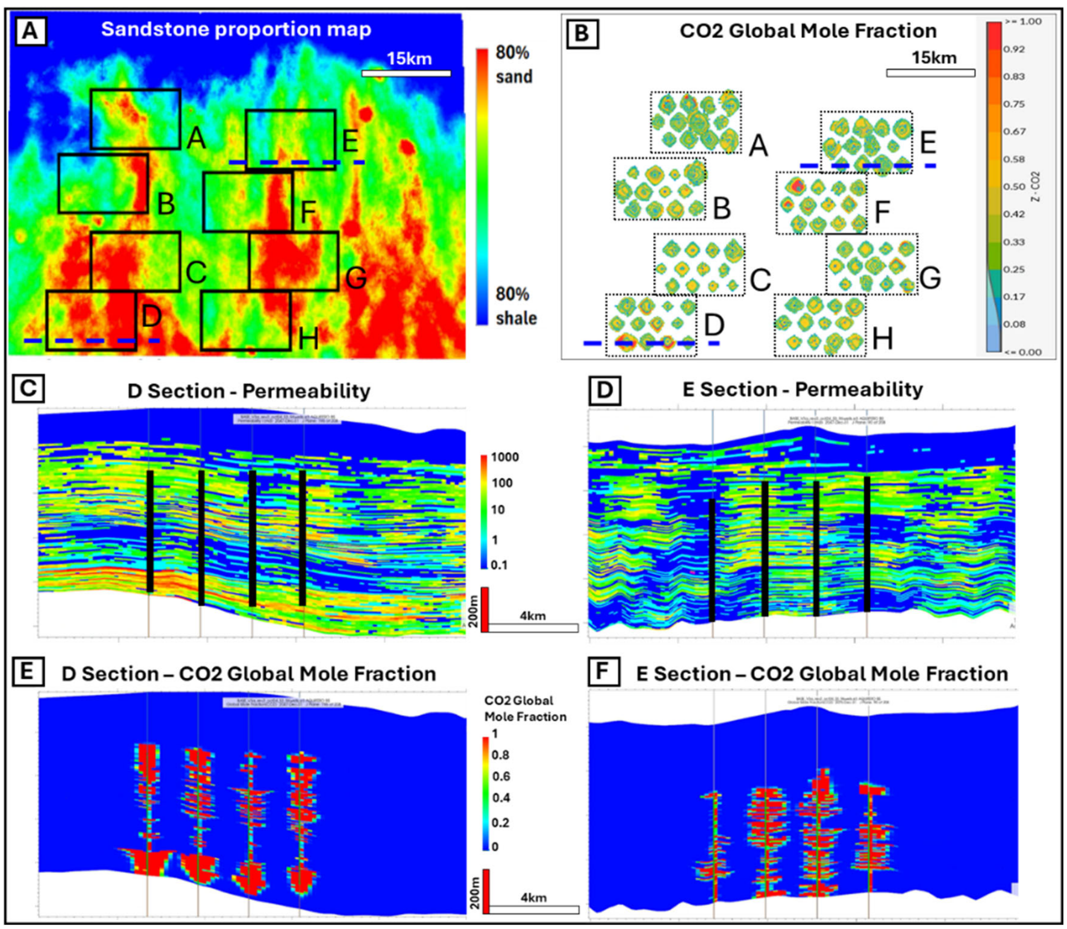
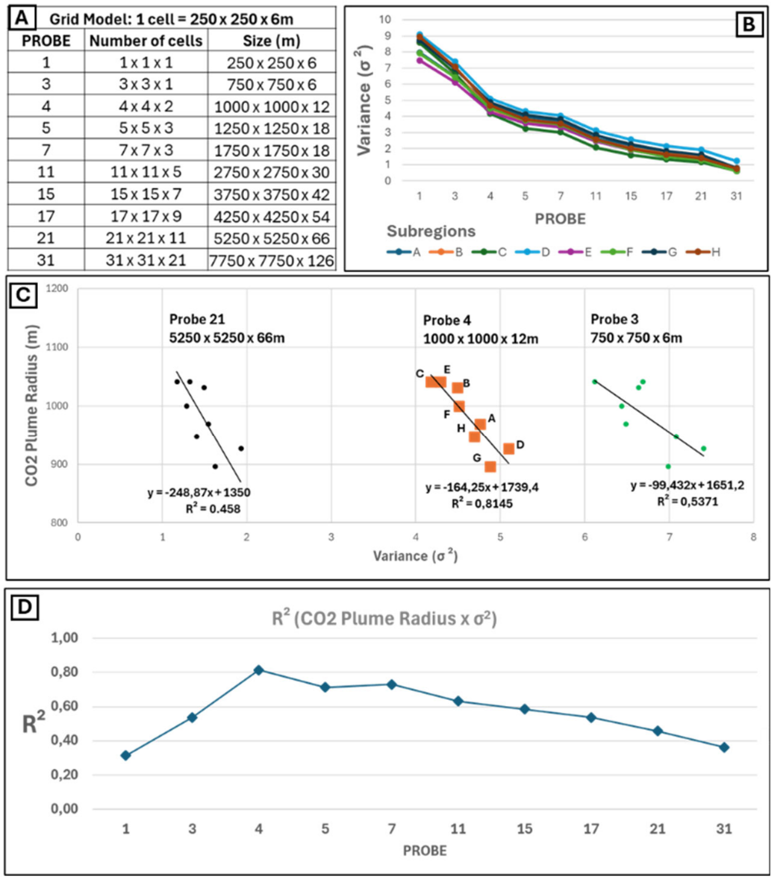


Figure 2 *A) Sandstone proportion map with subregions A to H within the CCS HUB Area. B) CO_2 global mole fraction map after the injection of 200 MM tons of CO_2 within 12 injection wells in each subregion. C - D) Permeability sections in subregions D and E, respectively, with the injection interval shown in black. E - F) CO_2 global mole sections in subregions D and E, respectively. The locations of these sections are represented as blue dashed lines in A) and B).*



PROBE	Number of cells	Size (m)
1	1 x 1 x 1	250 x 250 x 6
3	3 x 3 x 1	750 x 750 x 6
4	4 x 4 x 2	1000 x 1000 x 12
5	5 x 5 x 3	1250 x 1250 x 18
7	7 x 7 x 3	1750 x 1750 x 18
11	11 x 11 x 5	2750 x 2750 x 30
15	15 x 15 x 7	3750 x 3750 x 42
17	17 x 17 x 9	4250 x 4250 x 54
21	21 x 21 x 11	5250 x 5250 x 66
31	31 x 31 x 21	7750 x 7750 x 126

Figure 3 *A) Probe sizes used for the rolling averaging window. B) Correlation between CO2 Plume Radius and the variance of each subregion where Probe 4. D) Correlation between the probes and the R^2 of CO2 Plume Radius vs. Variance (σ^2).*

Conclusions

The site screening process is the initial step in evaluating CCS projects. Developing methods that can define potential areas to prioritize efforts makes this process faster and more reliable. This paper presents a method to measure the local heterogeneity that impacts CO2 behaviour in deep saline formations. The variance of the geometric mean permeability, calculated using a rolling window sized according to the dimensions of geological elements in 3D reservoir models, is used as a reservoir heterogeneity index. This index was calculated for the study area in the Santos Basin and correlated with CO2 plume radius obtained from flow simulations. The results indicate that subregions D and G have the shortest distance migrations of CO2. Assuming that the migration distance of the plume has a direct relationship with monitoring costs, this could be an important factor in selecting these two areas as candidates for detailed mapping in the next stages of site screening.

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