Assessment of the Impact of Sedimentological Heterogeneity on Multi-Phase CO2 Injection in Shallow-Marine Reservoirs

van der Kooij, R.; Martinius, A.; Geiger, S.; Hampson, G.; Jacquemyn, C.; Jackson, M.; Petrovskyy, D.; Baird, K.

DOI
10.3997/2214-4609.202421232

Publication date
2024

Document Version
Final published version

Citation (APA)
van der Kooij, R., Martinius, A., Geiger, S., Hampson, G., Jacquemyn, C., Jackson, M., Petrovskyy, D., & Baird, K. (2024). *Assessment of the Impact of Sedimentological Heterogeneity on Multi-Phase CO2 Injection in Shallow-Marine Reservoirs*. Paper presented at 5th EAGE Global Energy Transition Conference & Exhibition GET2024
, Rotterdam, Netherlands. https://doi.org/10.3997/2214-4609.202421232

Assessment of the Impact of Sedimentological Heterogeneity on Multi-Phase CO2 Injection in Shallow-Marine Reservoirs

R. Van Der Kooij[1], A. Martinius[1], S. Geiger[1], G. Hampson[2], C. Jacquemyn[2], M. Jackson[2], D. Petrovskyy[2], K. Baird[3]

[1] Delft University Of Technology; [2] Imperial College London; [3] Heriott-Watt University

Summary

In this contribution we compare results between fast screening methods based on flow diagnostics with results from full-physics simulations for CO2-brine displacement. Specifically, we analyse how either method identifies the key geological features that control CO2 plume migration across an ensemble of reservoir models for the shallow marine system present in the Johansen and Cook formations of the Northern Lights project. Our results indicate that many of the heterogeneities that appear to control CO2 plume migration based on the fast flow diagnostics also control CO2 plume migration when considering the complex fluid flow physics inherent to CO2-brine displacement. However, the magnitude of impact differs between both methods, conforming the hypothesis that more complex fluid flow processes increase the impact of geological heterogeneity on reservoir flow. Our results suggest that fast-screening methods like the one proposed by Jackson et al. (2022) are a reliable approach to analyse which heterogeneities at a given storage site are most likely to control CO_2 plume migration, helping geoscientist and reservoir engineers to design more meaningful reservoir models that contain the key geological heterogeneities and allow us to predict CO2 plume migration more reliably.

Assessment of the Impact of Sedimentological Heterogeneity on Multi-Phase CO_2 Injection into Shallow-Marine Reservoirs

Introduction

Subsurface CO_2 storage is one of several potential methods to be used for reaching the reduction of CO_2 emissions as required by the Paris Climate Agreement (Paris Agreement, 2015). Subsurface projects are subject to uncertainty because of our incomplete understanding of geological heterogeneities (Ringrose & Bentley, 2015). Hence, quantifying the impact of different types of geological heterogeneity (e.g., reservoir architecture, petrophysical property variations) on CO_2 plume migration and trapping is essential for proper site evaluation and project planning. Jackson et al. (2022) used the Rapid Reservoir Modelling (RRM) (Jacquemyn et al., 2021) tool for building an ensemble of diverse geological models covering a broad range of heterogeneities inherent to the Johansen and Cook formations of the Northern Lights project. Subsequently, they used the flow diagnostics, which are based on reduced physics, single-phase pressure solutions, to investigate which types of heterogeneities in the model ensemble impact CO_2 storage most (Petrovskyy et al., 2023. Lie, K. A., Møyner, O., & Krogstad, S., 2015. Møyner, O., Krogstad, S., & Lie, K. A., 2014).

While the work of Jackson et al. (2022) enabled a very fast screening of geological heterogeneities, the question remains if the same geological heterogeneities impact CO_2 migration once more advanced physics, i.e. two-phase flow including gravitational and capillary forces, are considered. Comparing the results between the full-physics and reduced-physics modelling will hence allow us to assess under which condition the screening workflow created by Jackson et al. (2022) allows us to analyse the key reservoir uncertainties without performing more time-intensive flow simulations.

In this work we therefore use the model ensemble that Jackson et al. (2022) created for the Johansen and Cook formations. This ensemble contains a total of 32 models representing the shallow-marine reservoir system of the Northern Lights project. The models are subjected to dynamic simulation that incorporates two-phase flow processes during CO_2 injection into the saline aquifers, using DARTS (Delft Advanced Research Terra Simulator) (Lyu & Voskov, 2023. Wapperom et al., 2023).

Method

The Johansen and Cook formations of the Northern Lights project are characterised as shallow-marine sandstones. The 32 models built by Jackson et al. are built up of four facies associations, which include mixed fluvial, tidal and wave-dominated depositional environments. The models were created to include eight distinct types of sedimentological heterogeneity using experimental design, where each type is set to one of two defined settings. Four of these heterogeneity types concern large scale (10m – 3km) features, such as the visible difference between models A and B in Figure 1, such as the planform geometry and the clinoform dip. The other four types of heterogeneity are small scale (<10m) features. The precise definition and quantification of the settings for each heterogeneity type can be found in Jackson et al. (2022). The model dimensions are 2500m by 3000m by 200m, divided into a grid consisting of 101 by 101 by 71 blocks. The models all contain an initial reservoir pressure of 250 bar and a reservoir temperature of 80°C.

For dynamic simulation, DARTS is used to simulate two-phase (CO_2-brine) flow throughout the models. The models are set to run for 10 years of CO_2 injection. The well placement and controls are taken from Jackson et al. (2022), meaning a single pair of injection and production wells is used. All models are run twice, once where the injection-production pair are placed on the centers of the South and North boundaries respectively and once where the pair is placed on the centers of the East and West boundaries respectively. The wells are pressure controlled, with a constant injection pressure of 300 bar and a constant production pressure of 200 bar.

The injection data taken from the simulation results is used for calculation of the cumulative injected volumes using CO_2 density at reservoir conditions and is then converted to pore volumes injected (PVI). Using the PVI after 10 years of CO_2 injection and the heterogeneity settings for each model, an average response of all models is taken. Comparing the difference from the average response caused by setting a heterogeneity from its low to its high setting allows for the quantification of a heterogeneities effect on PVI after 10 years.

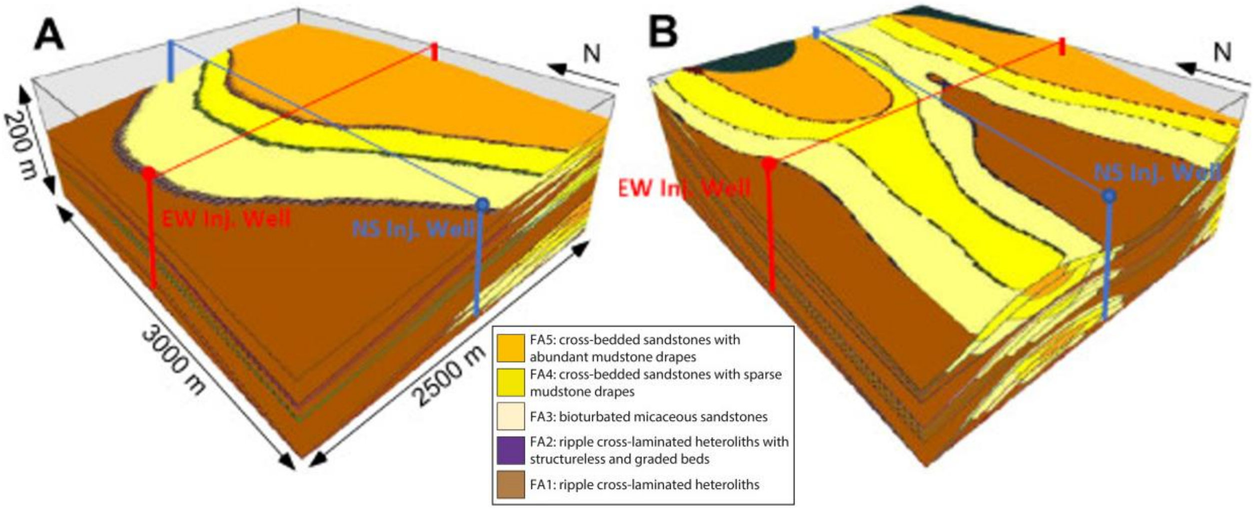

Figure 1 *3D perspective views of selected models, illustrating contrasting stratigraphic architectures that result from combinations of the settings for different heterogeneities: (A) model number 9, characterised by an arcuate planform geometry, gentle clinoform dip, and large facies-association interfingering extent; (B) model number 4, characterised by an elongate planform geometry, steep clinoform dip, and small facies-association interfingering extent; Legend between models indicates the facies associations described by the colours. Figure taken and modified from Jackson et al. (2022).*

Results & Discussion

Figure 2 shows results for 10-year injection into 30 of the 32 Johansen and Cook formation models. Models 28 and 30 have been excluded due to a high computational cost of simulating in these models, caused by particularly unfavourable heterogeneity configurations in these models with respect to injectivity. The figure shows the response of PVI compared to the average response when changing a type of sedimentological heterogeneity from its low setting to its high setting.

Notably, when changing dip extent of facies interfingering along clinoforms, mudstone drape continuity and extent in heterolithic cross-bedded sandstones and bioturbation intensity to their high settings has a significant negative impact (over 60% reduction) on PVI after 10 years of injection. Conversely, changing planform geometry, and to a lesser extent clinoform dip, from low to high has a significantly positive effect (69% and 22% increase respectively) on PVI.

Heterogeneity that has a relatively minor negative impact (7.5% reduction) on PVI is mean vertical spacing of carbonate-cemented concretions in between transgressive surfaces. Heterogeneity types that have a relatively minor positive impact (4.2% and 4.5% increase respectively) include mean lateral extent of carbonate-cemented concretions in between transgressive surfaces and lateral continuity of carbonate-cemented concretionary layers along transgressive surfaces.

Furthermore, CO_2 plumes after 10 years of injection are visible in Figure 3, where the models used correspond to those in Figure 1. Model 4, which is shown in Figure 1A is visible on the top of Figure 3, while Model 9, shown in Figure 1B, is visible on the bottom of Figure 3. The plume in Model 9 has reached the Northern boundary of the model within the 10 years, while the plume in Model 4 reaches just over halfway.

Comparing the tornado plot in Figure 2 to its North-South counterpart in Figure 12 of Jackson et al. (2022) indicates that most of the major key features that control the behaviour of the plume in the simplified physics flow diagnostics is also relevant in more complex physics approach. Namely, this concerns the dip extent of facies interfingering along clinoforms, clinoform dip and planform geometry, although the magnitude of their impact is increased in the two-phase flow approach. This is due to the two-phase simulation naturally being more responsive to changes caused by heterogeneity.

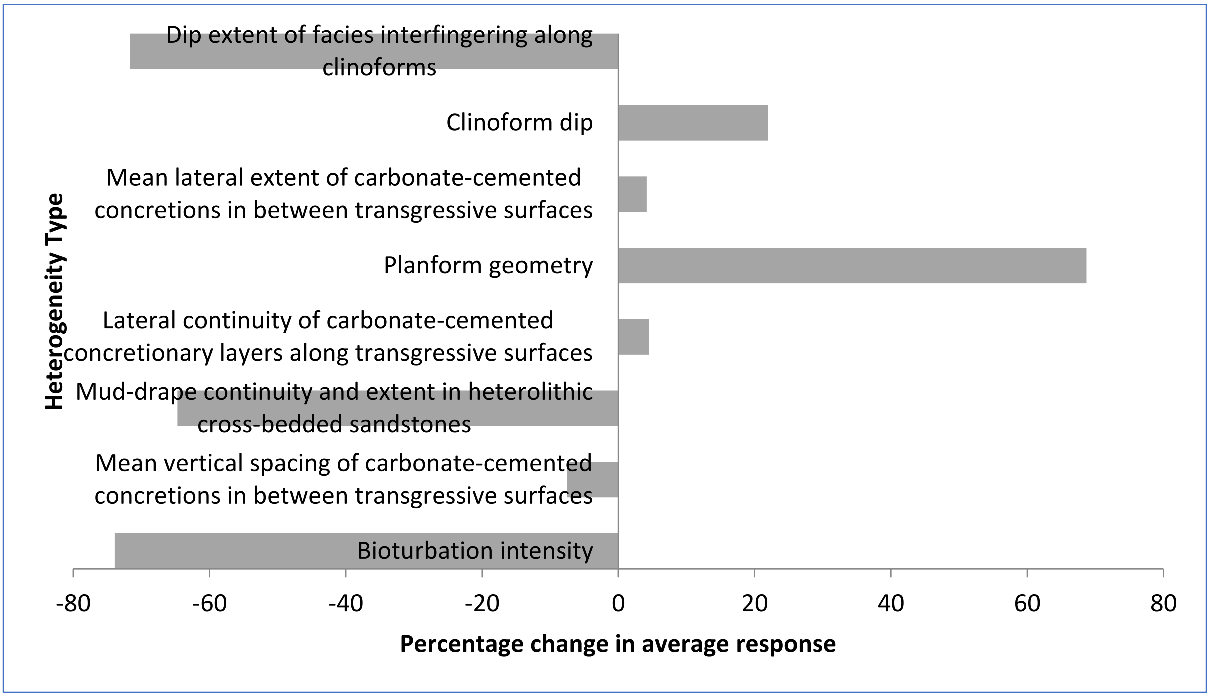

***Figure 2** Tornado chart showing the average percentage changes in pore volume injected at breakthrough time that result from varying each factor from its low setting to its high setting. Results are based on simulation results after 10 years of injection into 30 of the 32 Johansen and Cook models (models 28 and 30 have not been included).*

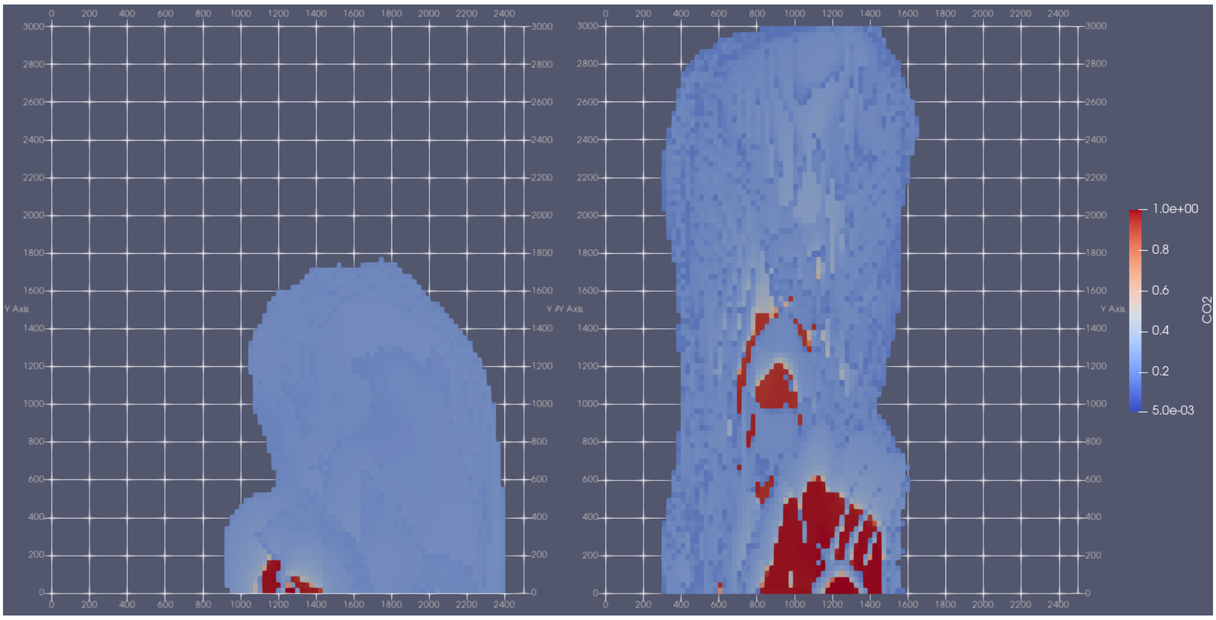

***Figure 3** Plan-view snapshots showing CO_2 plumes in the full model extent (2500mx3000m) after 10 years of injection for Model 4 (left) and Model 9 (right), corresponding to the models in Figure 1A and 1B respectively. The colour scale indicates high CO_2 saturation in red and low saturation in blue. The injection well in both cases is placed at the middle of the Southern boundary, while the production well is placed at the middle of the Northern boundary. Low CO_2 streaks overlying the high CO_2 saturations are visualisation artifacts.*

Significant differences between the two approaches involve the role of mud-drape continuity and extent, as well as bioturbation intensity. The addition of complex physics in the form of capillarity in combination with pressure control for the injection well leads to increased pressure build-up in low permeability zones. This is what is happening when mud-drape and bioturbation settings are set to high.

Furthermore, the results in Jackson et al. (2022) are given at breakthrough time, which is different in every model, while the results in Figure 2 are all at 10 years injection. This means that models where less favourable injectivity is present are not subjected to a time restraint and the roles of heterogeneities causing bottlenecks instead lead to favourable conditions for CO_2 trapping.
Figure 3 confirms that breakthrough does not occur within 10 years for all models with lower injectivity for a South-North well configuration. The planform geometry is clearly a driving factor for how much can be injected in a given amount of time, which is supported by the results shown in Figure 2.

Conclusions

The fast screening method presented by Jackson et al. (2022) for the characterisation and analysis of CO_2 storage sites proves to be a reliable method. Many of the key heterogeneities that most impact the single-phase pressure solution of the flow diagnostics are still relevant when reproducing the same scenarios using two-phase dynamic simulation, although their magnitudes are different. Some heterogeneities have a completely opposite effect, which is attributed to the fact that two-phase flow simulation including capillarity will lead to an increased effect caused by lower injectivity, combined with the difference in expected results from 10 year simulation compared to the expected results for results at the time of breakthrough for all models.

References

Jackson, W. A., Hampson, G. J., Jacquemyn, C., Jackson, M. D., Petrovskyy, D., Geiger, S., Machado Silva, J. D., Judice, S., Rahman, F., & Costa Sousa, M. (2022). A screening assessment of the impact of sedimentological heterogeneity on CO2 migration and stratigraphic-baffling potential: Johansen and Cook formations, Northern Lights project, offshore Norway. *International Journal of Greenhouse Gas Control, 120.* https://doi.org/10.1016/j.ijggc.2022.103762

Jacquemyn, C., Pataki, M. E. H., Hampson, G. J., Jackson, M., Petrovskyy, D., Geiger, S., Marques, C. C., Machado Silva, J. D., Judice, S., Rahman, F., & Costa Sousa, M. (2021). Sketch-based interface and modelling of stratigraphy and structure in three dimensions. *Journal of the Geological Society, 178*. https://doi.org/10.1144/jgs2020-1

Paris Agreement. (2015). Retrieved from https://unfccc.int/resource/docs/2015/cop21/eng/10a01.pdf

Lie, K. A., Møyner, O., & Krogstad, S., (2015). *Application of flow diagnostics and multiscale methods for reservoir management* [Paper presentation]. SPE Reservoir Simulation Symposium, Houston, Texas, USA. https://doi.org/SPE-173306-MS

Lyu, X., & Voskov, D. (2023). Advanced modeling of enhanced CO_2 dissolution trapping in saline aquifers. *International Journal of Greenhouse Gas Control, 127.* https://doi.org/10.1016/j.ijggc.2023.103907

Møyner, O., Krogstad, S., & Lie, K. A. (2014). The application of flow diagnostics for reservoir management. *SPE Journal, 20*(3), 306 – 323. https://doi.org/10.2118/171557-PA

Petrovskyy, D., Jacquemyn, C., Geiger, S., Jackson, M. D., Hampson, G. J., Machado Silva, J. D., Judice, S., Rahman, F., & Costa Sousa, M. (2023). Rapid flow diagnostics for prototyping of reservoir concepts and models for subsurface CO_2 storage. *International Journal of Greenhouse Gas Control, 124. https://doi.org/10.1016/j.ijggc.2023.103855*

Ringrose, P., & Bentley, M. (2015). *Reservoir model design: A practitioner's guide* (1st ed.). Springer.

Wapperom, M., Lyu, X., Nichita, D.V., & Voskov, D., (2023, March 28 – 30). *A unified thermal-reactive compositional simulation framework for modelling CO_2 sequestration at various scales* [Paper presentation]. SPE Reservoir Simulation Conference, Galveston, Texas, USA. https://doi.org/10.2118/212182-MS