Coupling Flow-Model and Seismic Uncertainty for Robust CCS Reservoir Assessment

Introduction

CCS Class VI permitting requires operators to establish reliable monitoring frameworks supported by comprehensive subsurface-flow simulations. These simulations can be generated as an ensemble of models that reflect plausible combinations of reservoir properties and injection scenarios, resulting in a broad spectrum of predicted Areas of Review (AoR) extents. Although this ensemble captures the full range of geological and operational uncertainty, monitoring programs in practice often rely on a single dynamic realization known as P50, supplemented only by selected statistical outliers such as P10 and P90. Consequently, most models in the ensemble can remain unused.

The methodology proposed in this study leverages the entire suite of dynamic realizations to design a monitoring strategy that progressively retains or discards models based on their predicted response to focused seismic observations in a divide-and-conquer-like manner. As monitoring data are acquired over time, only those models whose forecasted detectability patterns remain consistent with observed seismic detection from focused seismic monitoring (Morgan & Mari, 2024) are preserved. This iterative reduction of the model space progressively constrains the underlying reservoir parameters, thereby narrowing uncertainty and improving confidence in the evolving characterization of the storage complex.

The experiment presented in this study seeks to establish an optimized focused-monitoring configuration and to simulate corresponding focused-seismic responses with the objective of isolating a single or a small subset of reservoir models that remain consistent with the observed detection signals. This iterative identification process reduces uncertainty in key reservoir parameters, thereby improving the characterization of the subsurface throughout the injection phase and mitigating operational risk.

The focal point of this paper is to explore the power of the proposed method with a range of focused seismic detection uncertainty, including a real onshore case uncertainty. The introduction of uncertainty levels allows for a more conservative convergence of all flow models into a reduced number of models compliant with real reservoir behavior while keeping the essence of the divide and conquer strategy.

Method

The case study shown in this paper is a synthetic proxy of the Utsira Formation at Sleipner. This synthetic case study was constructed for this specific workflow. 91 dynamic models were generated using the same geological structure, but with variability in reservoir parameters (such as porosity, thermal conductivity, rock compressibility and permeability) and with variability in injection parameters (total CO_2 mass injected). This model includes five injection wells with spacing around 8 kilometers apart. For the 10 years of simulated injection, an average of 52 Mt of CO_2 was injected. Out of the 91 dynamic models generated, one model was selected in a blind-test manner as the real model within the ensemble.

The workflow of the method is composed of four main steps.

- The Predictive Monitoring step performs automated estimation of seismic detectable positions to all flow models using CO_2 saturation, pressure or mass variations across time through petroelastic modeling (Gestin et al., 2025). The positions that allow distinctions between different models are selected and called “distinctions spots”.
- The Identity Cards step described each model by a detection signature which is the estimated detection of the model for all distinction spots. Models that share the same identity card are grouped into detection clusters. Two models that share the same spot positions but have a different estimated detection response across all spots do not share the same identity card and belong to two separate clusters (Figure 1).

- The Monitoring Design step builds a monitoring plan using the identified distinction spots as a layout for focused seismic monitoring, respecting economic and environmental constraints of CCS on seismic acquisitions.
- The Iterative Update step incorporates newly acquired seismic data and monitoring results to progressively refine the ensemble of viable models by discarding those that are inconsistent with the observed detectability patterns. The clusters of models that remain compatible with the monitoring results are then propagated into the workflow and used as the basis for the next round of model reduction, in the next year of injection.

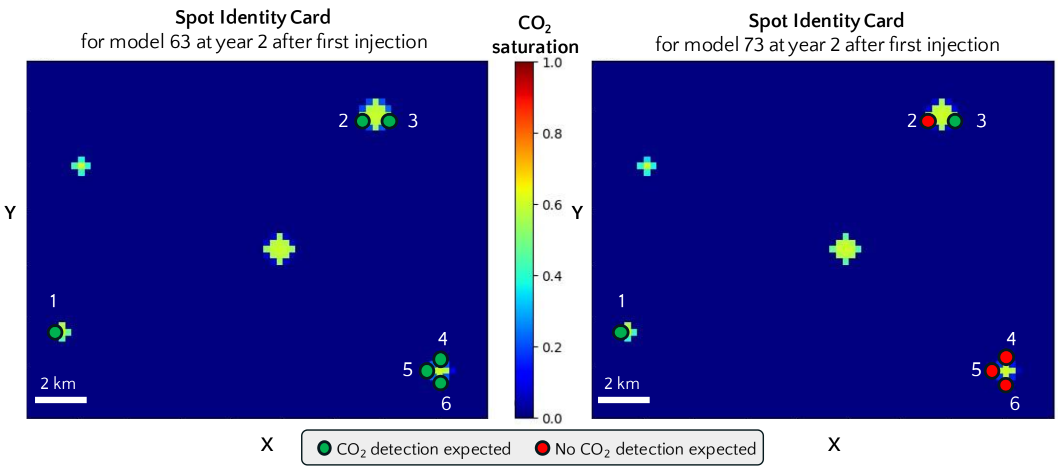

Figure 1 *Identity Card for two reservoir models showing predictive CO_2 detectability at the selected distinctions spots. Model 63 (left) predicts detection at all six spots, while model 73 (right) predicts detection at only two spots. These distinct binary patterns place the models in different clusters for monitoring iteration after 2 years of injection.*

This study also emphasizes the critical role of accurately characterizing the detection uncertainty associated with focused-seismic monitoring. An incorrect estimate of this uncertainty can cause genuine reservoir behaviors to be mistakenly rejected in favor of less representative models, thereby compromising the reliability of the workflow. To mitigate this risk, the method incorporates a reservoir-specific detection-uncertainty parameter that tolerates a limited degree of mismatch between observed and predicted seismic responses, while still ensuring a consistent and efficient narrowing of the model ensemble. Ultimately, a real focused-seismic case study is used to provide an initial, field-based estimate of the practical magnitude of this uncertainty.

Results

The procedure is applied across a range of seismic detection uncertainty levels, from 55% down to 0%. A 0% uncertainty assumption indicates that observed detectability outcomes are expected to match the petroelastic-model predictions exactly. When a non-zero uncertainty is introduced, 10% for example, the Iterative Update step is modified such that model clusters are retained for the next cycle only if their identity cards exhibit at least 90% consistency with the identity card inferred from the focused seismic detections. As the allowed uncertainty increases, a greater number of clusters satisfy this coherence criterion, resulting in a slower reduction in the model ensemble and a more gradual tightening of reservoir parameters uncertainty. The models most representative of the real reservoir system remain within the surviving ensemble if assumed uncertainty does not fall below the actual field uncertainty

A real onshore case study using CO_2 injection for Enhance Oil Recovery in Saskatchewan, Canada was used to estimate the real-world detection uncertainty of focused seismic for CO_2 detection (Peruch et al., 2025). In this field setting, focused seismic monitoring was implemented for 4 years. Ambiguous CO_2-related seismic responses were observed in 4 of 16 baseline measurements and in 5 of 16 monitor surveys. Based on these observations, the detection-uncertainty level applied in this study is set to 25%.

During the first year, the full ensemble of 91 reservoir realizations is evaluated. The Predictive Monitoring and Identity Card steps identify 28 distinction spots and partition the ensemble into 28 corresponding model clusters. When applying the 25% detection-uncertainty level derived from the real case study, the simulated focused-seismic response of the true model produces an identity card that excludes all simulated clusters with less than 75% coherence relative to this pattern. After this filtering step, 42 models remain in the ensemble. The workflow then proceeds to the second year, where a new iteration of Predictive Monitoring, Identity Card construction, and model selection is performed. Through successive iterations, the method ultimately converges to a single model whose predicted detectability behavior matches that of the real reservoir (Figure 2).

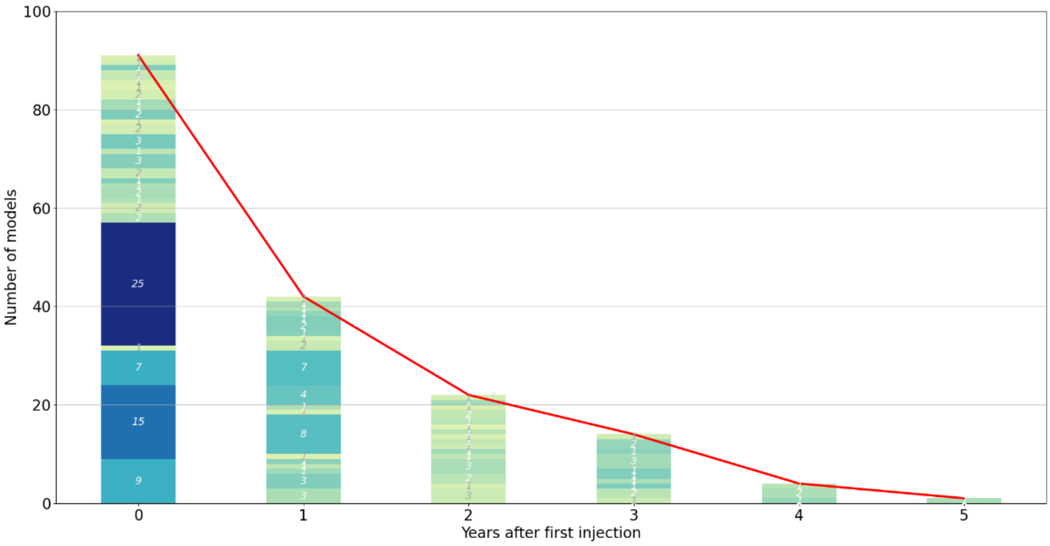

Figure 2 *Evolution of the number of models and model clusters across successive iterations of the method. Detection uncertainty value is set to 25% (real case study value). Each cluster (block with the number of models at the center) represents all the models that share the same identity card. The red line is the total number of models selected after each iteration.*

The experiment shows how the number of retained models evolves as a function of the assumed focused-seismic detection-uncertainty level. When the uncertainty is below 10%, the ensemble converges rapidly to a single model that reproduces the detectability behavior of the real reservoir by the third year after injection begins (Figure 3). This trend reflects the strong distinction power achievable when detection uncertainty is low, enabling a sharp and decisive reduction of reservoir model ambiguity. As seismic detection relies on interpretation and seismic response may sometimes not be as sharp as expected, detection uncertainty below 10% is unlikely even when spots are placed according to a strong expected seismic response. The workflow still converges for larger uncertainty levels up to approximately 35% but over a longer timescale, typically by the seventh year. In these higher-uncertainty scenarios, the ensemble shrinks more gradually at each iteration. The model reduction rate per cycle is about a factor of 2 for 25% uncertainty, roughly 1.5 for 35%, and close to a factor of 5 in the idealized 0% uncertainty value. While the latter represents an exceptionally strong narrowing of reservoir uncertainty, it is not realistic, as perfect detectability is unattainable in practice. From 40% detection uncertainty and onward, the method does not fully reach convergence. However, after 10 years of iterations of the divide-and-conquer method, the final number of selected models is 11 and 20, respectively for 55% uncertainty and 40% uncertainty, which corresponds to a model reduction of a factor of 5. The method still provides reduction in overall uncertainty of reservoir properties. Such a low uncertainty in focused seismic monitoring is unlikely: In an offshore real focused seismic monitoring project, detection uncertainty only reached about 30% (Roth et al., 2023).

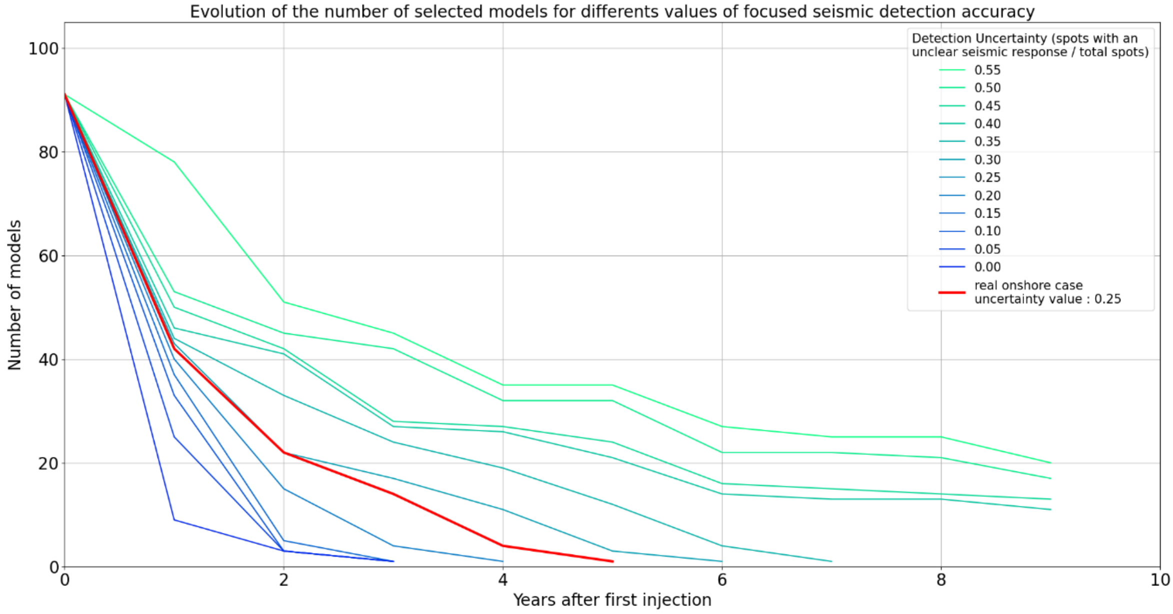

Figure 3 *Evolution of the number of selected models after each iteration of the method. Each line represents a different focused seismic detection uncertainty. The result of the real onshore case study detection uncertainty is the red line. The red line also corresponds to the same red line in figure 2.*

Conclusions

This workflow reduces reservoir-related uncertainty by integrating operator-derived flow models with frequent focused seismic monitoring. It enables more reliable subsurface monitoring programs and increases confidence in the annual evolution of the CO_2 plume. The identity-card clustering method minimizes the number of monitoring locations while retaining the ability to discriminate among competing flow-model predictions, thereby supporting more robust injection strategies and regulatory reporting. Future enhancements of this workflow involve distinguishing between distinction spots that exhibit a clear focused-seismic detection signal and those for which the response is ambiguous. This refinement would allow spots with unambiguous detectability to be treated with effectively 0% uncertainty, while excluding uncertain spots from the decision process.

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References

Gestin, K., Al Khatib, H., Randazzo, S., and Katz, D. [2025] Enhancing 2D Legacy Seismic Data Value for CCS Monitoring Using Predictive Maintenance. CCUS Conference, Houston

Morgan, E., Mari J. [2024] The Greensand Example: Enabling CCS Surveillance Using Focused Seismic Monitoring. 17th CO2 GEONET Open Forum.

Peruch, P., Chen S., and Morgan E. [2025] The value of frequent spot seismic : 4 years of monitoring on the Weyburn field. *First EAGE workshop on geophysical techniques for monitoring CO2 storage*.

Roth T. et al. [2023] Focused Seismic Monitoring in the Greensand CCUS Project, The Fourth EAGE Global Energy Transition Conference and Exhibition, p.1 - 5