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Divide and Conquer using Predictive Monitoring to Reduce CCS Flow Model Uncertainties and Ensure Containment

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Abstract

Carbon Capture and Storage (CCS) projects seeking Class VI permits must develop subsurface flow models to define the Area of Review, estimate CO_2 storage capacity, set injection rates and design monitoring plans. Many operators run large stochastic model sets but submit only a few representative cases (P10, P50, P90), leaving most realizations unused. This new strategy incorporates all model realizations into the monitoring design using agile, non-invasive spot seismic and predictive monitoring to reduce uncertainty throughout the project life cycle.

The workflow consists of four steps. First, a Predictive Monitoring steps compares all reservoir models to identify "distinctions spots" positions where CO_2 saturation, pressure or mass differ and are seismically detectable through petroelastic modeling. Next, each model is characterized by an Identity Card that tracks its predicted detectability pattern at these spots. Models with similar responses are grouped and progressively separated using a divide and conquer method. The Monitoring Design step then uses the distinctions spots as an acquisition layout for targeted seismic measurements, focusing on locations with high model divergence while respecting economic and environmental limits on spot seismic acquisition. Finally, the Iterative Update step integrated new seismic data to refine the ensemble, adjusting both the model set and the monitoring plan as the injection project continues.

Simulating hundreds of realizations before injections highlights high-value monitoring points. Targeted surveys confirm or rule out model clusters, narrowing uncertainty and improving plume forecasts. This adaptive approach increases the transparency, supports regulator-ready monitoring and serves as an "alarm system" when observations deviate from all predictions.

Introduction

CCS Class VI permits require operators to develop robust subsurface surveillance strategies supported by comprehensive flow-model analyses (EPA, 2018). These models define the Area of Review, estimate CO_2

storage capacity, determine injection rates and support monitoring-program design. To capture geological and operational uncertainty, operators typically generate an ensemble of reservoir realizations. In practice, however, storage capacity and subsequent monitoring plans are often based on only a few representative cases such as P10, P50 and P90, which limits the use of the full ensemble variability (Al Rassas et al., 2022). The divide and conquer workflow aims to overcome this limitation by incorporating the entire ensemble into the monitoring design. Instead of relying on a single representative model, the approach uses focused seismic observations to progressively eliminate non-representative realizations throughout the life of storage. The goal is to reduce flow-model uncertainty and improve the reliability of plume-migration forecasts as new monitoring data become available.

Methods

A synthetic case study based on a proxy for the Utsira Formation at Sleipner was constructed to evaluate the workflow. Reservoir engineers generated an ensemble of 91 flow-model realizations sharing the same structural framework but with varying porosity, permeability, rock compressibility, thermal conductivity and total injected CO_2 mass. The model includes five injection wells spaced about 8 kilometers apart with a 10-year CO_2 injection period (total of 52 million tons of injected CO_2). One realization was selected in a blind-test manner as the true reservoir model within the ensemble. The study aimed to evaluate whether the divide and conquer monitoring strategy could progressively reduce model uncertainty, converge toward a one model and determine how many yearly iterations of monitoring would be required.

Geophysicists identified distinction spots, specifically corresponding to areas where inter-model variations in CO_2 saturation exceed 10% (Gestin et al., 2025), a conservative seismic detection criterion for saline-aquifer settings. Reservoir engineers assessed CO_2 presence at these spots based on the true model. This workflow step mirrors a focused seismic monitoring acquisition (Morgan et al., 2024) (Peruch et al., 2025), where targeted measurements at selected locations enable operators to confirm or reject subsets of flow-model predictions. Distinction spots are then gathered into unique model identify cards. Each identity card is a binary vector indicating whether CO_2 would be detectable at each distinction spot. Redundant spots that produce identical detectability outcomes across the entire ensemble are removed to keep only the minimal set of informative locations. Models sharing the same identity card are grouped into clusters as they cannot be distinguished using focused seismic measurements at that time. Figure 1 illustrates two contrasting identity cards: model 63 predicts CO_2 detection at all six spots, whereas model 73 predicts detection at only two of them. Since their detectability patterns differ, the two models belong to different clusters.

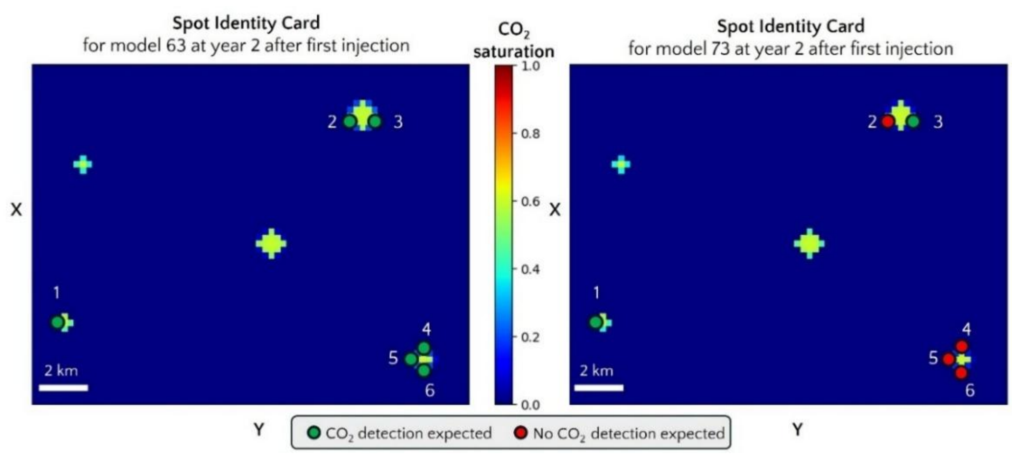

Figure 1 : Identity cards for two reservoir models showing predicted CO_2 detectability at the selected distinction spots. Model 63 (left) predicts detection at all six spots, while model 73 (right) predicts detection at only two spots. These distinct binary patterns place the models in different clusters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

Applying the distinction-spot identity cards to the full ensemble of 91 models produces 28 unique clusters at the start of the workflow (Figure 2A). A first focused seismic acquisition tests the presence of CO_2 at the 28 initial spots, allowing only the five clusters consistent with the observed detectability pattern to be retained. During the second iteration, new identity cards are generated for the surviving models, this time requiring only six distinction spots. A second focused seismic acquisition would further reduce the ensemble to a single cluster of three models. A final iteration, using three new distinction spots, isolates one unique model after the third year of monitoring. Under the assumption of perfect match between predicted and observed detectability, the workflow converges to the true reservoir model in three iterations.

To evaluate the impact of seismic-detection uncertainty, the workflow was repeated using a detection-accuracy threshold of 90% for the first iteration and 85% for the following ones (Figure 2B). In this case, 3 of the 28 initial distinction spots are interpreted as non-detectable due to uncertainty, resulting in a larger number of clusters being retained after the first acquisition: 13 instead of 5. The second iteration produces a new identity card requiring 15 distinction spots, and a focused seismic measurement on these spots reduces the surviving clusters to five. A third iteration, based on 7 distinction spots, eliminates the remaining uncertainty and converges to a single validated model. Although detection uncertainty slows the reduction of the model space during the first iteration, both scenarios converge to the correct subsurface model by the third year of monitoring.

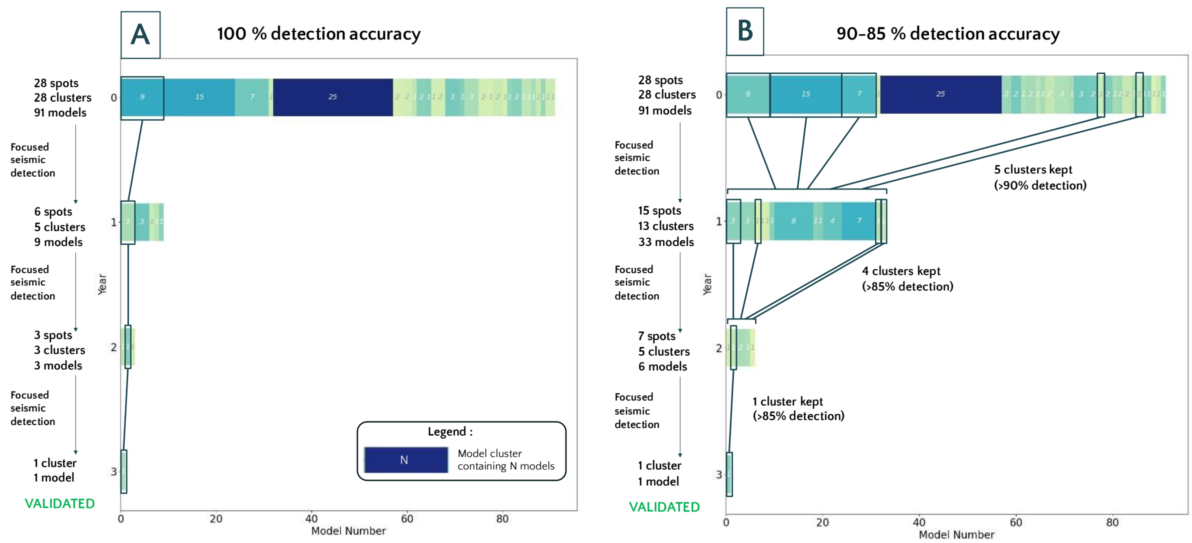

Figure 2. Evolution of the number of clusters and models throughout the divide and conquer method. Figure A is the clusters evolution for 100% detection accuracy. Figure B is the clusters evolution for 85-90% detection accuracy.

Results

The divide and conquer workflow shows that a small number of focused seismic measurements can efficiently constrain a large ensemble of flow models. Starting from 91 realizations grouped into 28 initial clusters, the divide and conquer workflow consistently reduces the number of plausible reservoir behaviors after each yearly monitoring iteration. Under ideal detection conditions, the first focused seismic acquisition eliminates most incompatible clusters and the method converges to a single model by the third year. When realistic seismic-detection uncertainty is introduced, the initial reduction is less aggressive and more clusters are retained after the first acquisition, yet the workflow still converges to a unique model within three iterations. These results demonstrate that focused seismic provides sufficient discriminatory power to identify the correct reservoir behavior even under non-ideal detection conditions, and that convergence remains achievable within the same three-year timeframe.

Overall, the results confirm that the workflow is robust to detection uncertainty and that its convergence speed is controlled primarily by the annual acquisition schedule rather than by the level of seismic repeatability. Regardless of whether 100 percent or 90–85 percent detection accuracy is assumed; the true reservoir model is consistently identified within three years.

Discussion

The convergence toward a single representative flow model strengthens confidence in plume-migration forecasts and improves the reliability of dynamic reservoir simulations. As uncertainty decreases, monitoring plans can be refined and CO_2-accounting estimates become more robust because key parameters, such as injected mass or plume extent, are better constrained.

The workflow could be further enhanced by generating updated flow-model realizations at each iteration. These new models would inherit narrower uncertainty ranges informed by the surviving subset, increasing ensemble robustness and improving the performance of subsequent divide and conquer cycles.

Conclusions

The primary objective of this workflow is to reduce reservoir-related uncertainty by combining operator-derived flow models with a lightweight monitoring strategy based on focused seismic acquisition. The resulting framework enables more reliable and efficient subsurface-monitoring plans and improves confidence in the year-to-year evolution of the CO_2 plume.

The identity-card clustering approach provides a rigorous way to minimize the number of monitoring spots while preserving the ability to distinguish among competing flow-model predictions. This reduction of uncertainty supports more robust injection strategies and strengthens confidence in CO_2 accounting and regulatory reporting.

Future developments could include constraining new flow-model realizations at each iteration to reflect progressively narrower uncertainty ranges, as well as defining upper limits on the number of distinction spots per cycle to streamline monitoring-acquisition designs. The workflow can also act as an anomaly-detection mechanism by identifying situations in which no simulated identity card matches focused seismic observations, indicating that the ensemble may require refinement.

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References

AlRassas, A.M., Vo Thanh, H., Ren, S. *et al.* Integrated static modeling and dynamic simulation framework for CO_2 storage capacity in Upper Qishn Clastics, S1A reservoir, Yemen. *Geomech. Geophys. Geo-energ. Geo-resour.* **8**, 2 (2022).

Gestin, Kévin, Al Khatib, Habib, Randazzo, Santi, and David Katz. "Enhancing 2D Legacy Seismic Data Value for CCS Monitoring Using Predictive Maintenance." Paper presented at the SPE/AAPG/SEG Carbon, Capture, Utilization, and Storage Conference and Exhibition, Houston, Texas, USA, March 2025. doi: https://doi.org/10.15530/ccus-2025-4186289

Morgan, Élodie, et Jean-Luc Mari. « The Greensand Example: Enabling CCS Surveillance Using Focused Seismic Monitoring ». 17th CO2 GEONET Open Forum, 2024.

Peruch Pauline, Sandy Chen, Elodie Morgan. « The value of frequent spot seismic : 4 years of monitoring on the Weyburn field ». First EAGE workshop on geophysical techniques for monitoring CO2 storage, 2025, 4.

EPA - Geologic Sequestration of Carbon Dioxide – Underground Injection Control Program Class VI Implementation Manual for UIC Program Directors (2018): https://www.epa.gov/sites/default/files/2018-01/documents/implementation_manual_508_010318.pdf