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Managing Fault-Related Risks in Gigatonne-Scale CO_2 Storage with Multiscale Modeling and Simulation

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Summary

Achieving climate neutrality requires rapid scale-up of CO_2 storage to gigatonne scale. Storage clusters—multiple injection sites sharing regional aquifers—offer economic benefits but introduce new challenges in subsurface pressure management. Elevated reservoir pressures can lead to fault slip and leakage, generating environmental and operational risks that span beyond individual license areas. Current site-focused workflows are insufficient for characterizing such cross-boundary effects.

This work introduces the research activities and key ideas of the international research project MuPSI which develops an integrated, multiscale screening and simulation approach to assess geomechanical risks in storage clusters. We present results of a new screening workflow that enables rapid evaluation of pressure interference and fault activation risk across regional aquifers. This is coupled with high-resolution modeling of fault response and new software to bridge region-, project-, and fault-scales. A new highly efficient approach for pressure-stress coupling offers greater software flexibility in geomechanical assessment of individual projects.

The approach is demonstrated using North Sea case studies, including the Horda Platform (Norway) and East Mey (UK). Outputs will support operators and regulators in improving investment decisions, permitting, and cross-license coordination. MuPSI also delivers stakeholder training and knowledge-transfer tools to accelerate adoption of robust, risk-informed storage cluster design.

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Introduction

The transition to climate neutrality demands rapid upscaling of carbon capture and storage (CCS) to gigatonne levels, with Europe alone targeting over 280 Mtpa of CO_2 storage by 2040. To meet this, CO_2 storage clusters, where multiple operators inject into shared aquifers, are emerging as a dominant strategy. However, this introduces complex geomechanical challenges, particularly concerning pressure interference across license boundaries. Elevated reservoir pressures from multiple injection points can reactivate faults and cause leakage, risks that are difficult to detect or manage using project-scale models alone.

The international research project "Multiscale pressure-stress impacts on fault integrity for multi-site regional CO_2 storage hubs (MuPSI)" aims to fill this gap by developing an integrated, multiscale modeling approach for geomechanical risk assessment in regional storage clusters. This paper outlines the approach, preliminary developments, and its application to North Sea case studies.

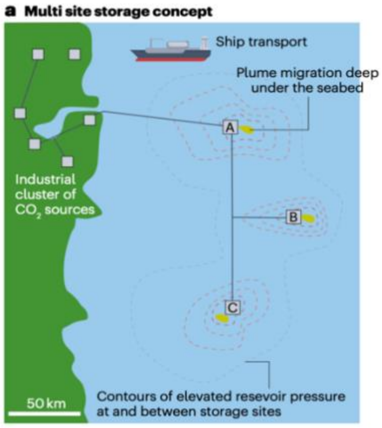

Figure 1 Conceptual diagram showing pressure interference between adjacent CO_2 storage licenses in a shared aquifer (Krevor et al. 2023).

Scientific problem and multiscale challenges

The large-scale deployment of CO_2 storage requires a shift in approach for evaluating geomechanical risks. In shared aquifer systems, where multiple injection licenses operate within a common hydrological unit, pressure perturbations do not remain confined to the licensed acreage of individual projects. Instead, they interact across distances of tens to hundreds of kilometers, altering the in-situ stress regime in a way that challenges conventional site-focused risk models. Such interference can cause reactivation of faults located far from injection wells and/or earlier than expected, where site-scale monitoring and mitigation may not be appropriately designed to capture such anomalies.

At the regional scale, the key challenge is early-stage identification of higher-risk locations within geologically complex large aquifers where pressure buildup can lead to geomechanical instability. Simplified models for regional storage assessment offer superfast and informative estimates to support screening and identify bottlenecks to CO_2 storage. Because reservoir pressurization is generally the most limiting factor to storage, these models need to incorporate pressure limits related to geomechanical constraints and acknowledge the dynamic evolution of injection-induced pressure build-up. Current tools often oversimplify the geomechanical constraints and dynamic evolution of pressure build-up, reducing confidence in screening results. Semi-analytical approaches offer efficiency but have been limited in capturing fault-related stress feedbacks, fault reactivation thresholds, and associated leakage risk.

The project scale introduces complexities due to varying reservoir properties, injection rates, and site-specific modeling approaches. Operators typically build high-fidelity models for their license area, but lack context on how neighboring activities affect their site. This creates blind spots in risk-based decision-making and ultimately undermines efforts to coordinate across stakeholders.

At the fault scale, uncertainties in fault permeability evolution, slip potential, and activation mechanisms present major limitations. Laboratory and field-scale data are sparse, and conventional models are computationally expensive, inhibiting their use in regional workflows. The lack of integration across these scales is a core bottleneck preventing reliable gigatonne-scale CO_2 storage.

Methods

MuPSI introduces a hierarchical, multiscale modeling and simulation framework specifically designed for geomechanical risk assessment in clustered CO_2 storage hubs. The core philosophy is to combine efficient, physically grounded models across scales with flexible coupling strategies that allow knowledge transfer between region, project, and fault levels—while respecting data ownership and level of detail relevant at the respective scales.

At the regional scale, MuPSI builds upon the open-source tool CO2BLOCK (De Simone and Krevor, 2021) that combines geomechanical estimations and analytical solutions of pressure changes due to CO_2 injection into multiple wells to provide first-order assessments of the dynamic storage resource of basin-scale storage hubs over decadal timeframes. The tool will be extended to resolve the spatial extent and rate of pore pressure increase in large heterogeneous aquifers ($\sim 10^6$ km²), incorporating more geologically realistic assumptions for flow and poroelastic stress calculations along with physically appropriate boundary conditions. A key innovation is the extension of these semi-analytical models to include structural elements such as faults and heterogeneity, which can allow practitioners to screen for geomechanical risks before allocating multiple licenses in a shared aquifer system. Coupling this with threshold models for fault slip and fracture reactivation enables the estimation of risk zones without relying on high-performance computing resources. Namely, the estimation of fault slip potential and induced seismicity is calculated in the associated module CO2BLOCKSEISM (Kivi et al., 2026). A probabilistic approach is used to deal with uncertainties in the hydraulic and geomechanical properties, state of stress, and fault distribution and attributes.

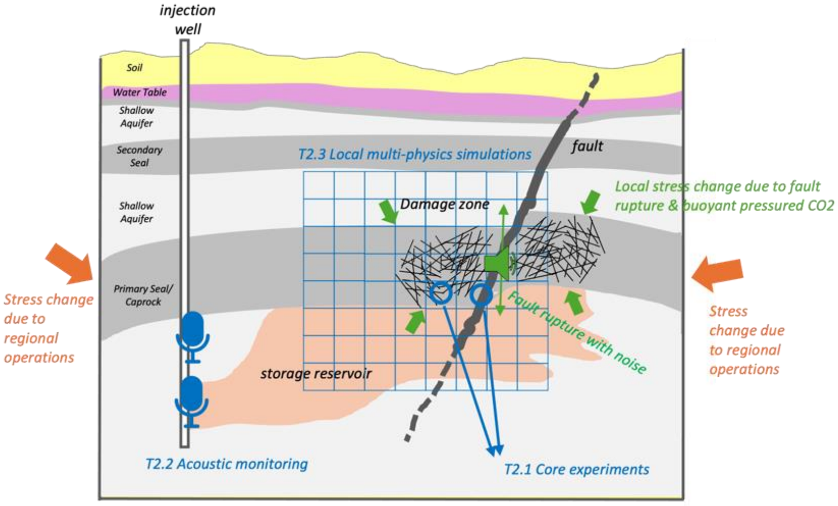

Figure 2: Overview of MuPSI conceptual framework linking regional, project, and fault-scale models.

At the fault scale, the project uses laboratory-derived parameters from real and synthetic fault materials to calibrate advanced constitutive models. These data help refine process understanding in the vicinity of faults triggered by local and regional stress changes. These processes have been investigated in previous projects (e.g., DETECT, FRISK, DeepNL), which highlighted that de-risking requires site-specific measurements and better constitutive models. We will run an experimental program to understand how the effective permeability of fractured caprock responds to stress changes and slip characteristics of the fault core material (Cartwright-Taylor et al. 2022). Experiments include triaxial testing under reservoir conditions, digital rock imaging, acoustic monitoring, and permeability evolution during loading-unloading cycles. These experimental results are used to refine the DETECT workflow (Snippe et al. 2022) with improved constitutive models and numerical schemes. This work then informs the development of vertically integrated fault leakage models for fast screening at regional scale (Ramachandran et al. 2023), where faults are treated as thin flow features whose transmissivity evolves as a function of effective stress and mechanical strain.

MuPSI's multiscale coupling strategy is based on a blockwise domain decomposition framework that employes principle of splitting the domain into small sub-problems, or blocks (Ahmed et al. 2021). Regional simulations define the large-scale pressure and stress field evolution, which is then transferred to the boundaries of project-scale models. These models may consist of operator-built high-resolution grids with bespoke petrophysical and structural interpretations. Within these, stress paths are tracked and passed to embedded fault models to assess local reactivation potential. If activation is detected, the risk of leakage is computed based on simplified, yet validated, permeability functions. The feedback loop completes when these localized risk indicators are aggregated back into regional maps, guiding permitting and monitoring strategies.

Software tools developed under MuPSI are designed for modular integration with industry-standard simulators (e.g., OPM, MRST, TOUGH-FLAC3D), and the entire workflow is scriptable in Python for reproducibility and automation. Security and confidentiality of project-scale data are maintained via a software-independent interface for data exchange that preserves internal project model boundaries (Tveit et al. 2025). This allows operators to benefit from regional insights without disclosing proprietary reservoir or fault data, fostering collaboration in multi-operator storage hubs. By merging rapid screening with high-resolution physics and multiscale interoperability, MuPSI offers an innovative and practical solution for de-risking future CCS hubs operating in shared geological formations.

Case studies and preliminary results

Two real-world case studies are used to demonstrate the MuPSI approach:

- Horda Platform (Norwegian North Sea): This site includes multiple licenses within the shared Troll aquifer. MuPSI models can be used to enable coordination of injection strategies in shared aquifer systems to minimize unwanted pressure build-up along faults.
- East Mey (UK North Sea): As part of the Acorn project, East Mey is an example of a scalable regional fairway. MuPSI hierarchical tools can improve early-stage screening of project development and legacy well risk in sites embedded in a large regional system.

Preliminary results are focused on new developments in efficient coupling injection-induced pressure build-up and geomechanical response. At regional scale, the screening tool has been successfully combined semi-analytical predictions of pressure build-up with a fast estimation of fault-slip potential to improve storage capacity estimates under uncertain geomechanical fault properties. The example workflow and results are shown in Figure 3. By combining deterministic and probabilistic approaches, the tool can provide more accurate estimates of large-scale CO_2 subsurface storage resources constrained by fault slip risk.

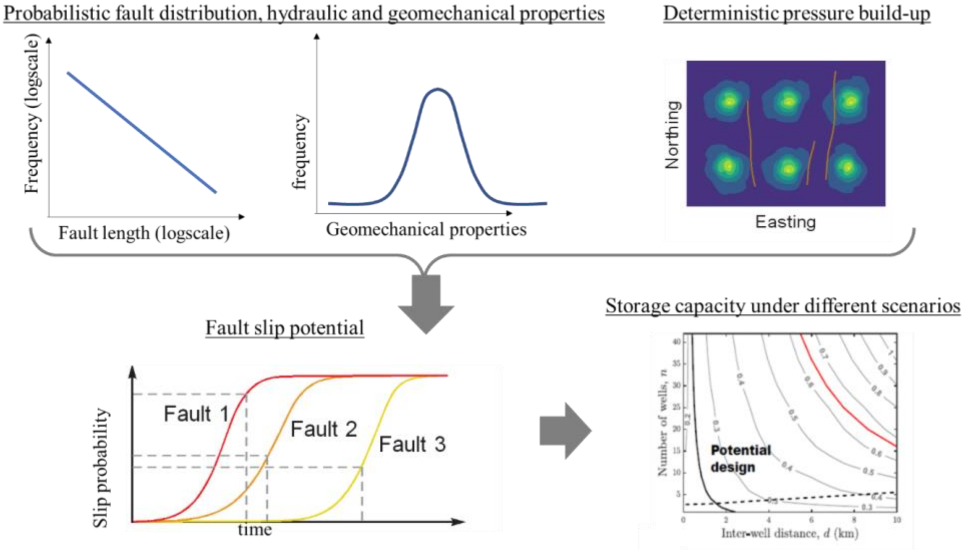

Figure 3: The prototype workflow coupling CO2BLOCK and CO2BLOCKSEISM for fast screening of regional capacity estimates constrained by stochastic fault risk is shown for a simple test model.

Impact and stakeholder engagement

Beyond technical innovation, MuPSI delivers value through stakeholder training, knowledge dissemination, and regulatory engagement. Tailored training modules and a digital knowledge toolkit are being developed for industry practitioners and regulators. A Community of Practice (CoP) is being formed to facilitate dialogue on scale-up challenges, data sharing, and regulatory alignment, particularly across national boundaries where aquifers are transboundary. These efforts aim to accelerate permitting, reduce investment uncertainty, and support transparent, science-based decision-making.

Conclusions

MuPSI provides an urgently needed multiscale modeling framework to assess and mitigate geomechanical risks in CO_2 storage clusters. By bridging region-, project-, and fault-scale dynamics, the project supports safer, more reliable deployment of gigatonne-scale storage. Ongoing case studies and tool development will pave the way for implementation in upcoming regional aquifer developments.

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