Abstract

Global deployment of CO₂ storage is projected to increase exponentially by 2100, which will involve developing many storage sites in the coming decades in diverse geological settings. Faults are known to be effective seals for hydrocarbons, yet they are considered a risk for leakage in the context of CO₂ storage [Wu et al. 2021]. This is partly due to evidence of natural CO₂ leakage through fault systems, but also from industrial experience. For instance, the In Salah CCS project induced flow along a fault that was activated due to pressure build-up. Sub-seismic faults can also be detrimental for injectivity by blocking fluid flow and causing unwanted pressure build-up. Therefore, understanding the mechanisms of fault flow is an essential aspect of reducing the risk of CO₂ storage in faulted zones.

Understanding fluid flow through the fault system should be evaluated at the field scale so the impact of reservoir dynamics can be properly quantified in leakage estimates. Faults are complex geological features comprised of the fault core and damage zone and are characterized by multiple rock types, slip surfaces, deformation bands and fractures. The fault thickness can vary between a few to tens of meters, depending on the size of the fault. The scale of heterogeneous features in the fault may be as small as millimeters to several centimeters in lateral extent.

From the perspective of reservoir simulation, the thicknesses of the fault and its components are often significantly smaller than the typical cell size in a simulation model. Classical simulation methods are reliant on resolving fault heterogeneity to accurately represent flow through the complex heterogeneous system. This strategy is therefore intractable at the field-scale. When considering fault-related leakage, additional overlying strata need to be included in the simulation model, further increasing the number of unknowns and associated computational time.

Another challenge is significant uncertainty associated with fault properties. This stems from the inability to observe faults directly in the subsurface, the low resolution of geophysical methods, and the difficulty translating outcrop and lab observations to subsurface conditions. Nonetheless, there are data that can be used to model uncertainty in the properties of faults at the fine scale. The difficulty is efficiently propagating modelled uncertainty through forward simulations to leakage estimates. The stochastic space associated with fault properties involves several

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random variables that span a large range in uncertainty. Classical Monte Carlo methods cannot be readily applied
due to the need for 1000s of model evaluations, especially when considering the large physical model required in the
forward simulations.

In this paper, we present new models, methods and algorithms to tackle the challenges of assessing fault-related
leakage in field-scale simulation under uncertainty. We review advances made in each of these three areas:

1. Upscaled models for reservoir permeability in the damage zone
2. Efficient strategy for coupling fault flow with field-scale flow simulation
3. Accelerated methods for uncertainty quantification

We demonstrate how these developments can be used to improve our understanding of fault-related fluid flow at the
field scale. We focus on the Vette fault of the Smeaheia storage prospect in the North Sea using the open-access
model that is available on the CO2 Data Share platform.

\textit{Upscaled damage zone permeability}

To include the permeability reduction associated with deformation bands into simulation models, we consider local
simulations with explicitly resolved bands. This gives high resolution of the flow, including of flow diversion which
exploits gaps between deformation bands, thereby invalidating simple permeability upscaling based on one-
dimensional harmonic means. We develop an improved analytical upscaling which accounts for the two-
dimensional nature of the flow and ultimately links the permeability directly to the fault throw [Berge et al., 2021].
The impact of the bands in terms of leakage risk is discussed in the light of field-scale simulations.

\textit{Efficient field-scale strategies}

Field-scale uncertainty quantification requires fast and repeated evaluation of reservoir models. The CO2STORE
module OPM Flow solver is used in this study. The Flow simulator is well suited for modelling along fault flow by
invoking the non-neighbour connection (NNC) keyword to represent a fault. In this way, flow along the fault does
not need to be explicitly discretized. The non-adjacent grid cells are virtually connected through transmissibilities,
here provided by the chosen fault model. These transmissibilites also include the effect of the damage zone
permeability. When coupled within an uncertainty quantification or risk assessment framework, the transmissibility
values are provided by sampling a stochastic fault model. Separate tests have shown that this approach to fault flow
gives a comparable answer to a fully discretized fault, but is more efficient.

\textit{Accelerated Uncertainty Propagation}

We develop a new sampling method for uncertainty quantification that tailors the sampling method to the problem at
hand. For CO2 storage, the relationship between expected values of CO2 leakage and input uncertainties is non-
smooth. An adaptive stratified sampling (ADSS) method greatly increases the performance of Monte Carlo
sampling by using information gained during previous samples to guide further model evaluations. The ADSS
method has been validated on various test cases with up to three orders of magnitude speedup compared to brute-
force Monte Carlo [Pettersson & Krumtscheid, 2021].

The above numerical advances can be coupled together into a workflow to quantify the likely leakage rates of faults
under uncertainty. The workflow develops a distribution of effective fault permeability based on the upscaling
methodology. We consider underlying uncertainties in the fine-scale fault core/damage zone model to produce a
probability distribution of effective fault permeability. The ADSS algorithm then generates samples that are
propagated through field-scale simulation via the fault-flow functionality in OPM Flow. A simple example is used to
demonstrate the workflow before being applied to the Smeaheia model.

The value of the approach presented here is that the uncertainty envelope around fault leakage can be quantified
efficiently and effectively using already available functionality in commercial reservoir simulators coupled to an
advanced sampling algorithm. The workflow is independent of the underlying detailed fault model, and therefore
any accepted fault model can be used given the specific setting and available data.
References:


Keywords: CO₂ storage; Fault risk assessment; Vertical fluid migration; Numerical methods; Reservoir simulations; Uncertainty