Evaluating the structural integrity of fault-bound traps for CO$_2$ storage

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Talk Outline

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• Workflow for evaluating structural integrity
• Case Studies
  - Natural CO\textsubscript{2} trap (Fizzy discovery, SNS)
  - Proposed CO\textsubscript{2} storage site (Troll, NSN)
• Conclusions
Introduction

Evaluating the structural integrity of fault-bounded traps for CO₂ storage requires a thorough assessment of the likely sealing / non-sealing behaviour of faults, in particular:

- will the fault act as a barrier, thus permitting CO₂ to accumulate, and if so what might the likely height of the trapped column be before the fault leaks?

- will the increased pressure generated by injection (or by a CO₂ column) trigger fault instability & reactivation, thus leading to loss of CO₂ from the trap?

This presentation will show how the workflow for assessing fault-seal bahaviour in hydrocarbon-water systems can be used to assess structural integrity in proposed storage sites for CO₂.
Modes of seal or leak in a faulted CO₂ storage reservoir

1. **Juxtaposition (across-fault seal)**
   (dominated by fault displacement & stratigraphy)

2. **Fault-rock processes (across-fault seal or leak)**
   (dominated by the capillary and permeability properties of the fault rock)

3. **Reactivation of existing faults (up-dip leakage)**
   (dominated by stress field and fault orientation)
A fault will be sealing to CO$_2$ ...

**IF ...**

Fault places beds with a very high capillary entry pressure (e.g. shales, clay) against the CO$_2$-bearing reservoir.

**OR ...**

Fault-zone deformation processes generate fault rock with a very high capillary entry pressure between two juxtaposed reservoirs.

**AND ...**

Fault has *not* been reactivated.

Workflow to evaluate fault seal:

- Construct a 3D framework model of the fault and reservoir stratigraphy
- Predict subsurface fault-zone processes
- Evaluate if the fault is critically stressed and close to frictional failure

van der Zee & Urai (2005)
Geological model of the subsurface

POOR PRACTICE:
Map with hand-drawn fault traces

BEST PRACTICE:
Three-dimensional faulted framework model

Benefits of a 3D faulted framework model:
- Evaluate the 3D ‘plumbing’
- Assess quality of input data using fault displacement analysis
- Incorporate well data to model reservoir geometry at the fault surfaces
- Apply predictive algorithms in true 3D geological context
The nature of the fault zone varies across the fault surface, depending on which lithotypes are being displaced and by what amount.

Clay smear may be significant over some parts of the fault surface but at greater depths cataclastic gouge may be developed where shale beds are absent.

In terms of fault-seal prediction, it is the **clay content** that is the primary control on seal behavior of faults in mixed clastic sequences.

The standard fault-seal predictor in the oil industry is **Shale Gouge Ratio (SGR)**, which in simple terms can be considered a predictor of upscaled fault-rock composition.

**High SGR** ~ high clay content & clay smears (high seal capacity).

**Low SGR** ~ low clay content & disaggregation zones (low seal capacity).
Global calibration of SGR by across-fault pressure data

Lines represent maximum buoyancy pressure that can be supported at a specific gouge ratio value (seal-failure envelopes) – similar trends to capillary threshold pressures of actual fault rocks.

Empirical equation defining seal-failure envelopes, e.g:

\[ P \text{ (bars)} = 0.175 \times \text{SGR} - 3.5 \]

Assuming that these envelopes represent fault-rock capillary threshold pressure \( P_c \) then potential maximum column height of trapped hydrocarbons (non-wetting phase) is given by:

\[ h_{\text{max}} = \frac{P_c}{(\rho_w - \rho_h)g} \]

(\( \rho_w \) = density water, \( \rho_h \) = density hydrocarbons and \( g \) = acceleration due to gravity)
Computing CO$_2$ fault-seal capacity from SGR

The previous slide gives a calibration relationship for hydrocarbon-water capillary threshold pressure $P_c$ of fault rock, as a function of SGR.

Can we adapt this proven technology in the context of CO$_2$ storage (a different immiscible phase)?

- Default oil-water interfacial tension ca. 30 mN/m$^{-1}$
- Default gas-water interfacial tension ca. 50 mN/m$^{-1}$
  (interfacial tension usually not measured at actual reservoir PT conditions)
- Experimental observations CO$_2$-brine interfacial tension: 28-35 mN/m$^{-1}$
  at pressures >100 bar or ~1km depth (Chalbaud et al 2006)

Therefore, the calibrated SGR analysis for oil-water can be applied directly to a CO$_2$-brine system.
Stress control of Hydraulically-conductive fractures


"..one fundamental criterion for fluid flow along faults is that the fault be critically stressed and close to frictional failure."

Fractures are hydraulically conductive when the ratio of shear stress to normal stress is >0.6, which corresponds to the condition for frictional failure.

Frictioanal failure on weak faults can occur at lower pressures than the “fracture gradient” determined for intact overburden.
Geomechanical Analysis – Key Points

**Stress Field**
- Risk of fault reactivation is assessed with respect to current in-situ stress field
- Stresses on existing fault plane are resolved into normal stress & shear stress
- Higher fluid pressure acts to reduce the applied stresses

**Fault rock mechanical properties**
- Failure envelopes are derived from laboratory testing of intact fault rock
- Faults assumed to be weaker than the intact reservoir rock (*not necessarily true in all cases*)

Various measures of how far the fault is from the failure envelope:

**Slip Tendency**
- \( T_s = \tau / \sigma_n \)
- Higher Ts

**Fracture Stability**
- Fracture Stability (P) is the pore-pressure increase required to shift a fault orientation (A) to failure line.
- The onset of slip is often taken to be at ~0.6.
- (the higher the slip tendency, the higher the risk)
- (the lower pore-pressure required, the higher the risk)
Case Study 1: Natural CO₂ Trap – Fizzy discovery

Southern North Sea gas fields (methane)

‘Fizzy’ (aka Ramsay)
50/26b-6 1995
50/26b-8 1997
348 Bcf GIIP (~10 Bm³)
50% CO₂, 41% CH₄, 9% N₂
GWC 7392 ft (TVDSS)

from Underhill et al (2009)
What is the 3D trap geometry?

3D view looking towards NE
Top Rotliegend TWT surface

The western boundary fault to the Fizzy-Oak horst comprises a linked fault system with a normal sense of offset at Top Rotliegend.

Red = shallow
Purple = deep
Perspective view looking NE, showing Top Rotliegend horizon picks (red).

Rotliegend interval at Fizzy & Oak faults also shown: upthrown (footwall - orange) and downthrown (hangingwall - brown). The Rotliegend (Leman Sandstone) interval was constructed below Top Rotliegend pick by using a constant-thickness isochore based on the interval thickness at 50/26b-6.
Isometric fault-plane diagram showing upthrown (footwall) and downthrown (hangingwall) Rotliegend interval, Fizzy fault.

The Fizzy GWC is close to the top of the Rotliegend self-juxtaposition near the intersection with the Oak Fault. However, the downthrown Rotliegend ramp dips down, away from the fault, so even if this connection is leaky it does not provide a migration pathway out of the upthrown trap.
Isometric fault-plane diagram showing upthrown (footwall) and downthrown (hangingwall) Rotliegend-Zechstein intervals, Fizzy fault.

The *downthrown* (hangingwall) Zechstein interval juxtaposes the entire upthrown Rotliegend reservoir.

**Fizzy accumulation has the Zechstein interval as a side-seal at the fault (juxtaposition seal).**
Case Study 2: Proposed CO$_2$ storage – Troll Field

Statoil’s Mongstad Refinery near Bergen.

Power Plant providing heat and electricity for the refinery and offshore facilities.

Around 2 M tonnes CO$_2$ per year will be produced.

**Where to store the CO$_2$?**

One solution is to store the CO$_2$ in the Troll oil & gas field:

- Large-volume tilted fault blocks.
- Geology well known from exploration and development seismic and well data.
- Additional reservoir layers (Lower Jurassic Johansen Formation) which are not involved in the hydrocarbon trapping.
Major normal faults might potentially provide pathways for the injected CO$_2$ from the deeper Johansen Formation (red) to the shallower Fensfjord & Sognefjord (blue/yellow) hydrocarbon reservoirs.

Therefore, it is necessary to test the structural integrity of the Johansen Formation, particularly to ensure that any injected CO$_2$ does not impact the oil & gas reservoirs. Study commissioned by NPD in 2008.
Based on seismic interpretation of NH0301D07 and NH0502 3D volumes.

Top Sognefjord, Top Fensfjord, Top Brent, Top Cook, Top Johansen and Top Statfjord horizons.

Detailed fault picks built into a 3D fault framework, structural QC to check fault geometries and displacement patterns.

Detailed lithological data from wireline logs of 12 appraisal wells within the field.

Proposed CO2 injection point lies to the south of study area, with migration northward into TWGP.

TWOP = Troll West Oil province
TWGP = Troll West Gas Province
TE = Troll East

Red = shallow
Purple = deep
Johansen Sand juxtapositions against Sogne. & Fens.

At the faults, colours show downthrown Sognefjord & Fensjord (blue & cyan) and upthrown Johansen sand (red).

Where the red stripe is separate from the blue/cyan, there is no juxtaposition.

Where the red stripe is covered up by the blue/cyan stripes on the same fault (arrowed), upthrown Johansen is juxtaposed against Sognefjord/Fensfjord.

TWOP = Troll West Oil province; TWGP = Troll West Gas Province; TE = Troll East
Synopsis of capillary fault-seal results

Shale Gouge Ratio (%) displayed on fault surfaces; red = clay smear

CO₂ column height derived from SGR-pressure calibration. At critical faults, maximum trappable CO₂ column is ca. 150m

Interfacial tension: ca. 28 mN m⁻¹
CO₂ density: 0.67 g cm⁻³
Water density: 1.035 g cm⁻³
To north in Q35 (Vega) and west in Q30 (Oseberg), a number of A-quality data-points indicate a present day **Strike-slip** regime with \( Sh_{\text{max}} \) oriented \(~081\).

In a strike-slip regime, \( Sh_{\text{min}} < S_v < Sh_{\text{max}} \).

\( S_v \) is obtained from the weight of the overburden.

\( Sh_{\text{min}} \) is obtained from fracture closure stress (31/6-A-21).

\( Sh_{\text{max}} \) is poorly constrained. Wiprut & Zoback (2002) report that \( Sh_{\text{max}} \) is around 1.3-1.4 \( x \) \( S_v \) in many northern North Sea fields. Frictional strength limits \( S_{1\text{eff}}/S_{3\text{eff}} \) to <3.1.
Stress Field – strike-slip regime

High-case Shmax assumed – faults presently critically stressed.

Av. depth Johansen Formation

Slip tendency of ~0.6 approximates shear strength of rock

Slip Tendency = Shear stress Normal stress

All possible fault orientations colour-coded for slip tendency

Weakest planes are vertical, trending NE and ESE.
Geomechanical attributes – proximity to failure

**Slip Tendency** (ratio normal to shear stress)

Slip Tendency on steep EW faults is nearer to failure

**Fracture Stability** (pore-pressure increase required to trigger reactivation)

Pore pressure increase converted to equivalent CO₂ column height

(Max. CO₂ column height (150m) from SGR fault-seal analysis)

(.CO₂ density: 0.67 g cm⁻³; water density: 1.035 g cm⁻³)
Conclusions

• The structural integrity of CO₂ traps can be evaluated using workflows and predictive algorithms originally developed for prediction of capillary seal of hydrocarbons, using appropriate CO₂ fluid properties.

• Three-dimensional faulted-framework models are an essential first step in assessing the structural integrity of a proposed CO₂ storage trap.

• Fault-plane diagrams are used to investigate the juxtaposition geometry of reservoir/non-reservoir intervals at the fault surface. Predictive algorithms for fault-sealing or stress-driven leakage enable a better understanding of the possible fault behaviour to be derived.