Evaluating the structural integrity of fault-bound traps for CO_2 storage

Graham Yielding & Peter Bretan
Badley Geoscience Ltd

Talk Outline

- Introduction
- Workflow for evaluating structural integrity
- Case Studies
  - Natural CO_2 trap (Fizzy discovery, SNS)
  - Proposed CO_2 storage site (Troll, NSN)
- Conclusions

Introduction

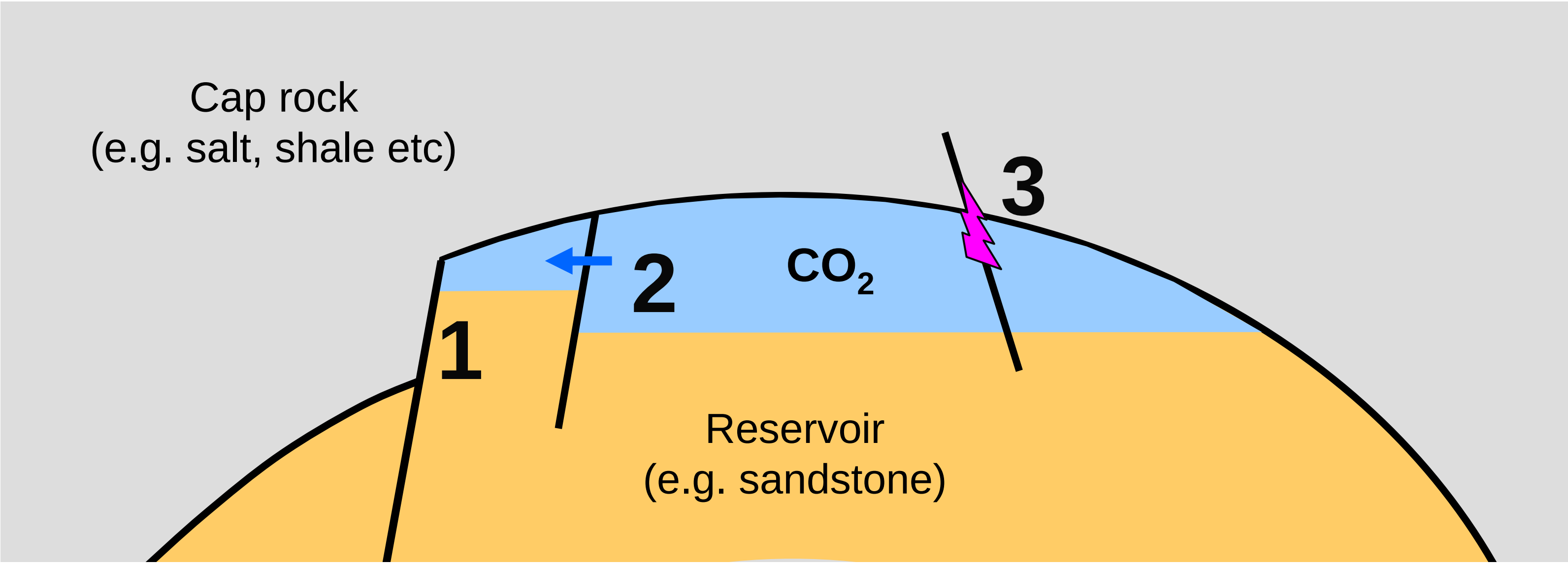
Evaluating the structural integrity of fault-bounded traps for CO_2 storage requires a thorough assessment of the likely sealing / non-sealing behaviour of faults, in particular:

- will the fault act as a barrier, thus permitting CO_2 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 CO_2 column) trigger fault instability & reactivation, thus leading to loss of CO_2 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 CO_2.

Modes of seal or leak in a faulted CO_2 storage reservoir



<u>1. Juxtaposition (across-fault seal)</u>

(dominated by fault displacement & stratigraphy)

<u>2. Fault-rock processes (across-fault seal or leak)</u>

(dominated by the capillary and permeability properties of the fault rock)

<u>3. Reactivation of existing faults (up-dip leakage)</u>

(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 ...

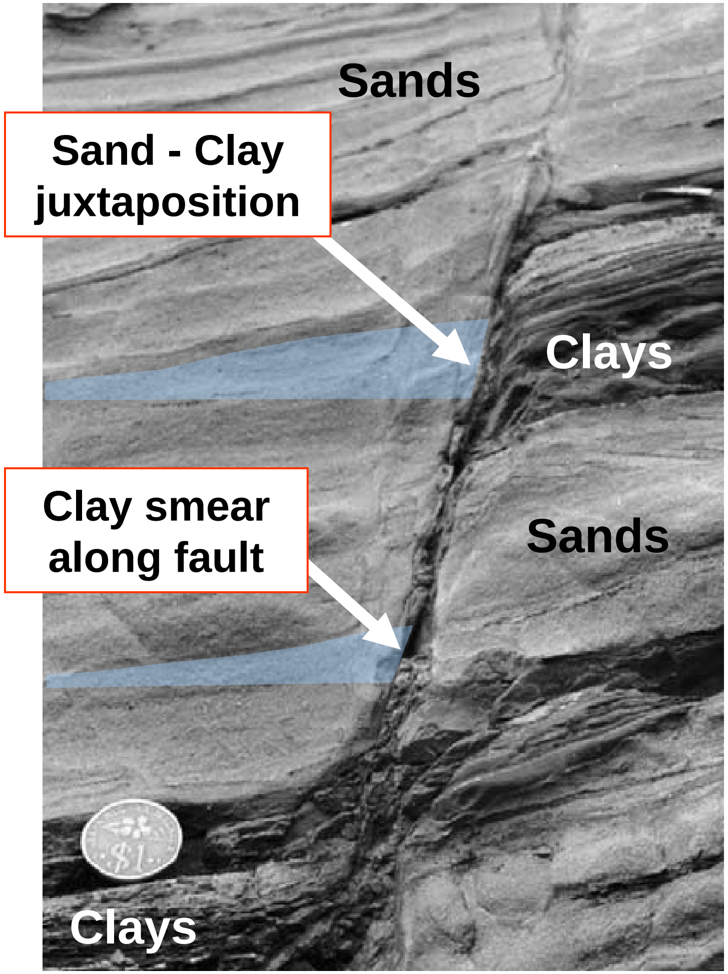
Fault-zone deformation processes generate fault rock with a very high capillary entry pressure between two juxtaposed reservoirs.

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

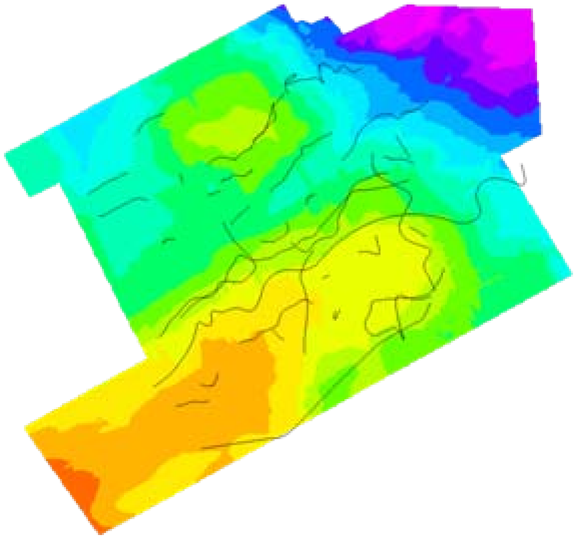


van der Zee & Urai (2005)

Geological model of the subsurface

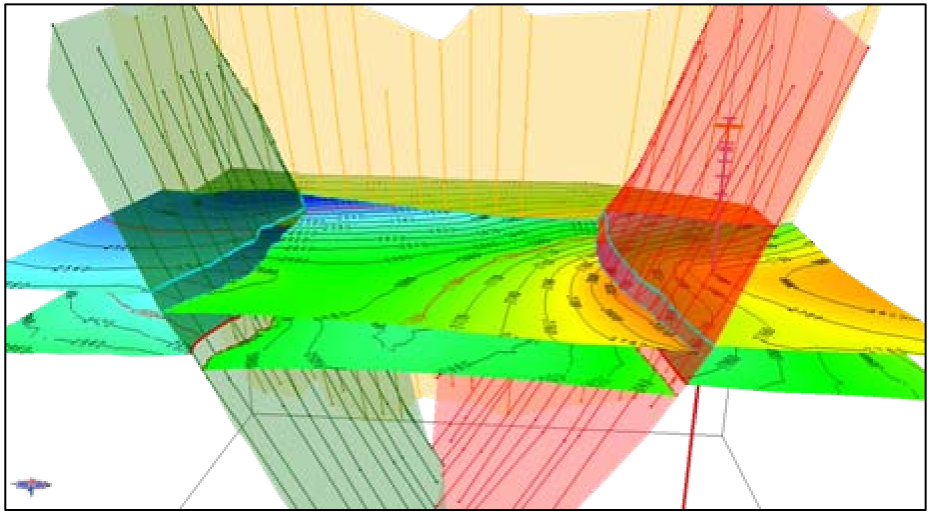
POOR PRACTICE:

Map with hand-drawn fault traces



BEST PRACTICE:

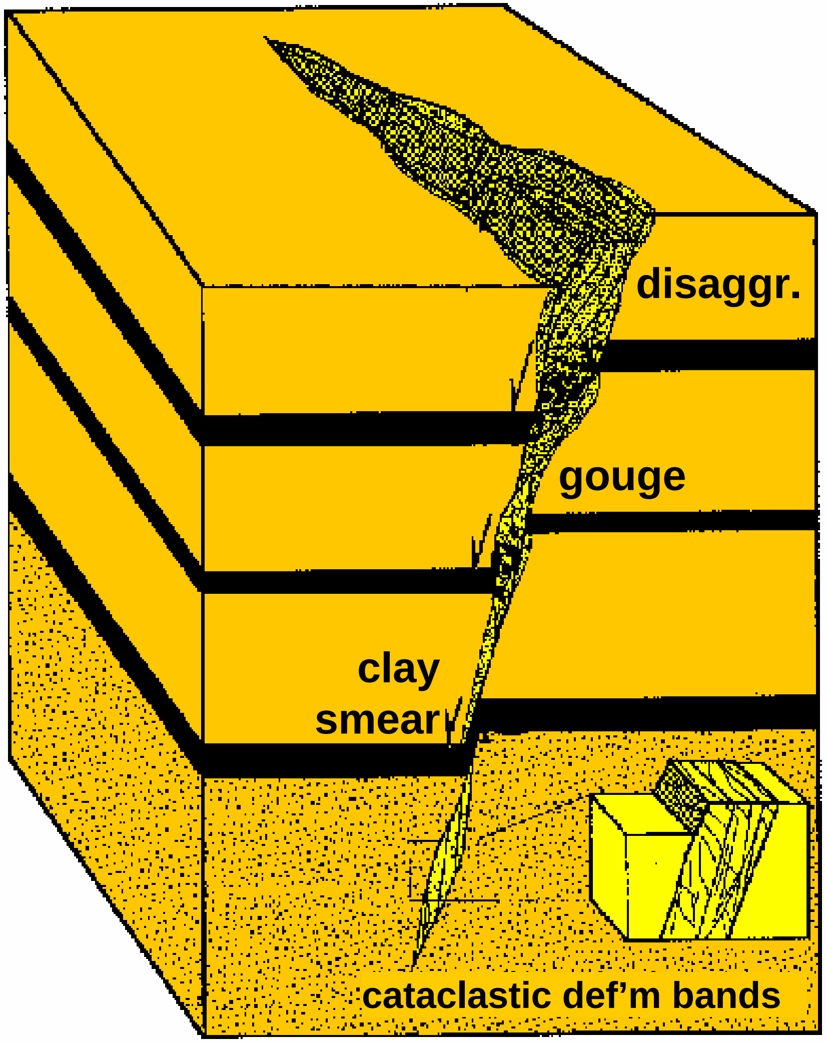
Three-dimensional faulted framework model



<u>Benefits of a 3D faulted framework model:</u>

- 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

Predicting fault-rock properties in the subsurface



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.

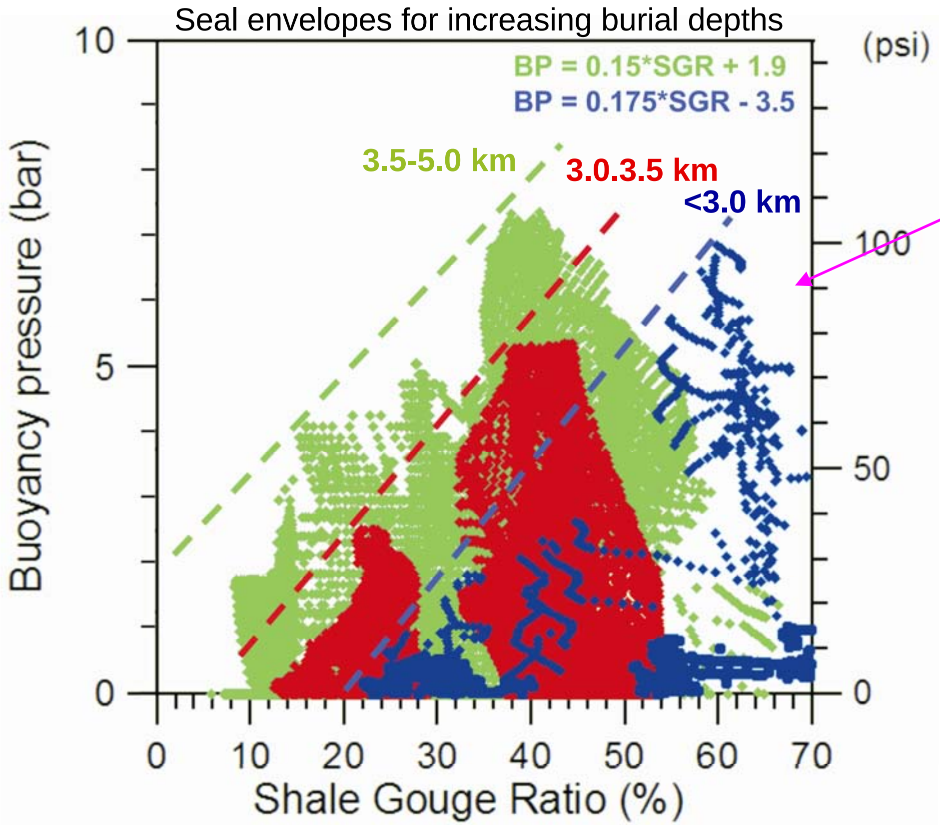
In terms of fault-seal prediction, it is the **clay content** that is the primary control on seal behavior of faults in mixed clastic sequences.

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.

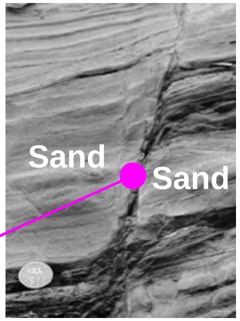
High SGR ~ high clay content & clay smears (high seal capacity).

Low SGR ~ low clay content & disaggregation zones (low seal capacity).

Global calibration of SGR by across-fault pressure data



From Yielding et al (2010)



Data from **sand-on-sand** reservoir juxtaposition. Plotting many datasets onto one diagram establishes a general trend of increasing SGR value supporting increasing hydrocarbon buoyancy pressure.

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:

$$\mathbf{P\ (bars) = 0.175*SGR - 3.5}$$

Assuming that these envelopes represent fault-rock capillary threshold pressure $\mathbf{P_c}$ then potential maximum column height of trapped hydrocarbons (non-wetting phase) is given by: $h_{max} = P_c / (\rho_w - \rho_h)g$

(ρ_w = density water, ρ_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)?

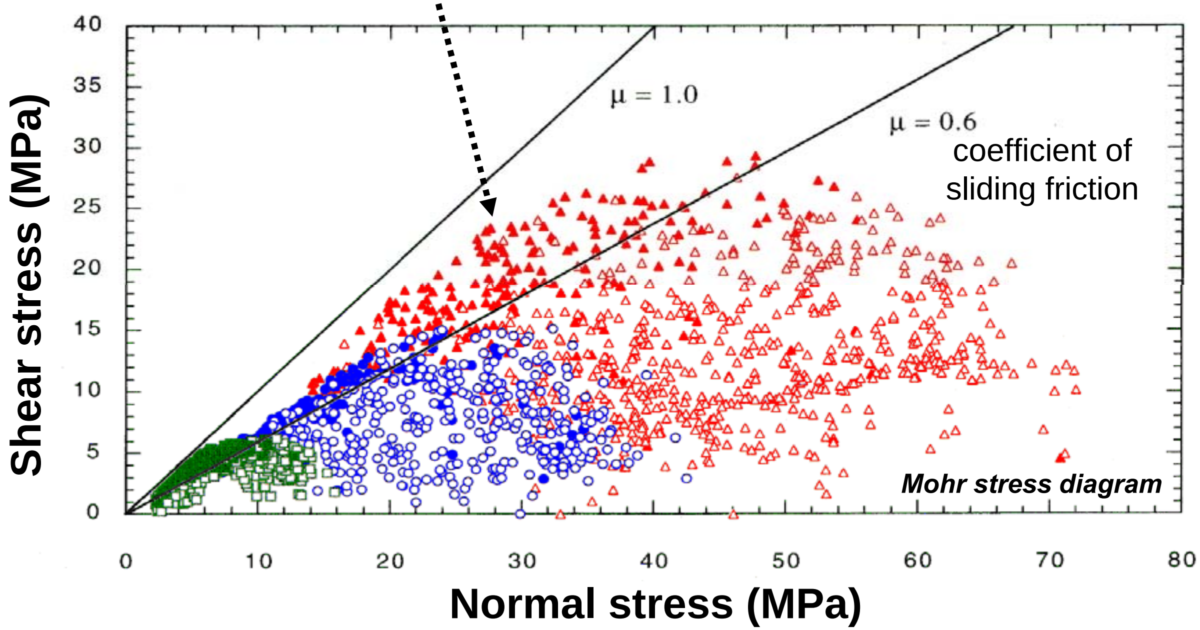
- Default oil-water interfacial tension ca. **30 mN/m^{-1}**
- Default gas-water interfacial tension ca. **50 mN/m^{-1}**

  (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

Hydraulically-conductive fractures = filled symbols



A Mohr stress diagram plotting normal and shear stress on logged fractures in three basement wells (different colours).

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

Barton et al 1995, Zoback et al 1996: studies of fractured crystalline basement.

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

Frictional failure on weak faults can occur at lower pressures than the "fracture gradient" determined for intact overburden.

Geomechanical Analysis – Key Points

Stress Field

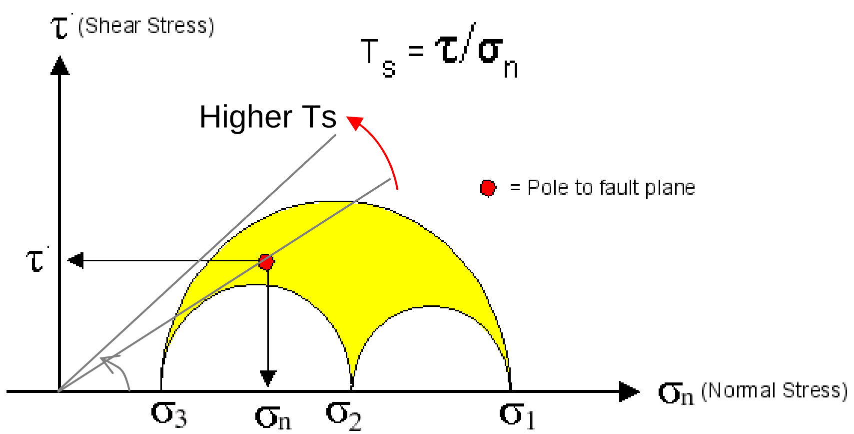
- Risk of fault reactivation is assessed with respect to current in-situ stress field
- Stresses on existing fault plane are resolved into normal stress & shear stress
- Higher fluid pressure acts to <u>reduce</u> the applied stresses

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*)

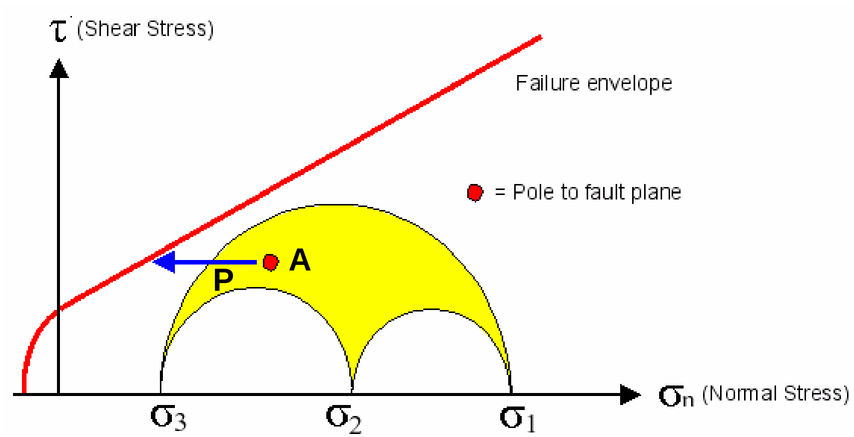
Various measures of how far the fault is from the failure envelope:

<u>Slip Tendency</u>



Slip Tendency is the ratio of shear to normal stress. The onset of slip is often taken to be at ~0.6. (the **higher** the slip tendency, the **higher** the risk)

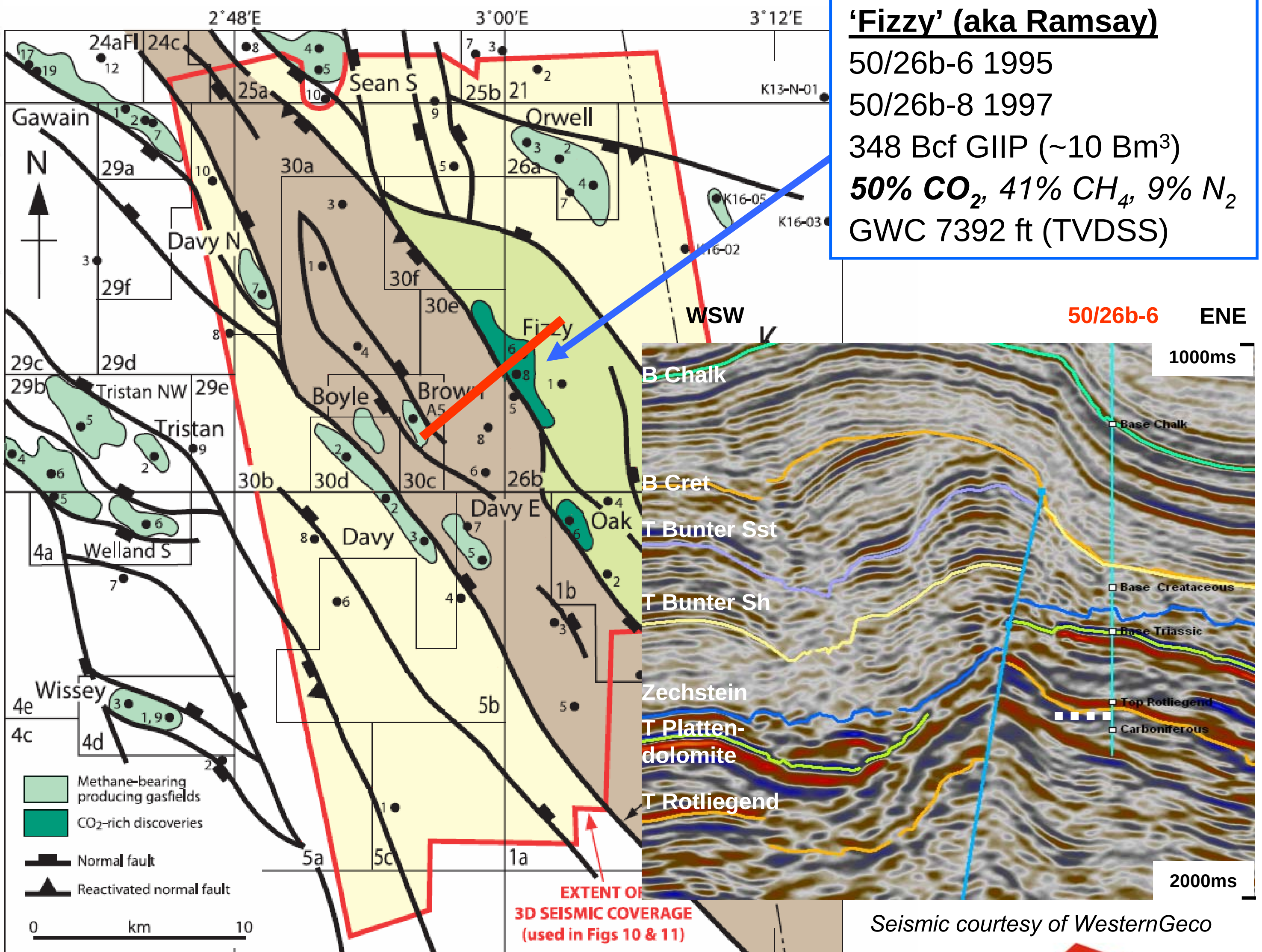
<u>Fracture Stability</u>



Fracture Stability (**P**) is the pore-pressure <u>increase</u> required to shift a fault orientation (**A**) to failure line. (the **lower** pore-pressure required, the **higher** the risk)

Case Study 1: Natural CO_2 Trap – Fizzy discovery

Southern North Sea gas fields (methane)



from Underhill et al (2009)

Seismic courtesy of WesternGeco

'Fizzy' (aka Ramsay)

50/26b-6 1995

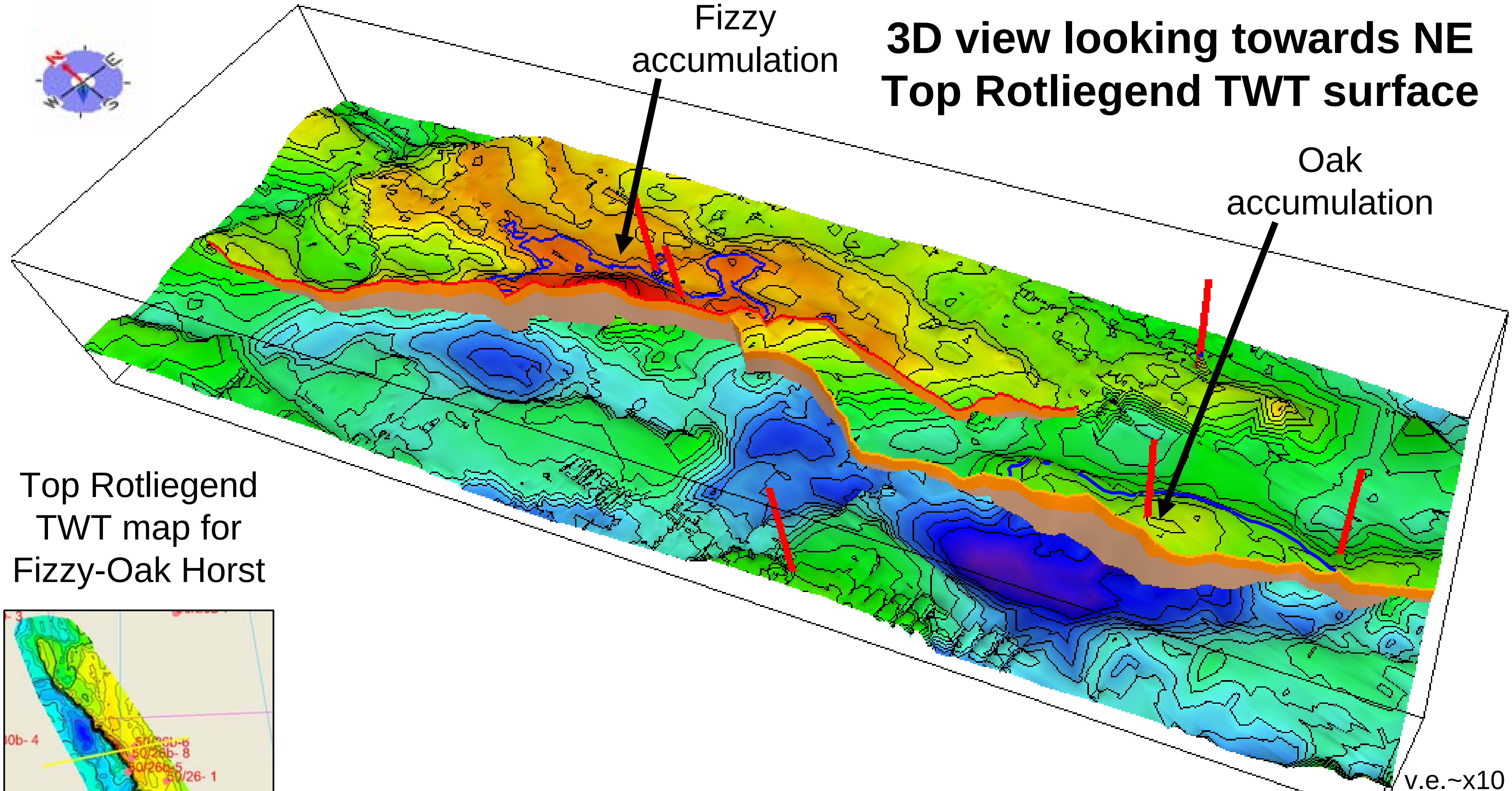
50/26b-8 1997

348 Bcf GIIP (~10 Bm^3)

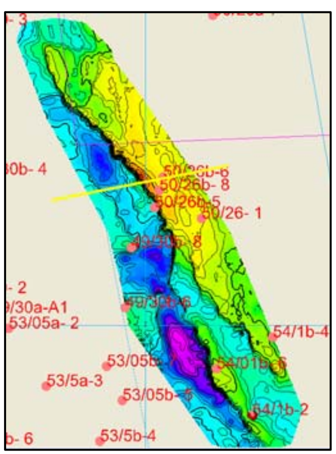
***50% CO_2**, 41% CH_4, 9% N_2*

GWC 7392 ft (TVDSS)

What is the 3D trap geometry?

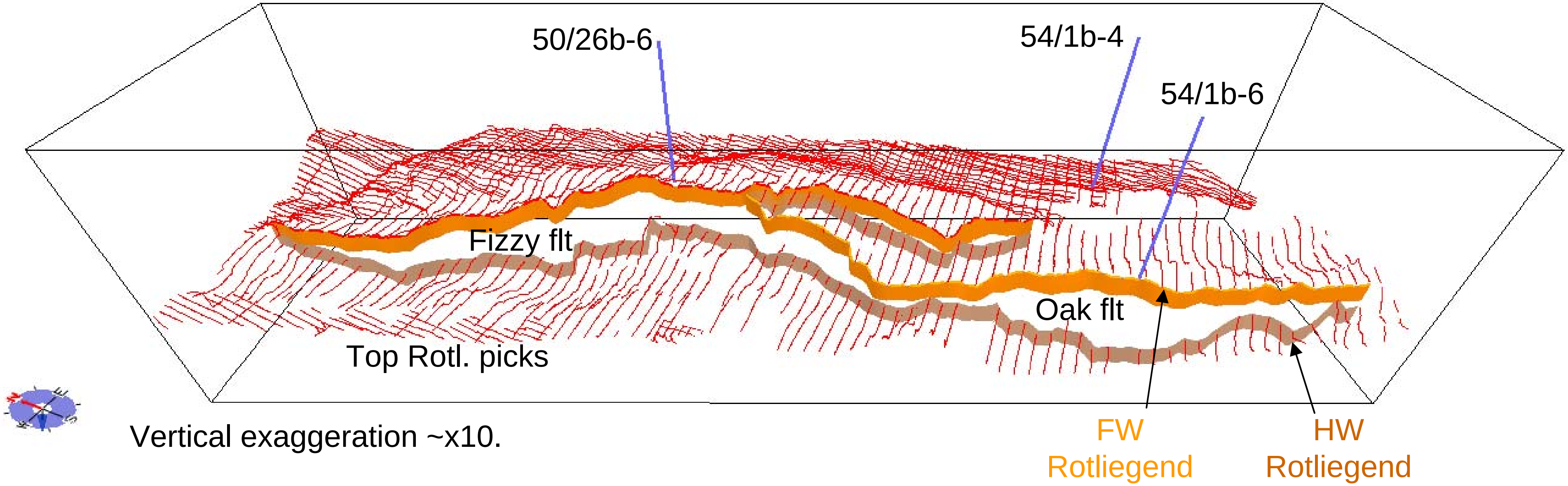


Top Rotliegend TWT map for Fizzy-Oak Horst



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

Fault-plane diagram – Rotliegend interval

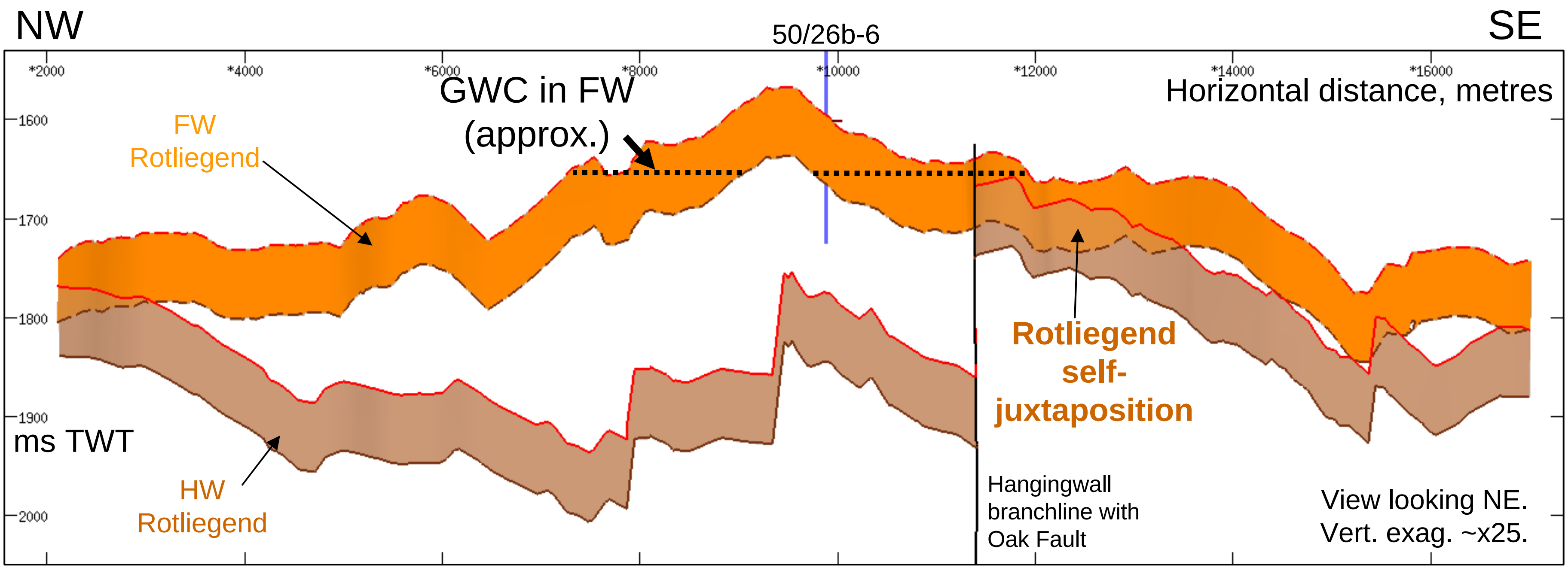


Vertical exaggeration ~x10.

Perspective view looking NE, showing Top Rotliegend horizon picks (red).

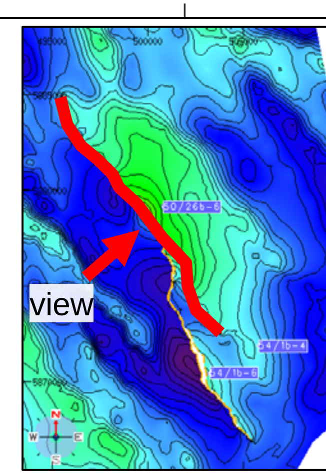
Rotliegend interval at Fizzy & Oak faults also shown: upthrown (footwall - orange) and downthrown (hangingwall - brown). The Rotliegend (Leman Sandstone) interval was constructed below Top Rotliegend pick by using a constant-thickness isochore based on the interval thickness at 50/26b-6.

Fault-plane (Allan) diagram – Fizzy Fault

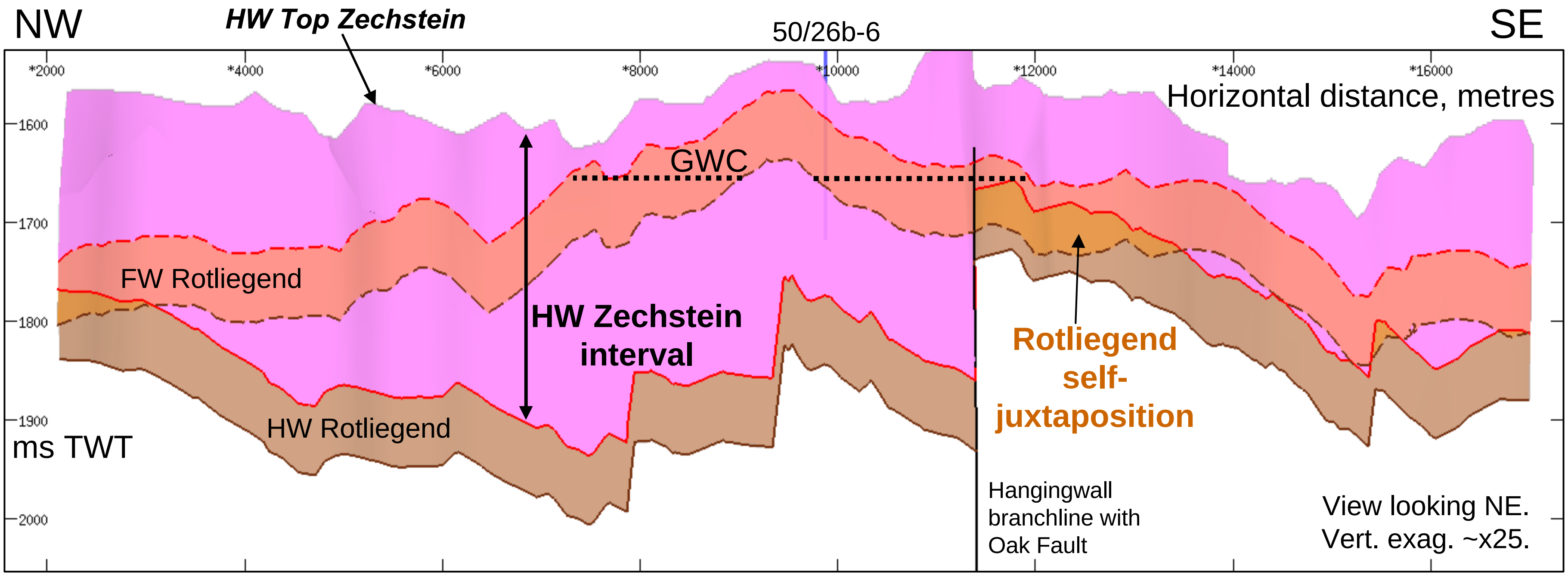


Isometric fault-plane diagram showing upthrown (footwall) and downthrown (hangingwall) Rotliegend interval, Fizzy fault.

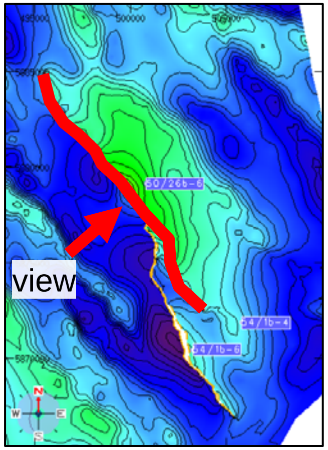
The Fizzy GWC is close to the top of the Rotliegend self-juxtaposition near the intersection with the Oak Fault. However, the downthrown Rotliegend ramp dips **down, away** from the fault, so even if this connection is leaky it does not provide a migration pathway out of the upthrown trap.



Fault-plane diagram – Fizzy Fault



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).

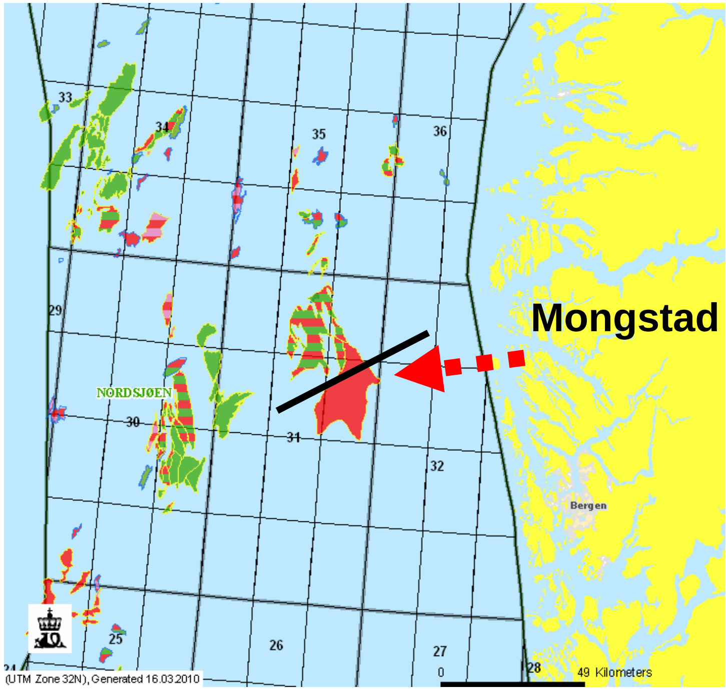
Case Study 2: Proposed CO_2 storage – Troll Field

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?

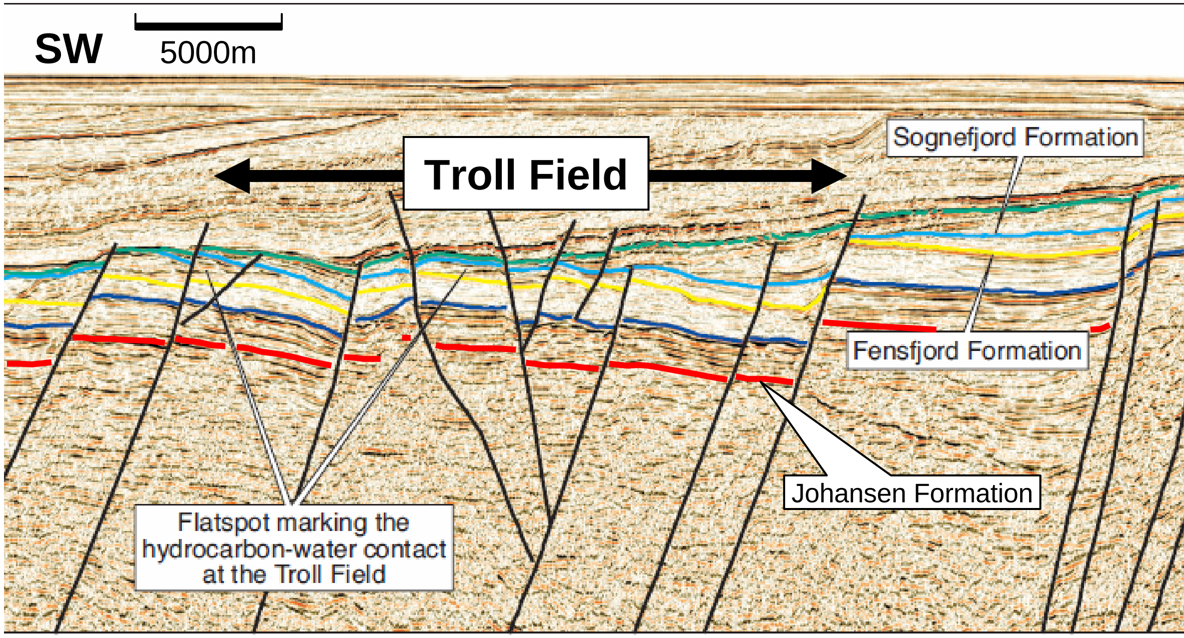


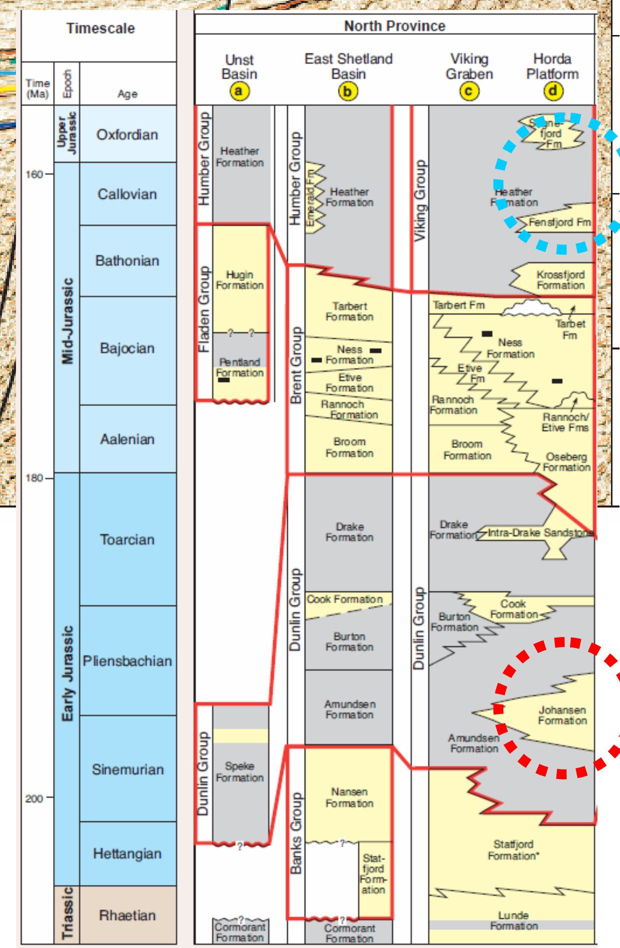
One solution is to store the CO_2 in the Troll oil & gas field:

- 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.

Troll Field structure & stratigraphy

(Fraser et al 2002)



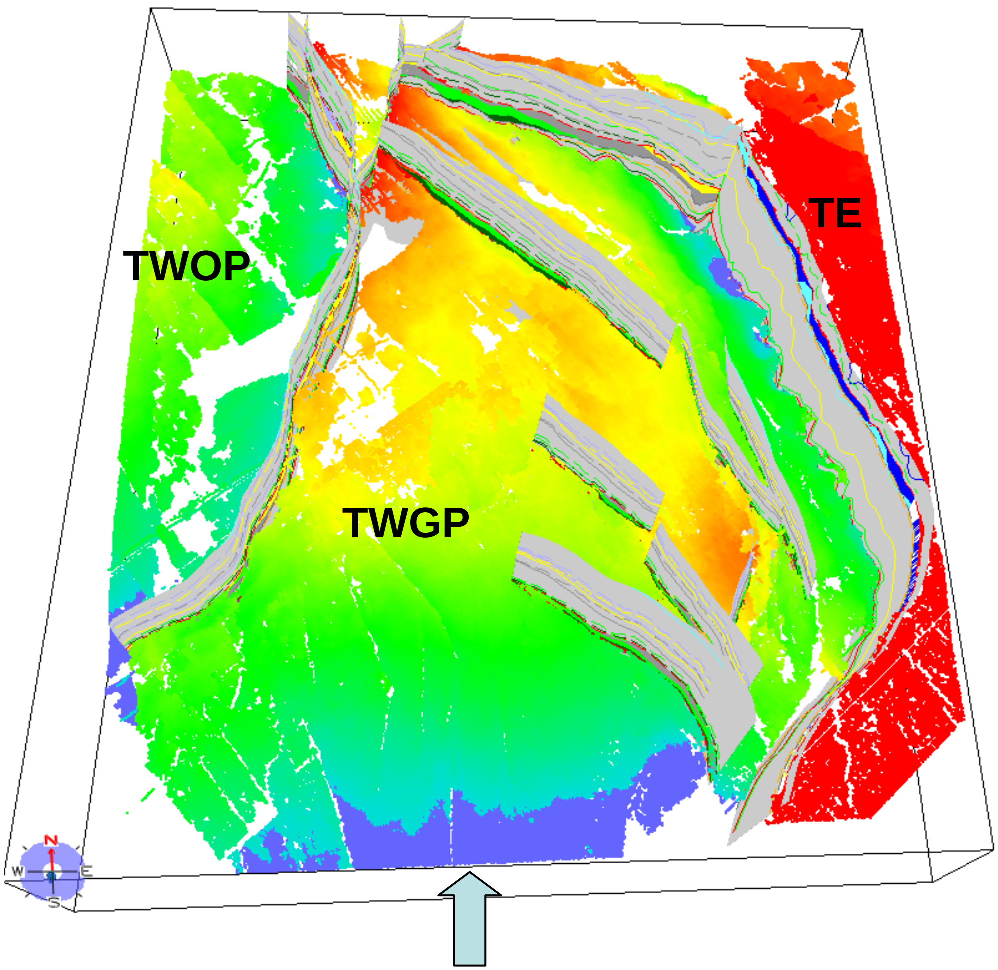


Major normal faults might potentially provide pathways for the injected CO_2 from the deeper Johansen Formation (red) to the shallower Fensfjord & Sognefjord (blue/yellow) hydrocarbon reservoirs.

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.

3D model build in TrapTester software

Top Johansen Formation
(3D view, looking north)



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

Based on seismic interpretation of NH0301D07 and NH0502 3D volumes.

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

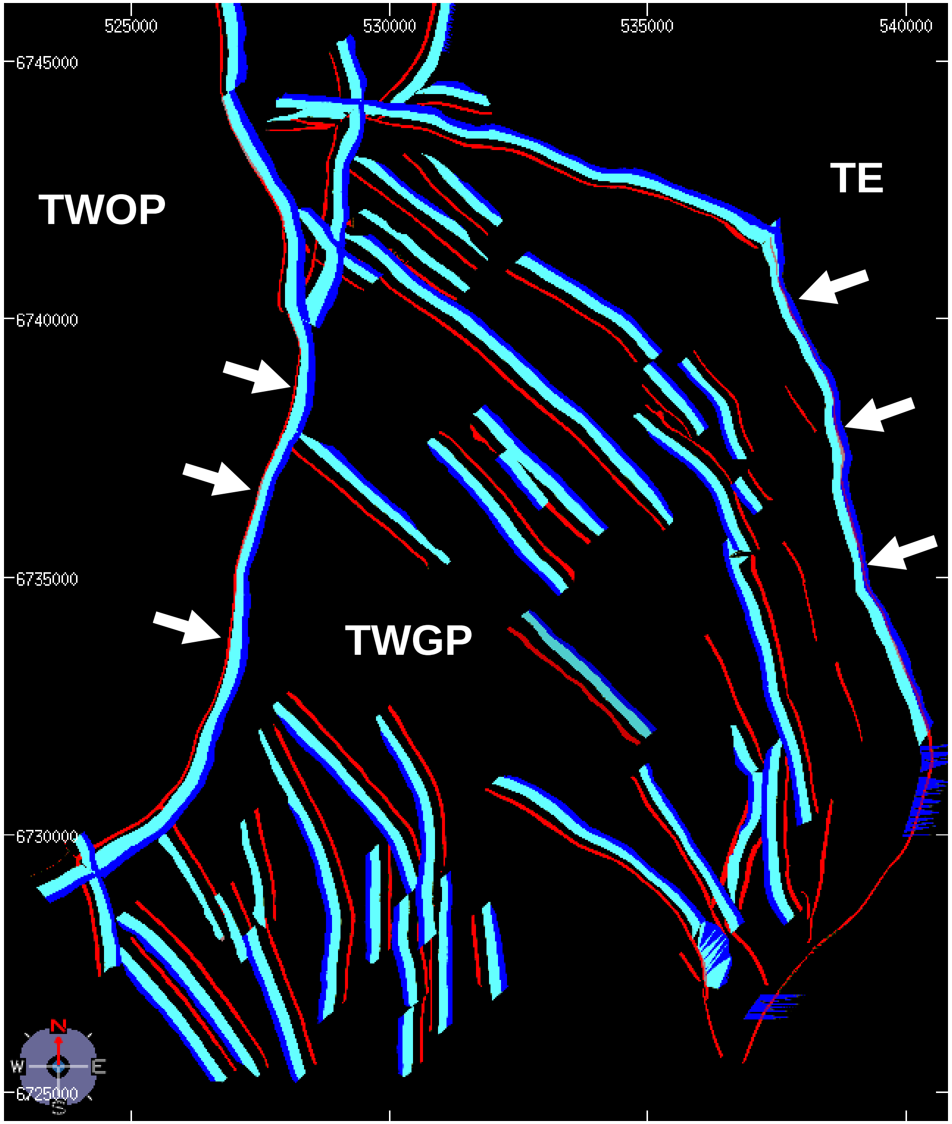
Detailed fault picks built into a 3D fault framework, structural QC to check fault geometries and displacement patterns.

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

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

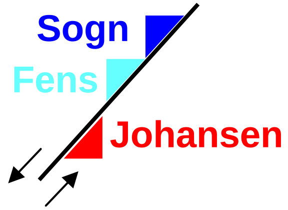
Red = shallow
Purple = deep

Johansen Sand juxtapositions against Sogne. & Fens.



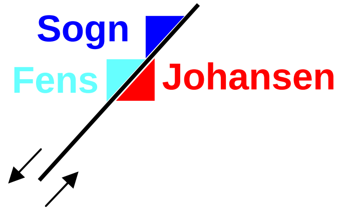
At the faults, colours show downthrown Sognefjord & Fensjord (blue & cyan) and upthrown Johansen sand (red).

Cross-section at fault:



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

Cross-section at fault:

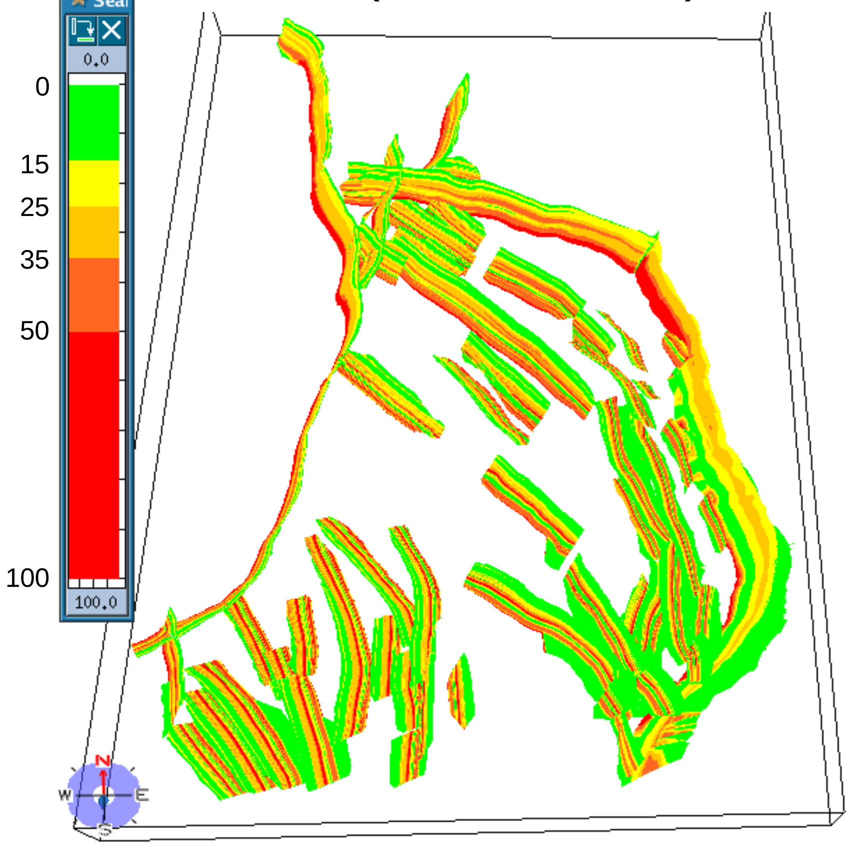


Where the red stripe is covered up by the blue/cyan stripes on the same fault (**arrowed**), upthrown Johansen is juxtaposed against Sognefjord/Fensfjord.

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

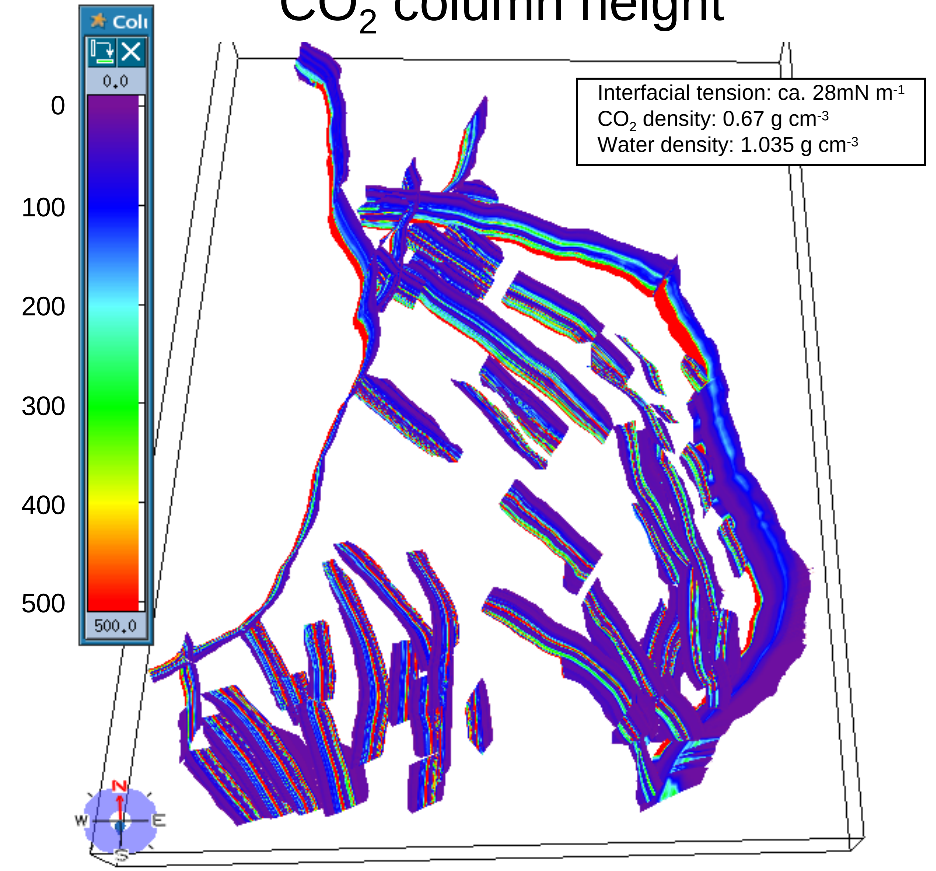
Synopsis of capillary fault-seal results

SGR (seal attribute)



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

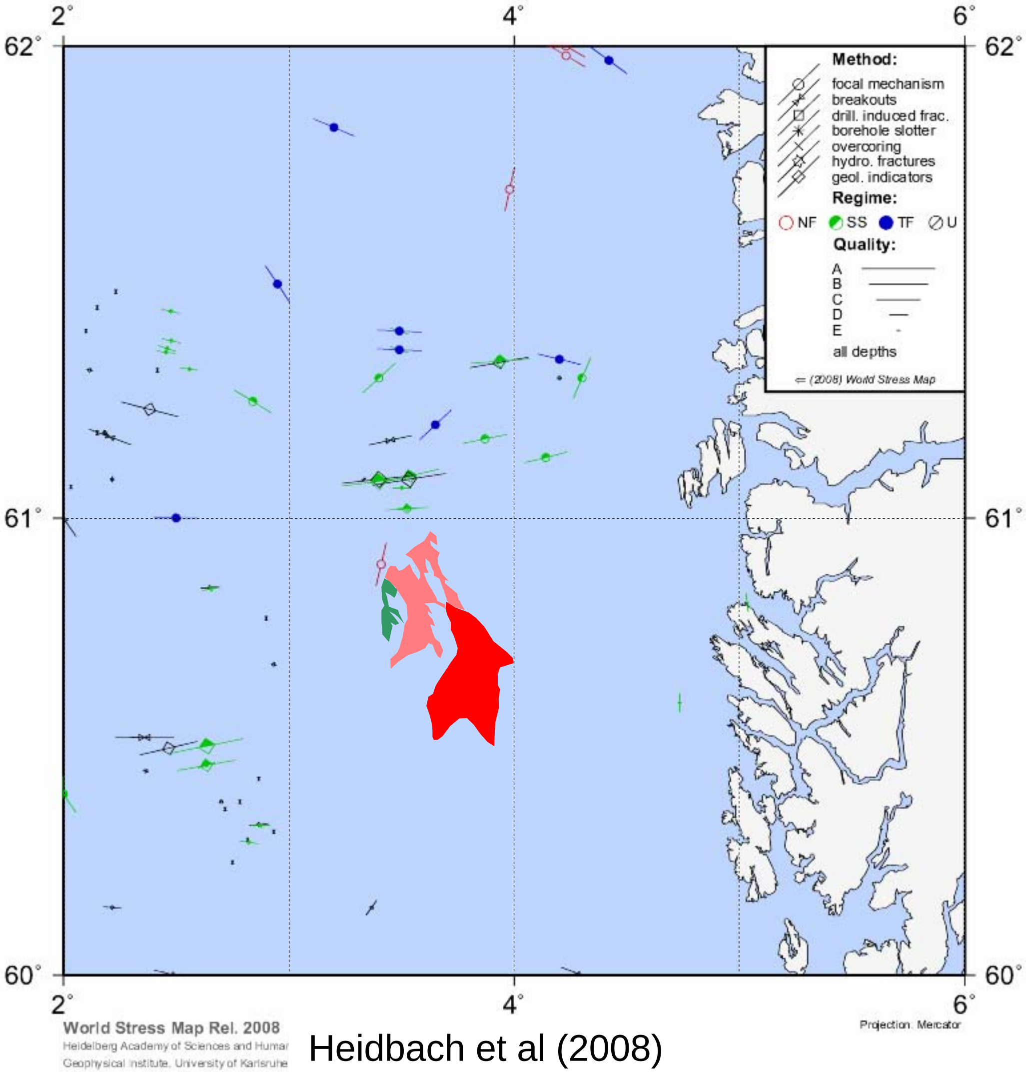
CO_2 column height



CO_2 column height derived from SGR-pressure calibration. ***At critical faults, maximum trappable CO_2 column is ca. 150m***

Badleys

Stress data for Troll area



Heidbach et al (2008)

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 Shmax oriented ~081.

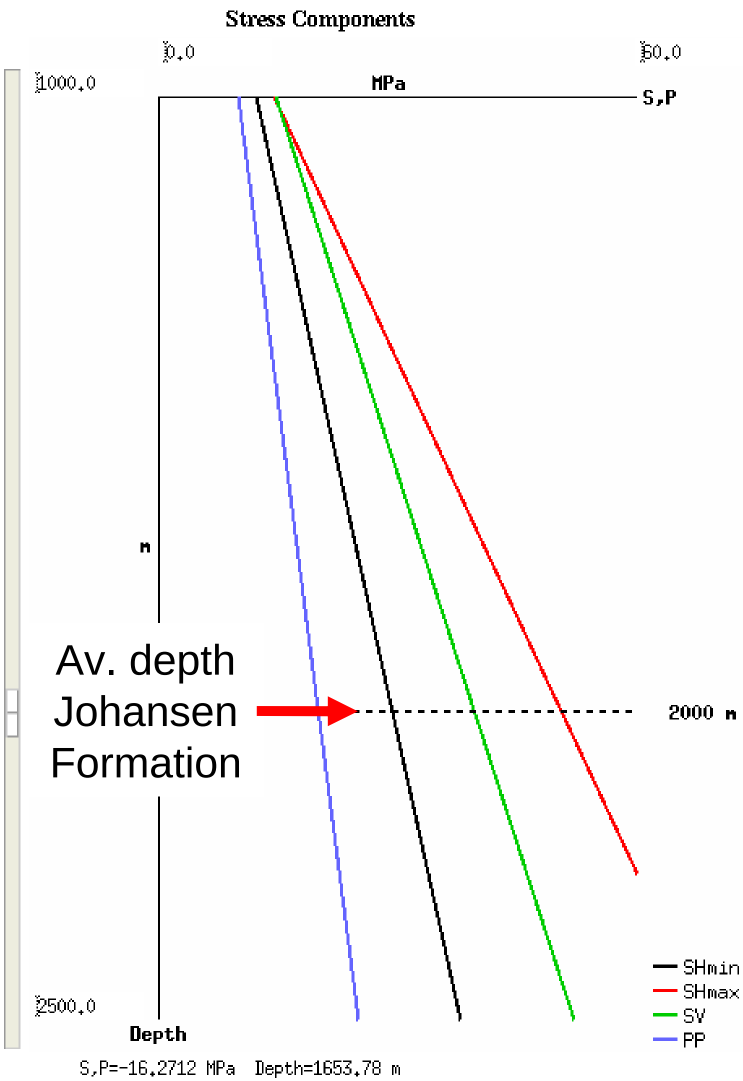
In a strike-slip regime, Shmin<Sv<Shmax.

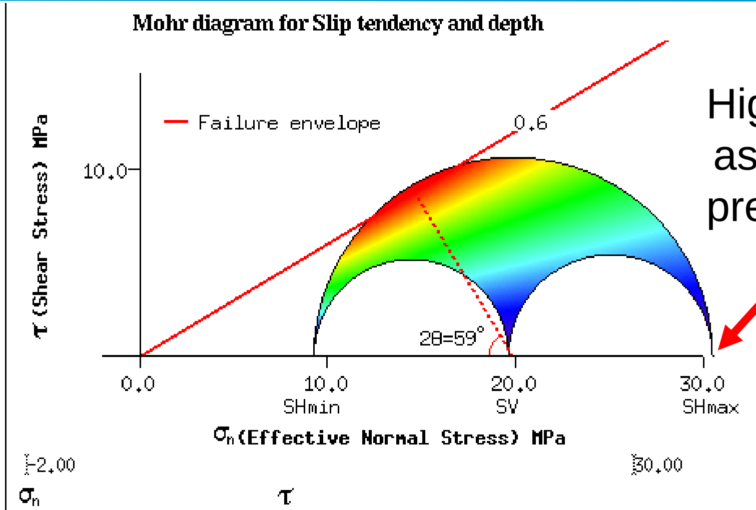
Sv is obtained from the weight of the overburden.

Shmin is obtained from fracture closure stress (31/6-A-21).

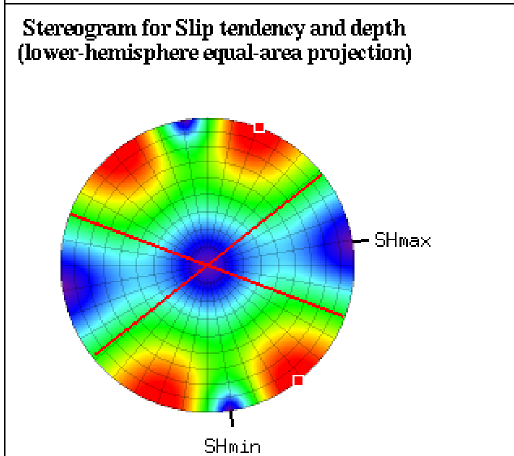
Shmax is poorly constrained. Wiprut & Zoback (2002) report that Shmax is around 1.3-1.4 x Sv in many northern North Sea fields. Frictional strength limits $S1_{eff}/S3_{eff}$ to <3.1.

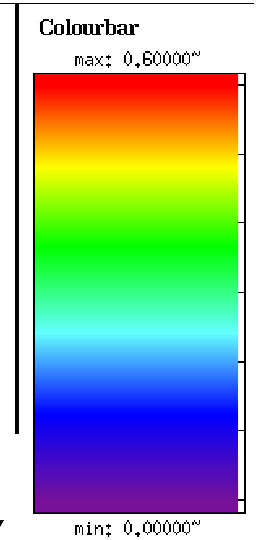
Stress Field – strike-slip regime





High-case Shmax assumed – faults presently critically stressed.





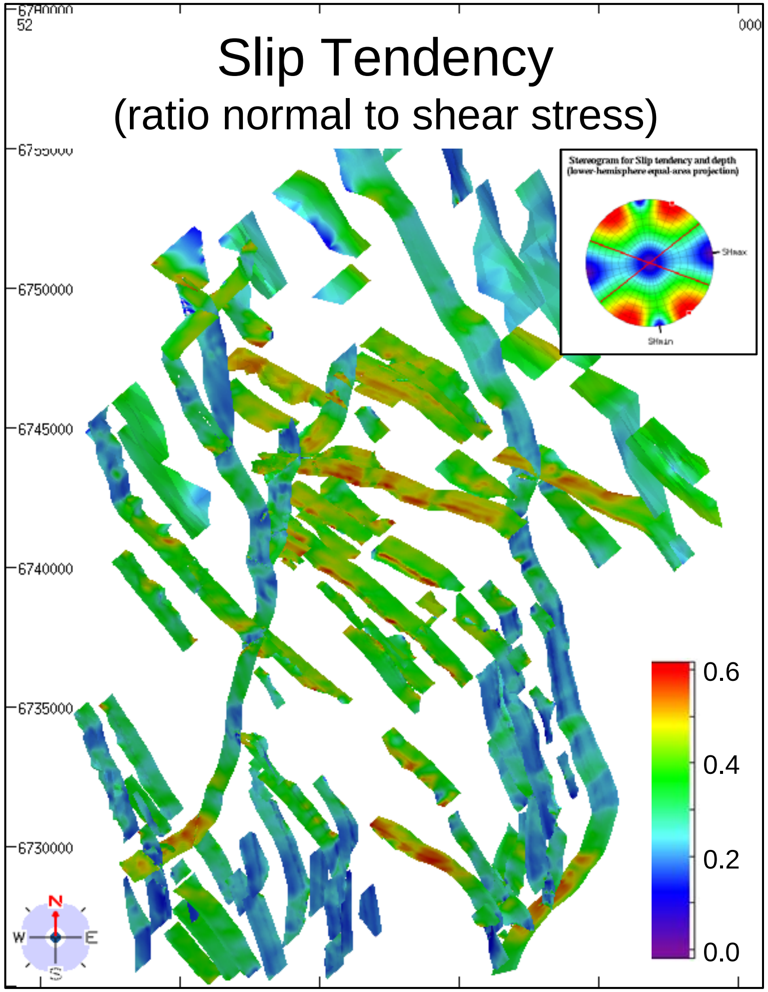
Slip tendency of **~0.6** approximates shear strength of rock

$$\textbf{Slip Tendency} = \frac{\textbf{Shear stress}}{\textbf{Normal stress}}$$

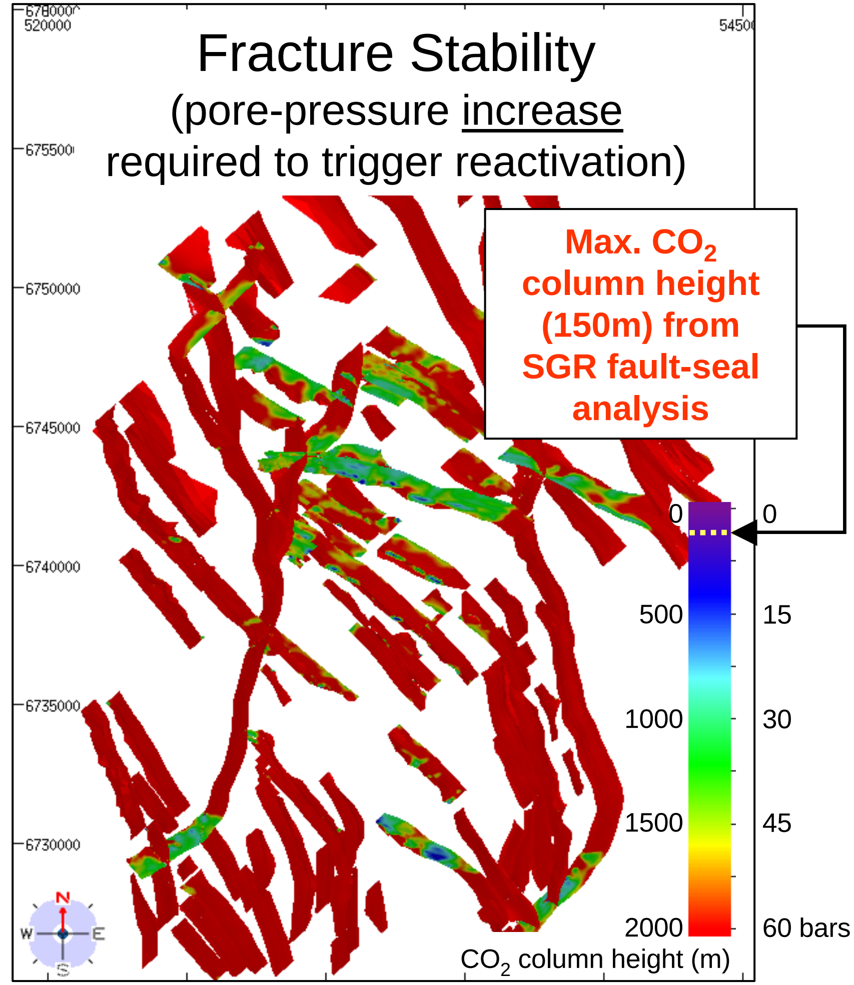
All possible fault orientations colour-coded for slip tendency

Weakest planes are vertical, trending NE and ESE.

Geomechanical attributes – proximity to failure



Slip Tendency on steep EW faults is nearer to failure



Pore pressure increase converted to equivalent CO_2 column height
(CO_2 density: 0.67 g cm^{-3}; water density: 1.035g cm^{-3})

Conclusions

- The structural integrity of CO_2 traps can be evaluated using workflows and predictive algorithms originally developed for prediction of capillary seal of hydrocarbons, using appropriate CO_2 fluid properties.
- Three-dimensional faulted-framework models are an essential first step in assessing the structural integrity of a proposed CO_2 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.