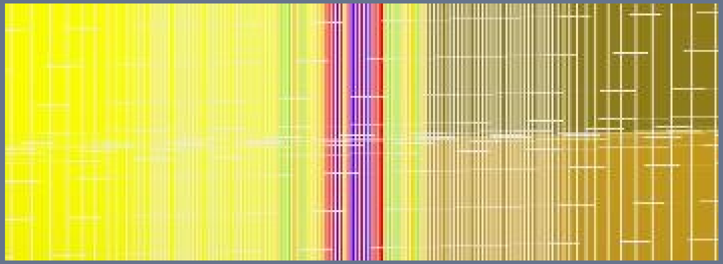
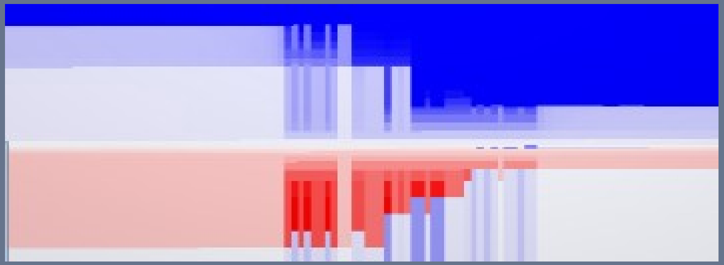
# Overcoming under-forecasting

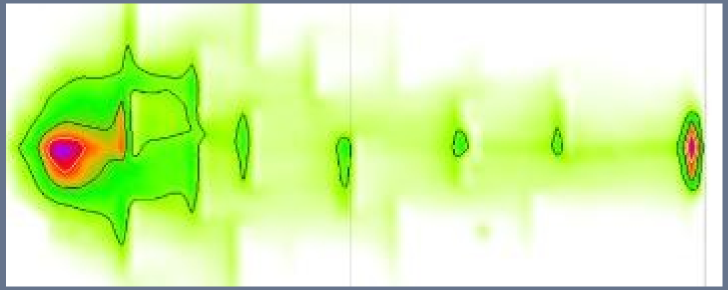
*Incremental storage through cumulative residence*

*Mark Bentley, Ed Stephens*
*TRACS & Heriot-Watt University*
*Michael Welch, DTU*

Danish CCS May 2026







# One word …

# Residence

*Specifically …*

*Mapping cumulative residence to quantify the impact of structural heterogeneity on incremental storage calculations*

# How sensitive is CCS to heterogeneity?

Critical order of magnitude perm contrasts – ‘Flora’s rule’

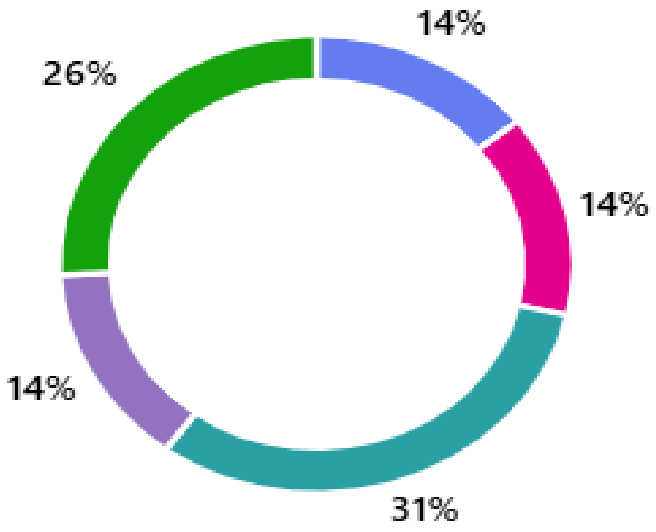
| | | | | |
|---|---|---|---|---|
| Critical permeability contrast | 3 orders | 2 orders | 1 order | |
| Fluid fill | dry gas | wet gas | light oil | heavy oil |
| Production mechanism | depletion (no aquifer) | depletion (with aquifer) | water injection | gas/steam injection |

So … where does CCS fit on this spectrum?

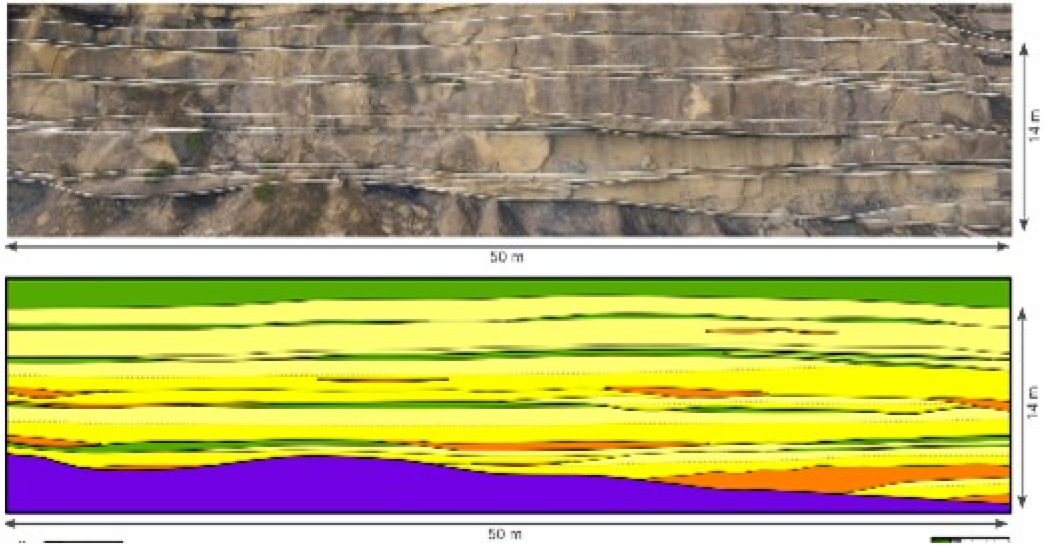
# Sensitivity to permeability heterogeneity (orders of magnitude)

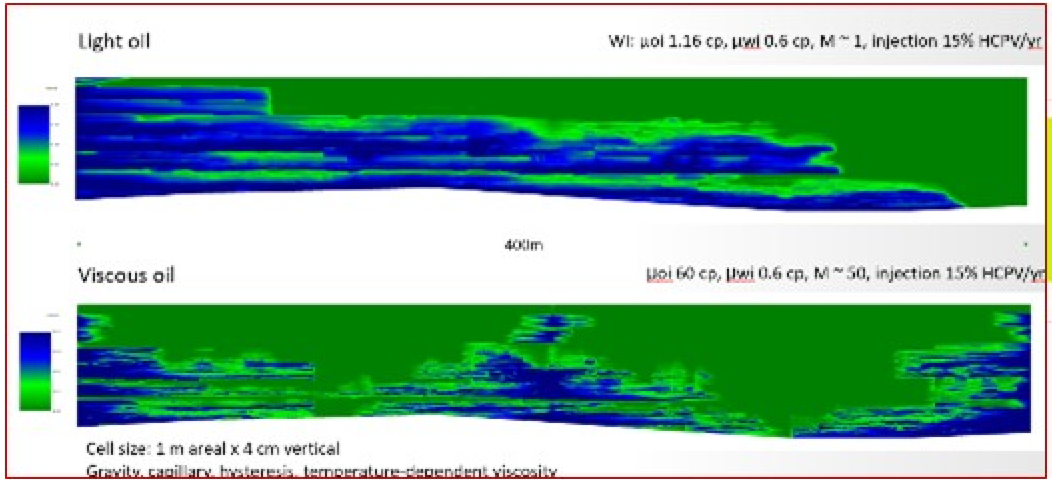
1. Sensitivity to permeability heterogeneity (orders of magnitude) (0 poeng)

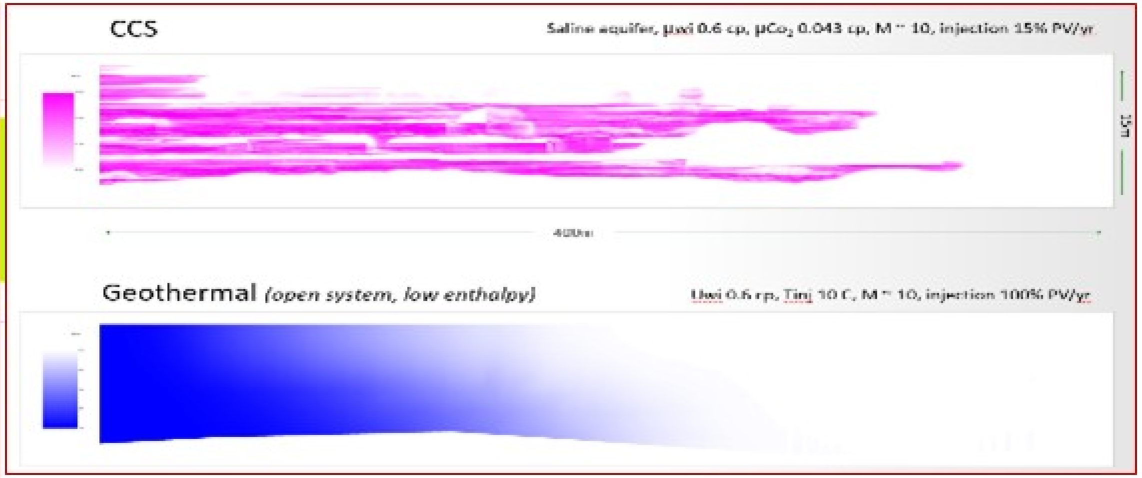
| | |
|---|---|
| A - Greater than 3 orders | 5 |
| B - 3 orders | 5 |
| C - 2 orders | 11 |
| D - 1 order | 5 |
| E - Less than 1 order | 9 |



# Fluid sensitivity to heterogeneity



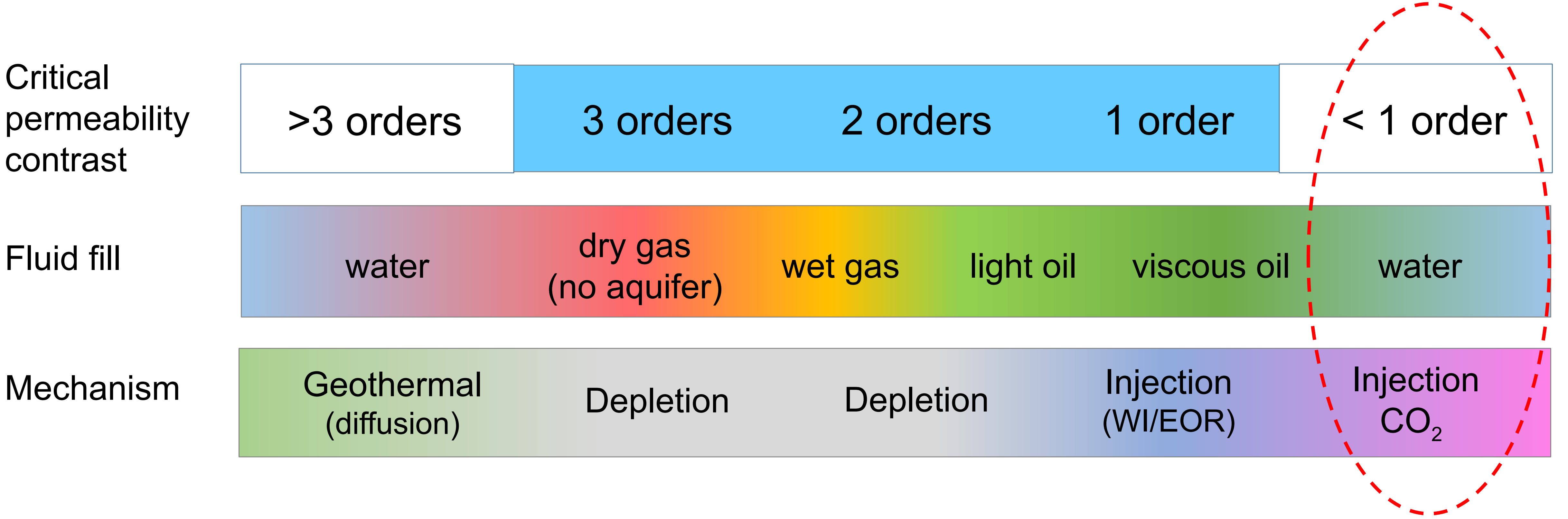




*Bentley & Stephens, 2025*

# How sensitive is CCS to reservoir heterogeneity?

Critical order of magnitude perm contrasts – “Flora plus”

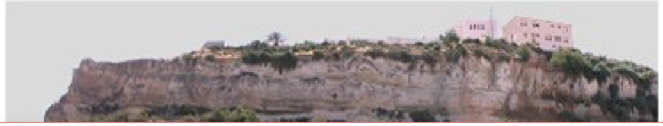



*Bentley & Stephens, 2025*

*for CCS*: highly sensitive

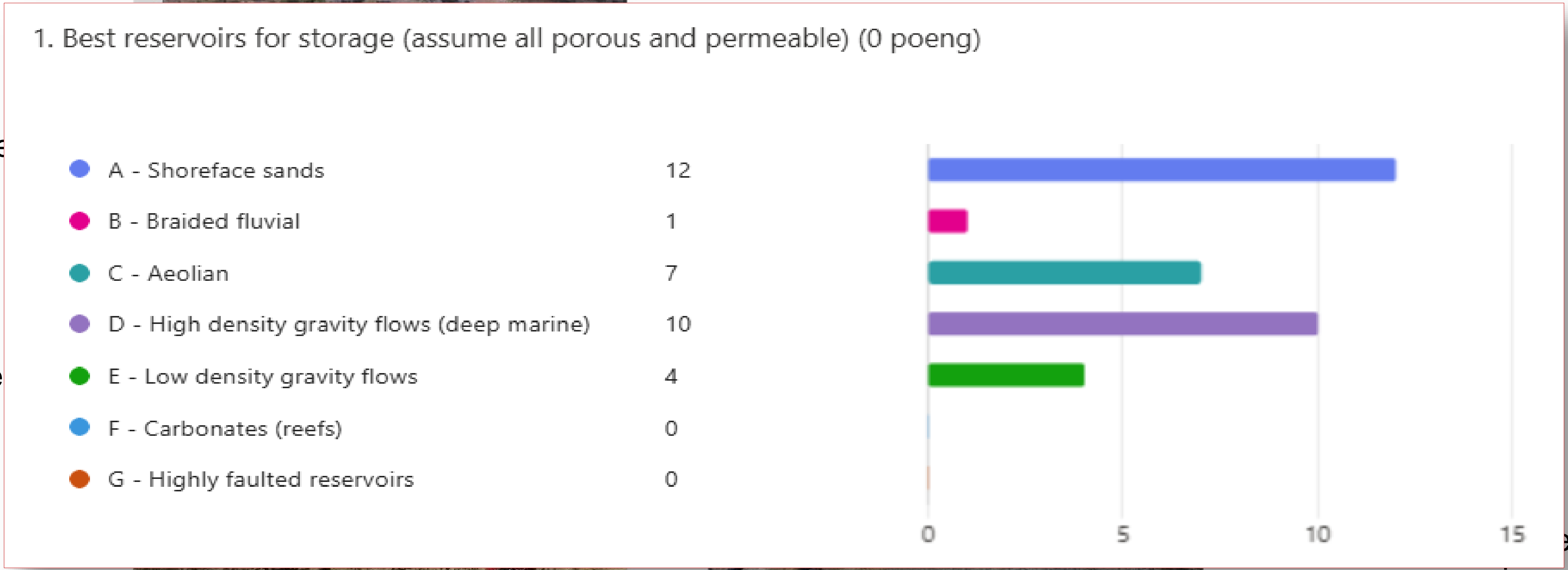
# Storativity & storage – what is the storage efficiency factor?

**A**
Middle-Upper Shoreface



**B**
Fluvial channe

**C**
Aeolian (dune

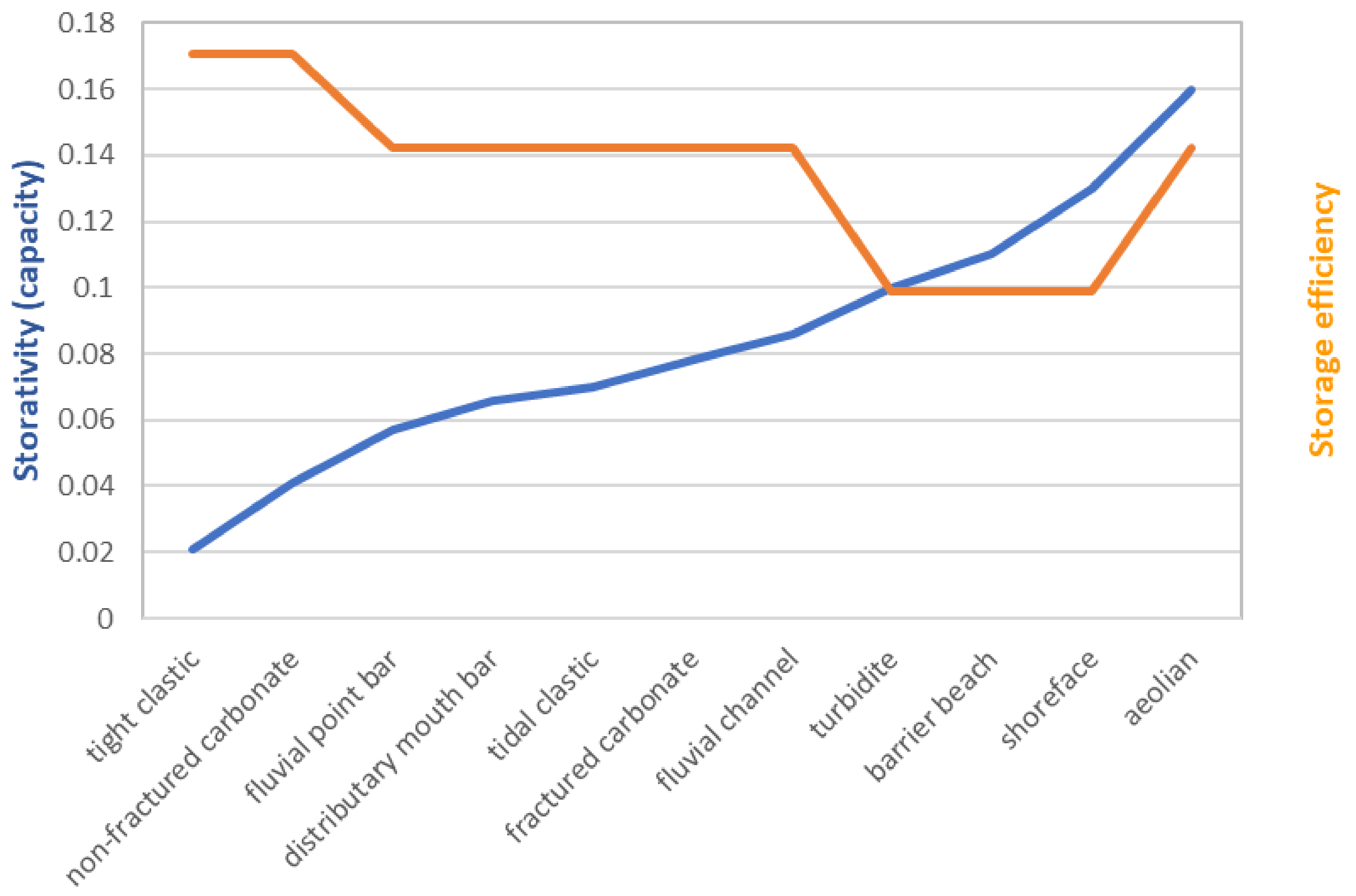



**D**
High density gravity flow

ed reservoirs

*Hamood Al-Shabibi, PDO/Heriot-Watt*

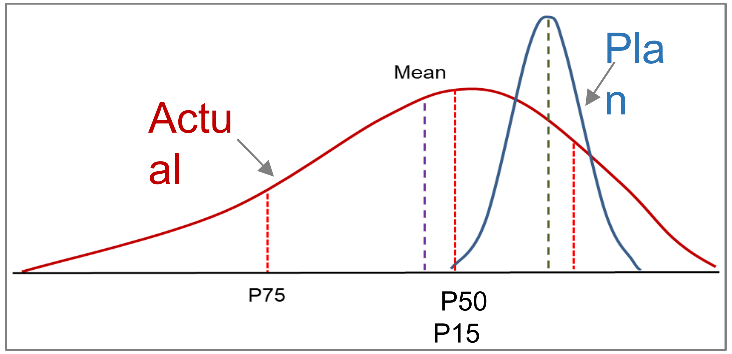
# Having your cake and eating it




*Hamood Al-Shabibi, PDO/Heriot-Watt*

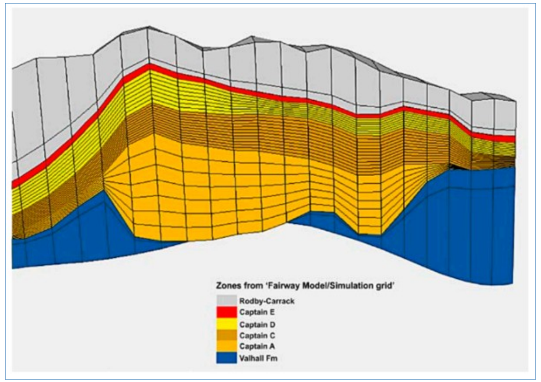
# Over-forecasting and under-forecasting

**Production**
*(including open geothermal)*



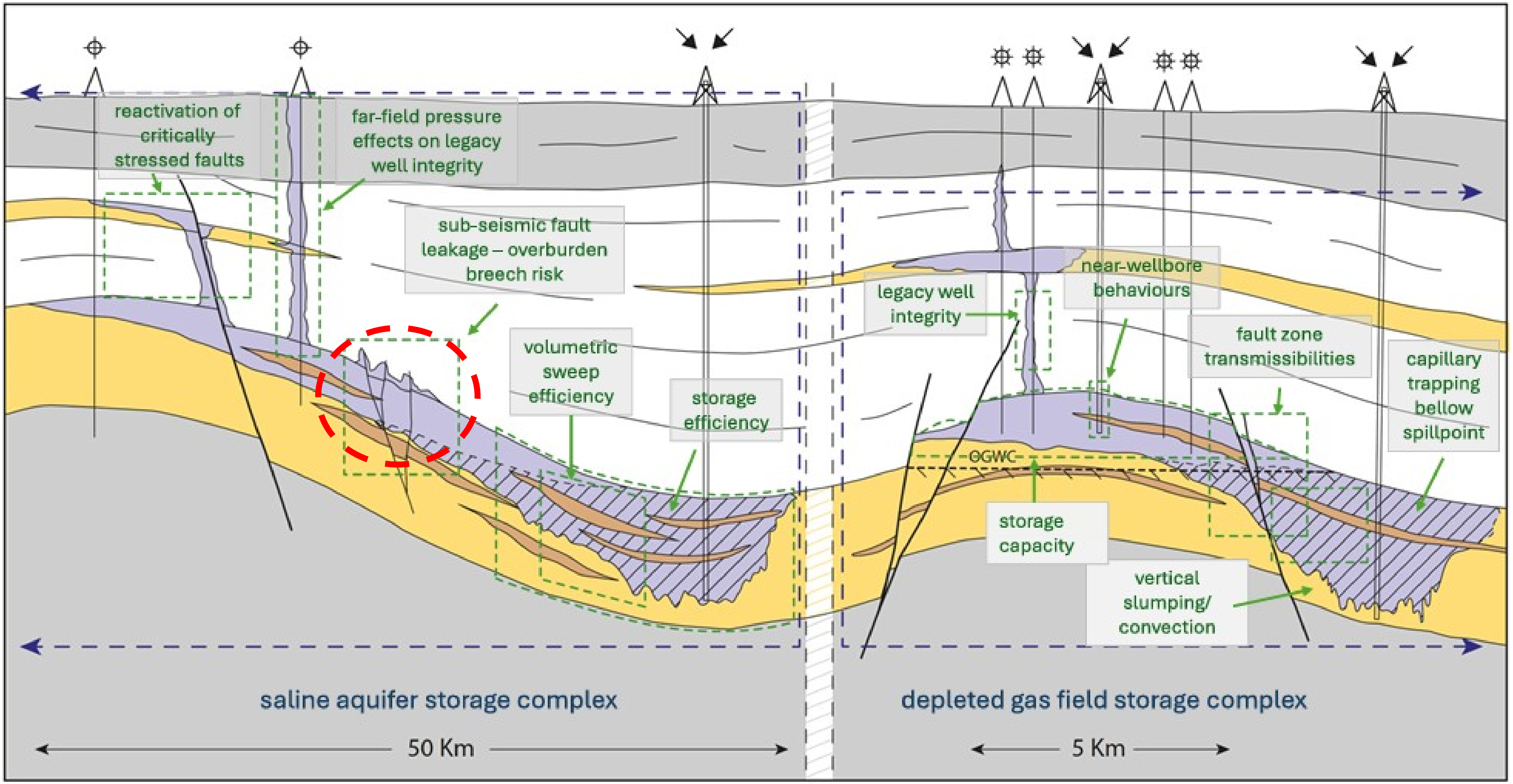

Heterogeneity = bad news story

**Storage**




Heterogeneity = good news story

# Structural heterogeneity – sub-seismic




*Bentley & Stephens, 2025*


2D faults
… with 1D transmissibility


*… with 3D properties*
*(and then REV them)*

# Fault heterogeneity issues for CCS

*We need to consider ….*

The effect on the **CO2 plume**:

2 phase problem – controlled by capillary entry pressure

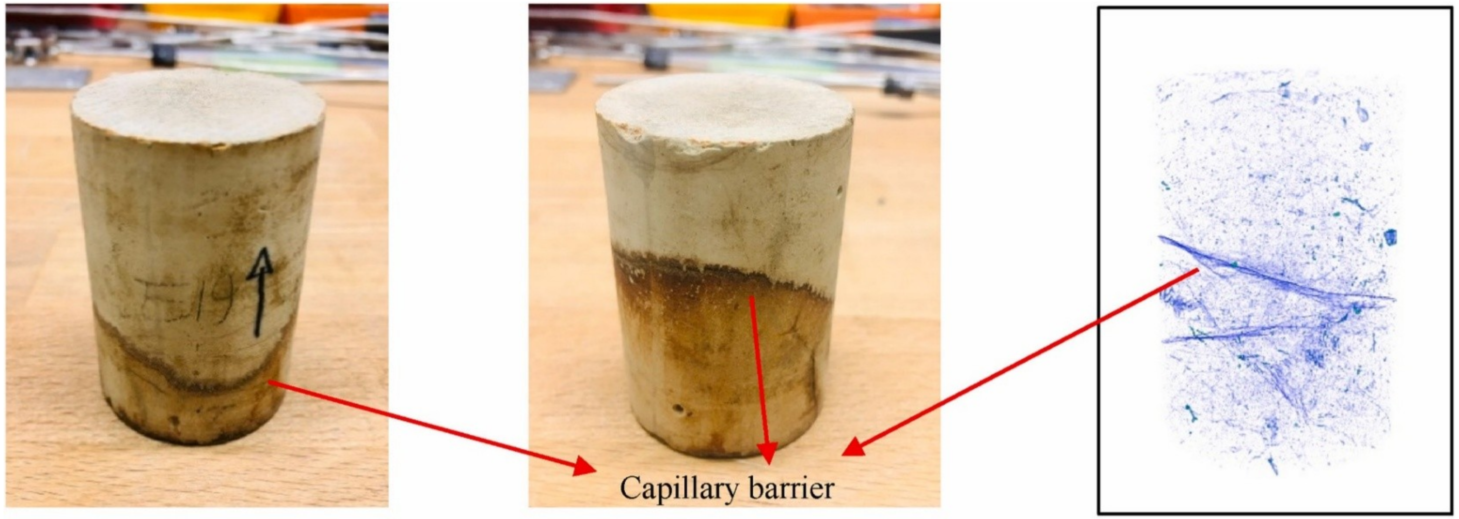
Faults may be completely sealing for CO2 – but it only takes one hole for the CO2 to leak

The effect on the **pressure front**:

If water can cross the fault, so can pressure

The fault may act as a baffle – water can cross, but the pressure front is slowed

*Arbuckle Mountains, Oklahoma*



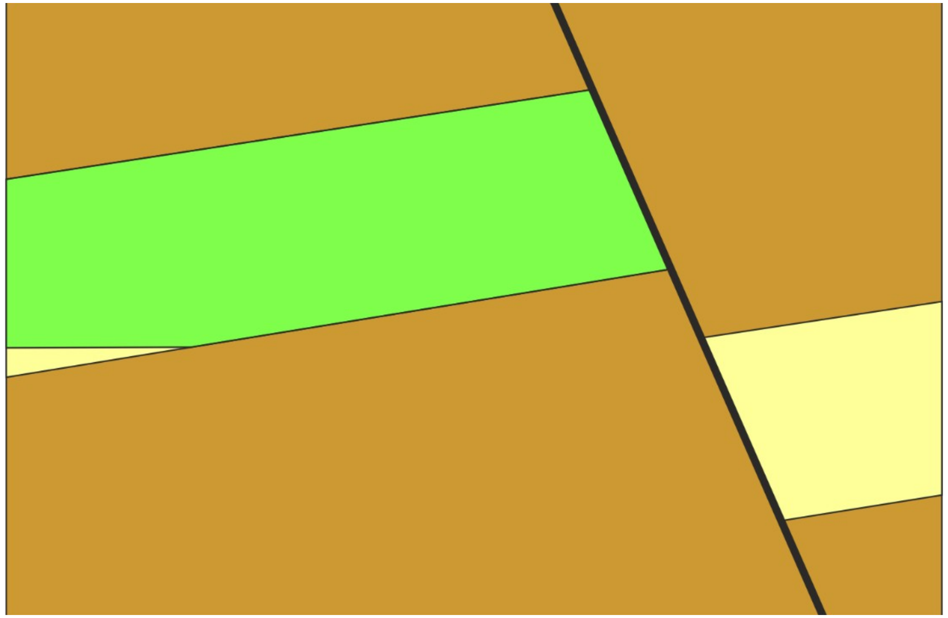

*from Mokhtari et al. 2022*

# Fault seal types

## Juxtaposition seal

The seal is reliable, as long as there are no permeable layers on the sealing side of the fault

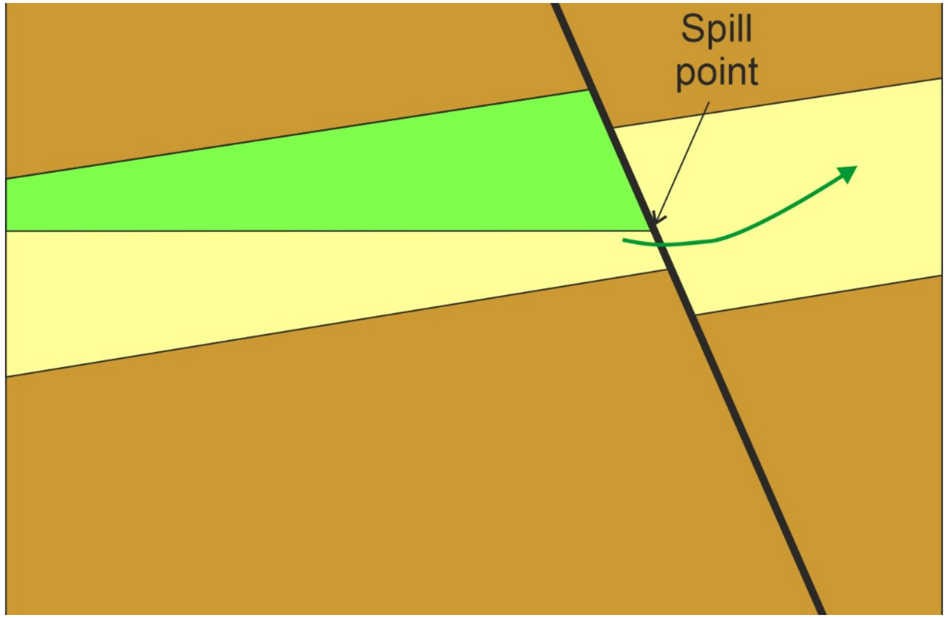
Structural trapping in the wedge



## Fault rock seal

Reservoir juxtaposed so the fault itself provides the seal. Less reliable

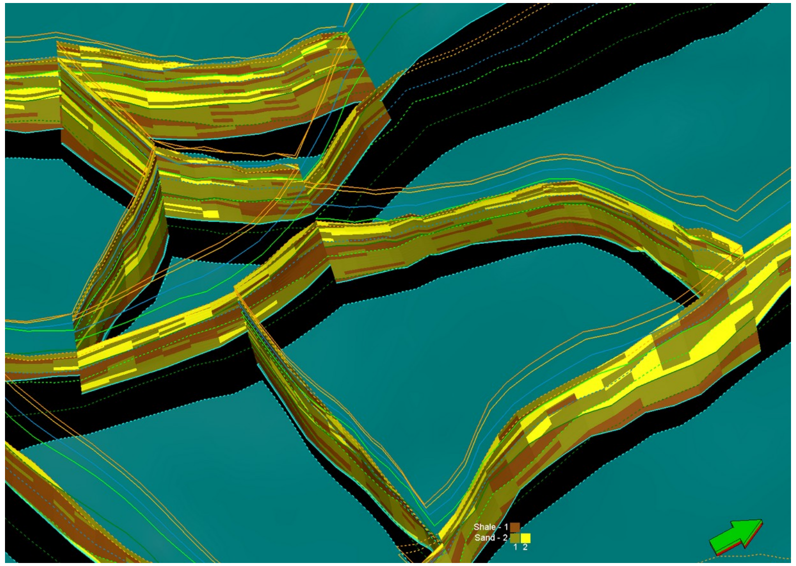
Capillary effect



# Juxtaposition seal

We can use juxtaposition diagrams to identify juxtaposition seals and leak points, and calculate wedge trapping volumes

Triangle diagrams plot stratigraphy against fault throw, to identify windows of reservoir juxtaposition. Useful when actual fault throw is not well known *e.g. sub-seismic faults*



Allan diagrams plot footwall and hanging stratigraphy along specific fault planes where the throw is known. Useful when fault geometry and throw is well constrained *e.g. seismic-scale faults*

# Fault rock

What is fault rock?

A mixture of material from all layers cut by the fault, e.g. a mixture of sand and clay - **fault gouge**

Sand grains may be broken down into smaller particles by cataclasis - **grain crushing**

Fault rocks may be preferentially **cemented**

Ductile layers may remain intact, forming continuous **smears**

*Northumberland, England*

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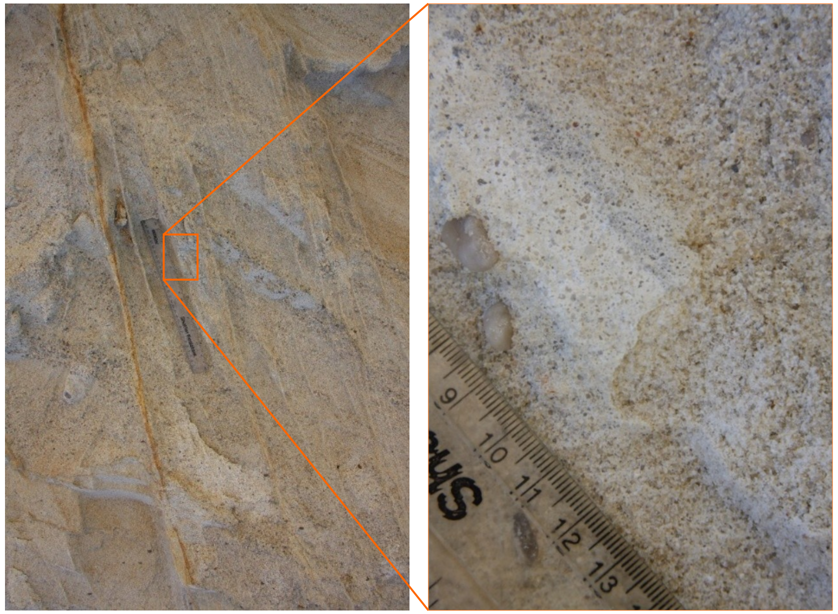
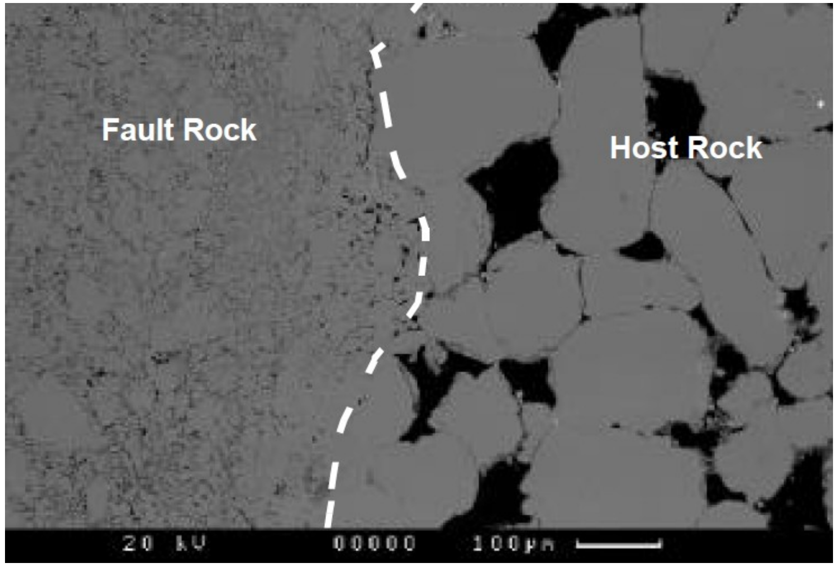


*Orange, France*



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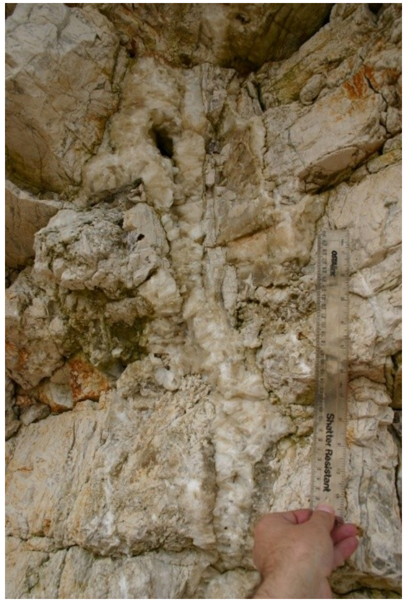
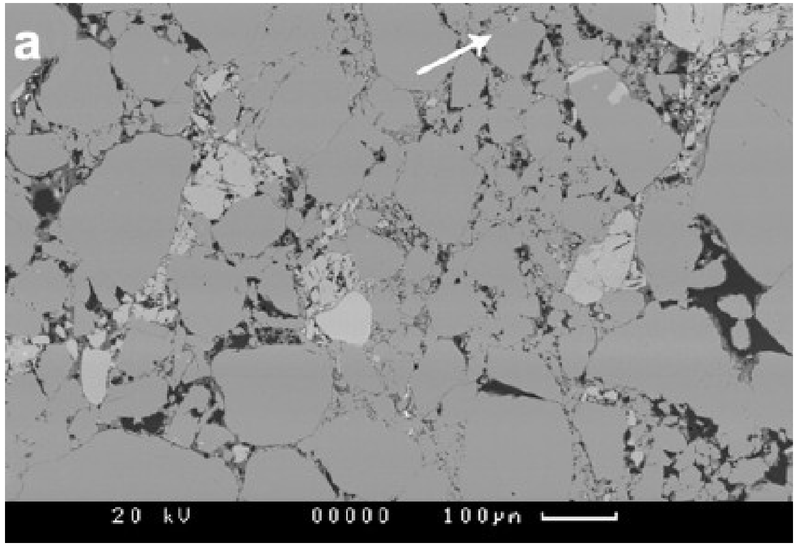


*Skull Creek, Colorado*




*Quartz cementation around cataclastic grains, from Tueckmantel et al. 2012*

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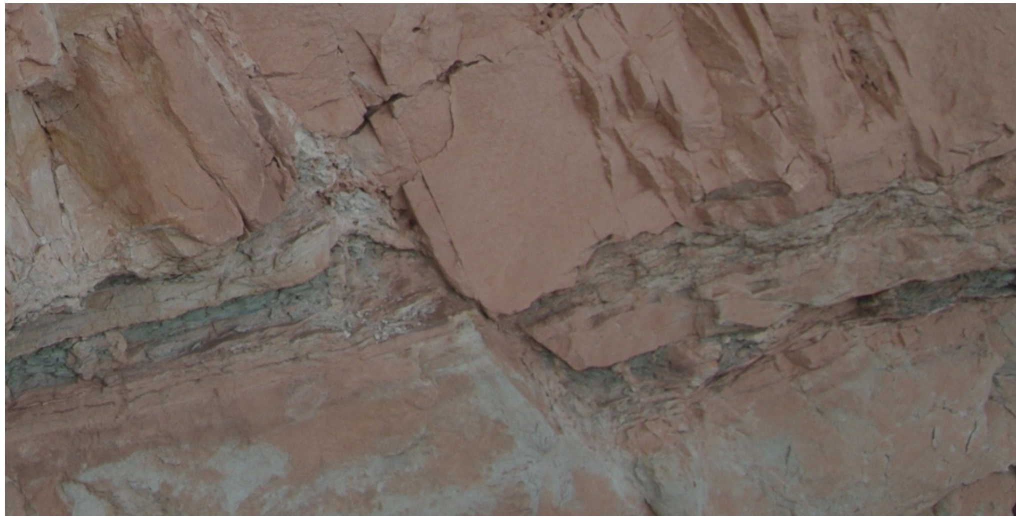
*Santa Cruz, Portugal*



*Dinosaur, Colorado*

# Fault rock petrophysics

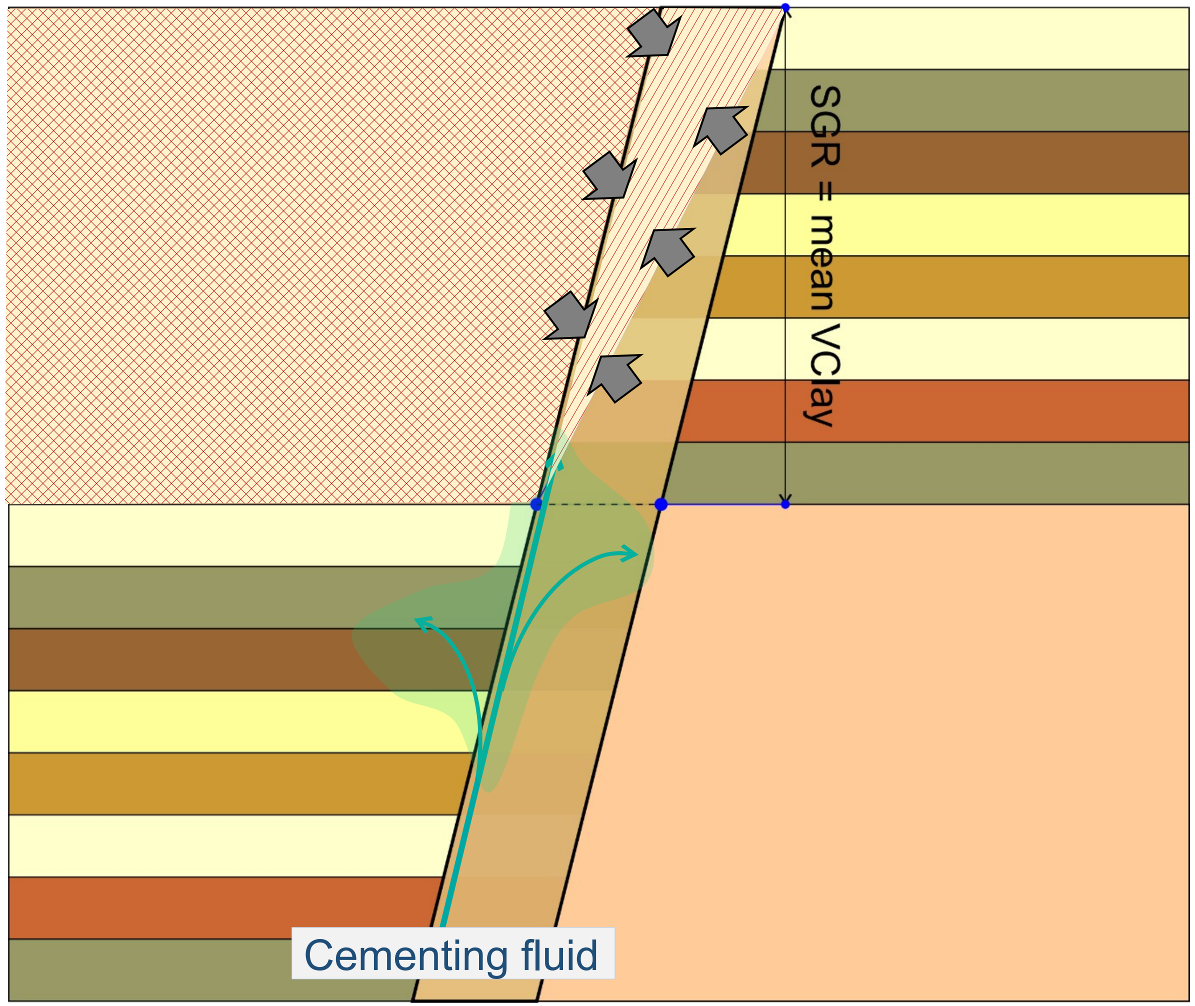
Fault rock properties are controlled by several factors

*(Fisher & Knipe 1998, Fisher et al. 2003)*

Fault rock composition, i.e. the proportion of sand and clay

Amount of cataclasis: the depth of burial (i.e. stress) at the time of faulting.

Amount of cementation - the maximum depth of burial after faulting (quartz cement) or fluid flow through the fault (calcite cement)



# Mercury injection

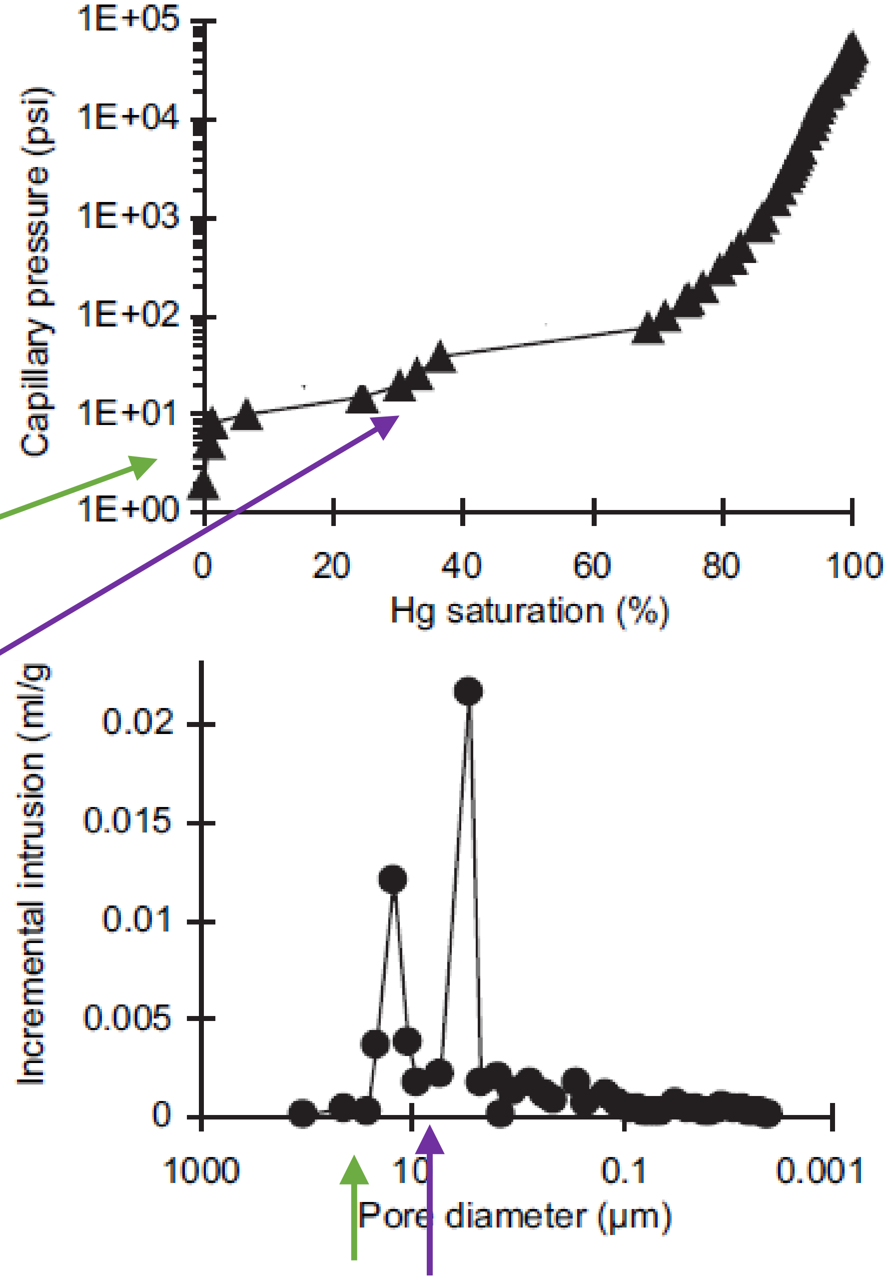
The trick is to cut the sample so the fault crosses it, and inject the mercury from one side

There will be 2 steep segments in the injection volume / pressure curve:

The first where mercury intrudes into the first half of the sample – but is blocked by the fault; this gives the capillary entry pressure of the host rock

The second where mercury crosses the fault into the second half of the sample; this gives the capillary entry pressure of the fault rock

By measuring samples from different faults, we can cross-plot fault rock capillary entry pressure against fault rock clay content




*Images from Tueckmantel et al. 2012*

# Fault rock capillary entry pressure vs clay content

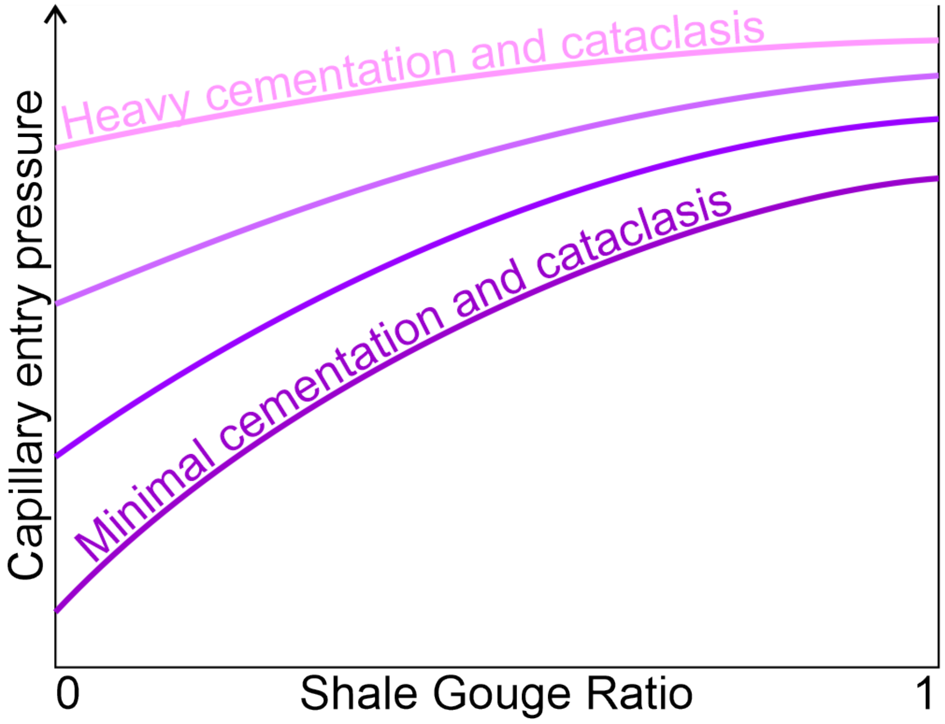
Faults with more cataclasis and/or cementation will have a low gradient and high values – generally good seals

Faults with less cataclasis and/or cementation will have a high gradient and low values – poor seals, especially at low clay content

We can then compare the curves with the calculated SGR to estimate capillary trap volume

*Note that there are some generic curves published in the literature – e.g. Sperrevik et al. 2002*

*Care must be taken when using these as they are very generic and take no account of local conditions*



# Fault zone architecture

So far we have considered faults as a single flat plane

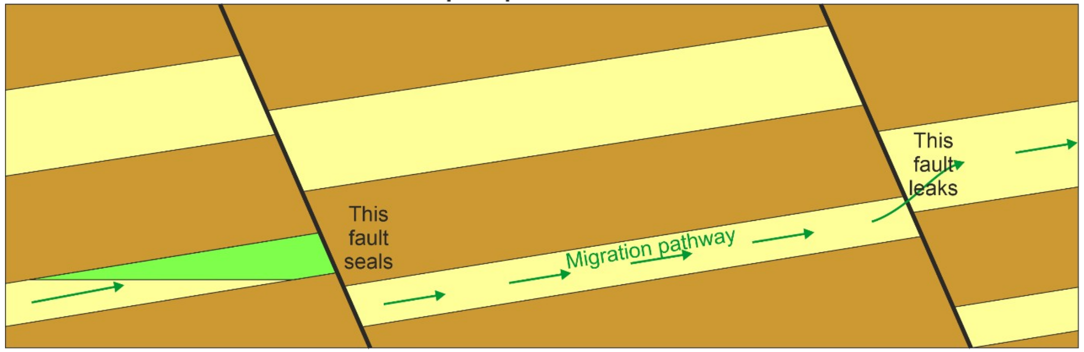
In reality faults are multi-planar objects with detailed internal architecture and geometry *(see papers by Walsh et al, Knipe et al, Fossen et al, Peacock & Sanderson ….)*

Complex fault zone architecture can provide potential leak pathways not obvious from simple fault seal analysis, e.g.:

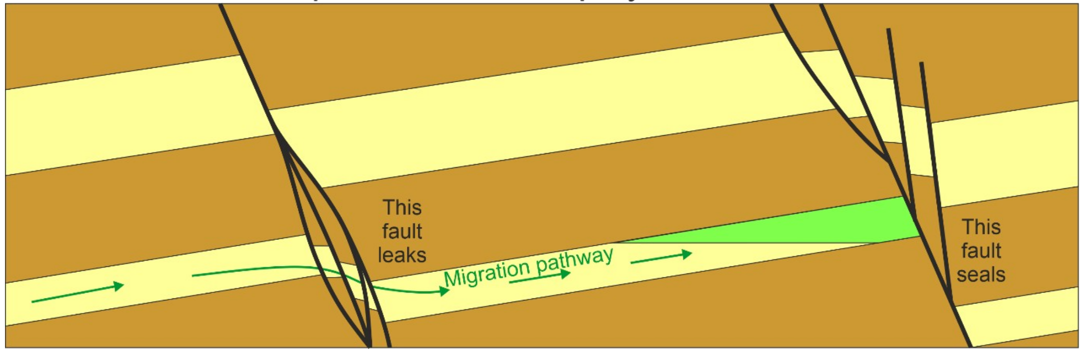
Fault bound lenses: for multiple fault strands, the throw on each strand < total throw, so seal calculations will be inaccurate - reservoir units may be juxtaposed on each strand, allowing additional flow

Relay zones: in 3D, faults tend to segment along strike; throws die out in the relay zones between segments, allowing additional flow

Simple planar faults




Complex faults with splays and lenses



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*Northumberland, England*

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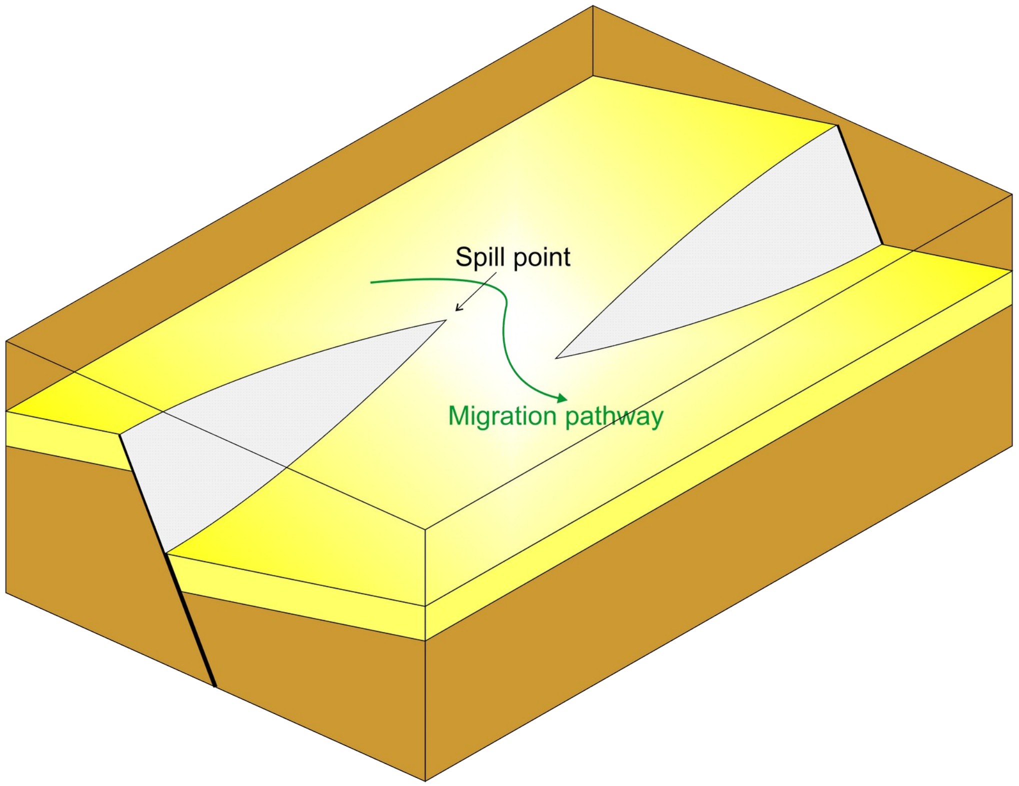

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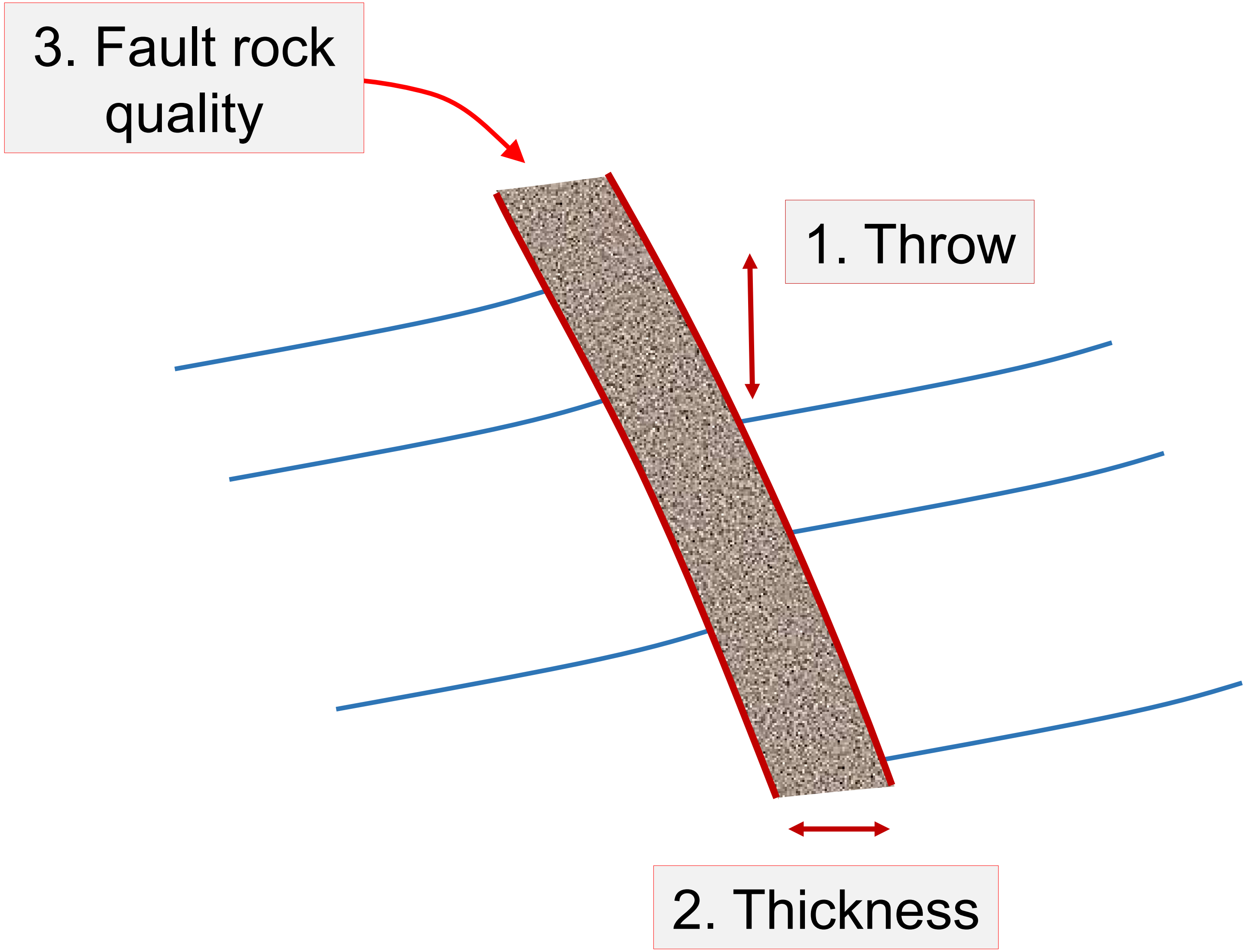
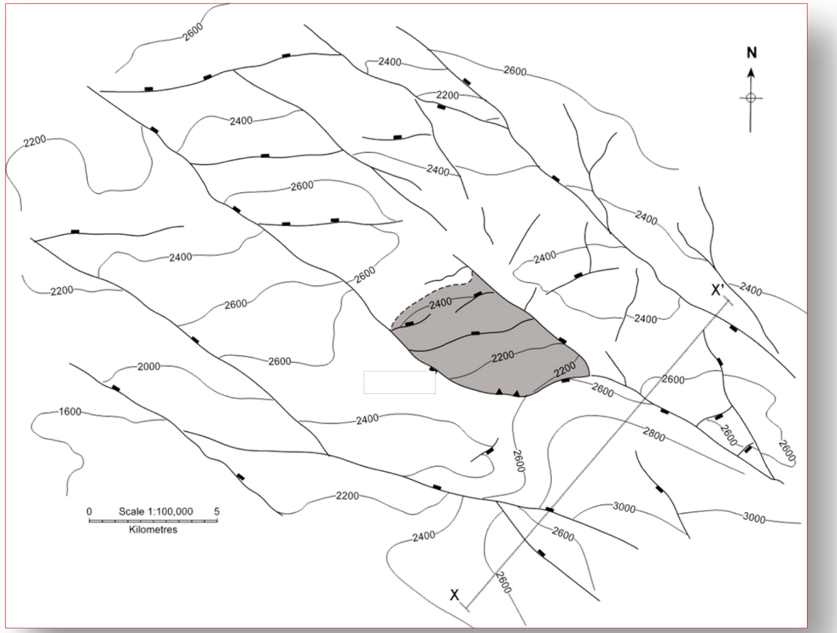
*Moab, Utah*

# Parameterising ‘Fault Intensity’



*How many faults … ?*

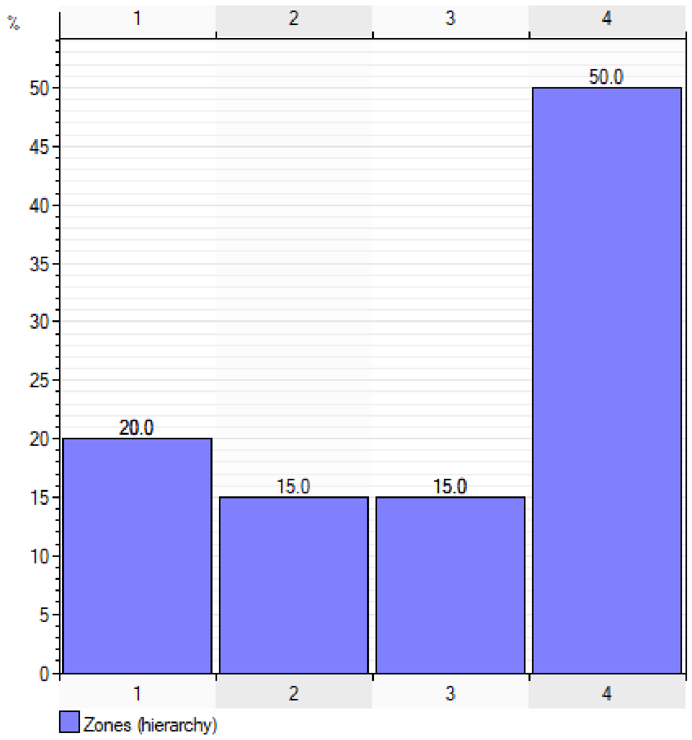
# Fault analogues

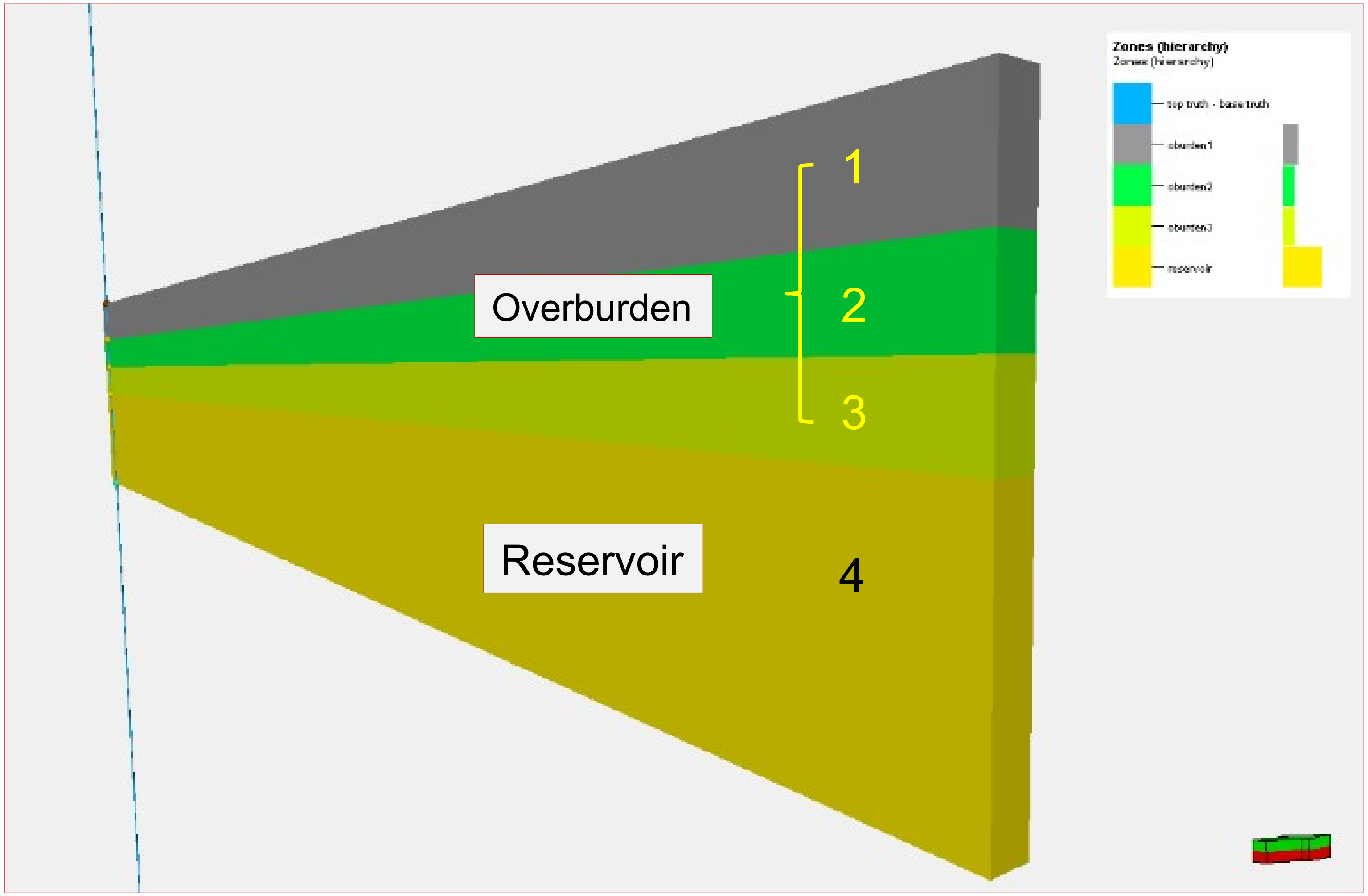
Narrow damage zone

Wide damage zone

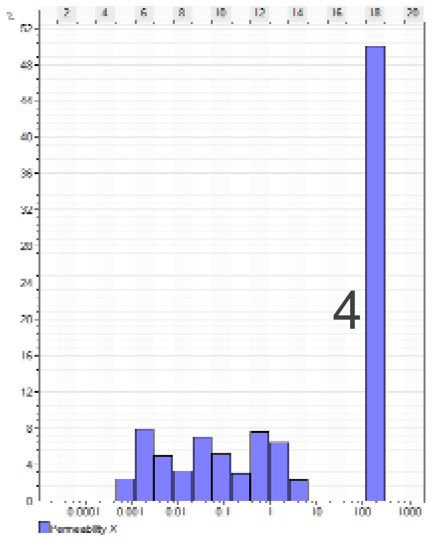
Cemented

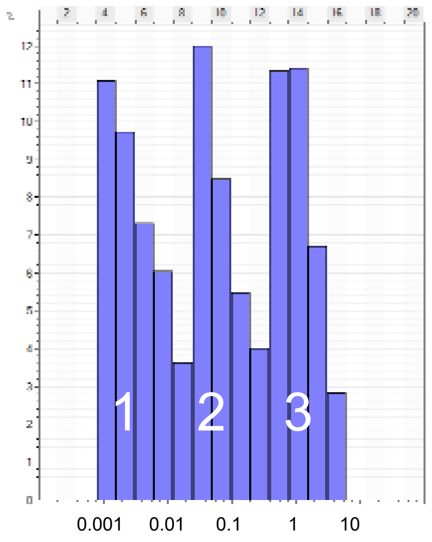
# Zones *(ca. host rock types)*

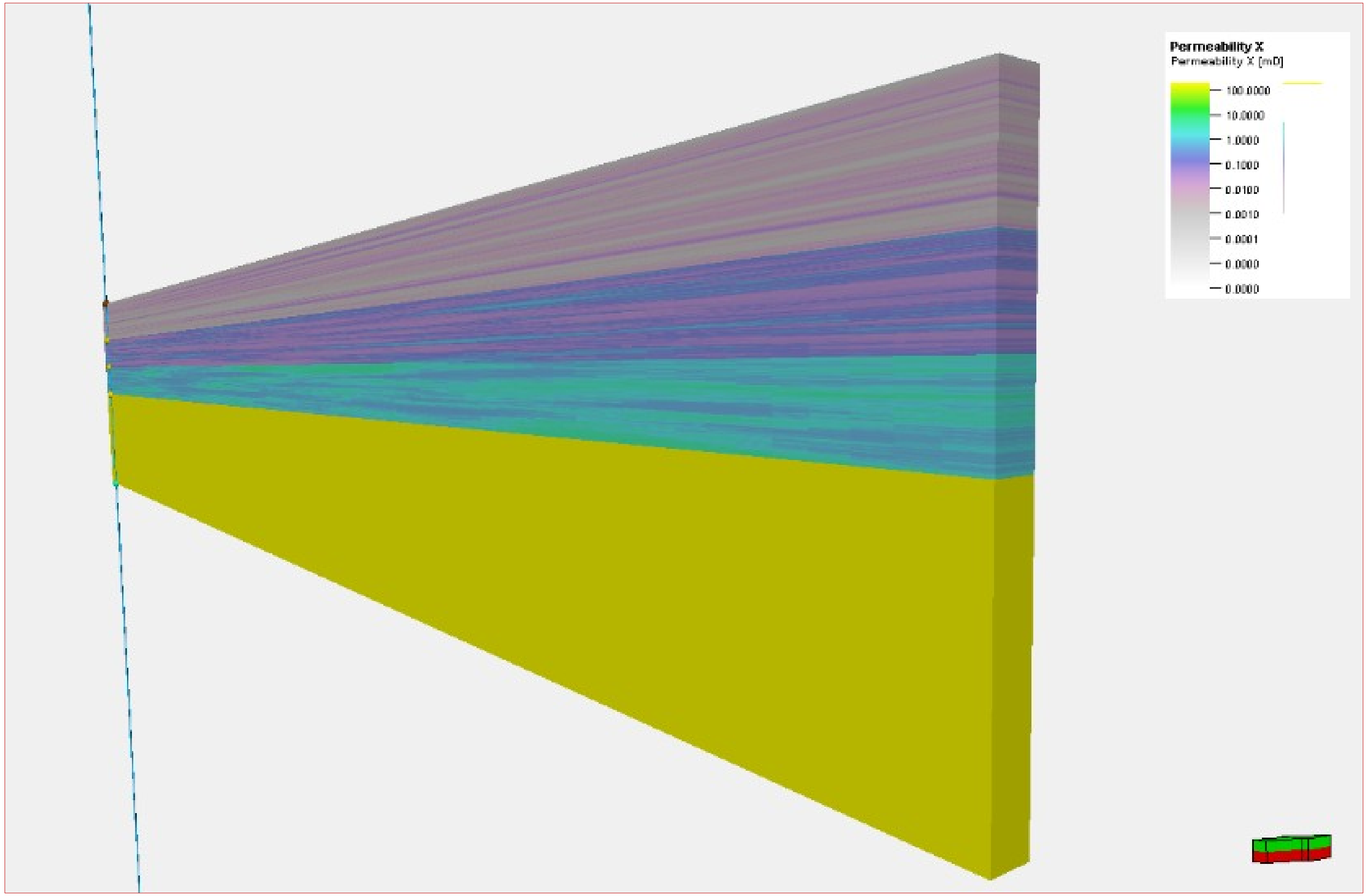


# Permeability X



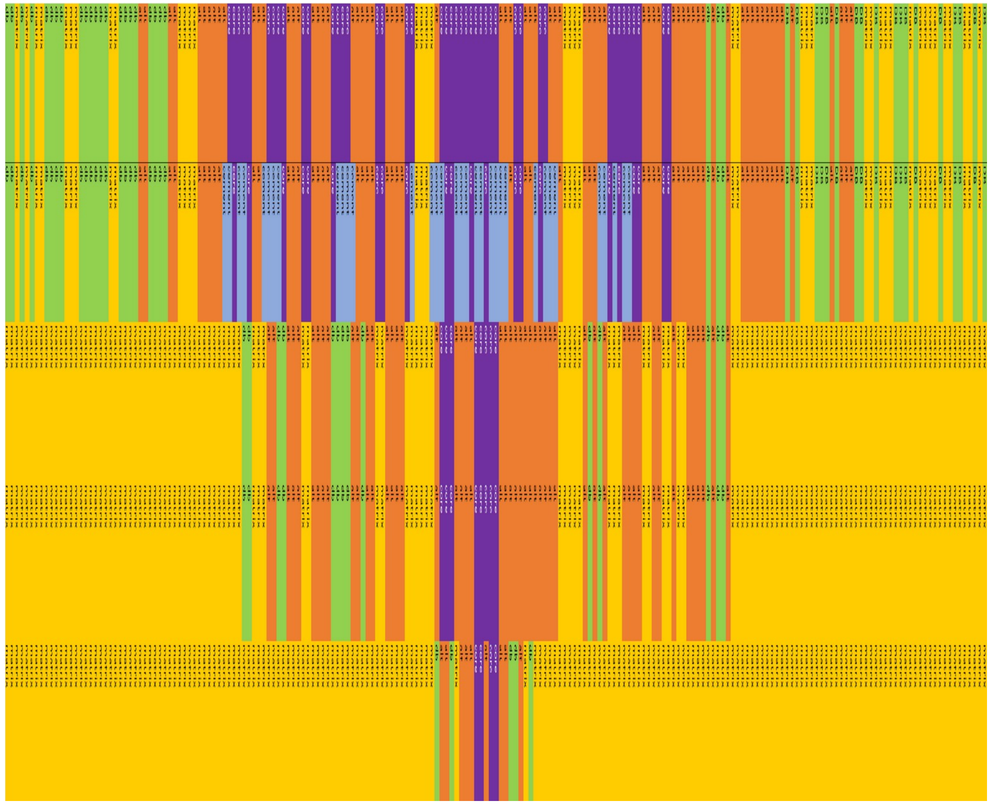
# Damage zone profiles

| 10m throw | 10m throw | 10m throw | no throw | no throw |
|---|---|---|---|---|
| 1m damage zone | 1m dz with cement | 50cm damage zone | 50cm damage zone | 10cm damage zone |

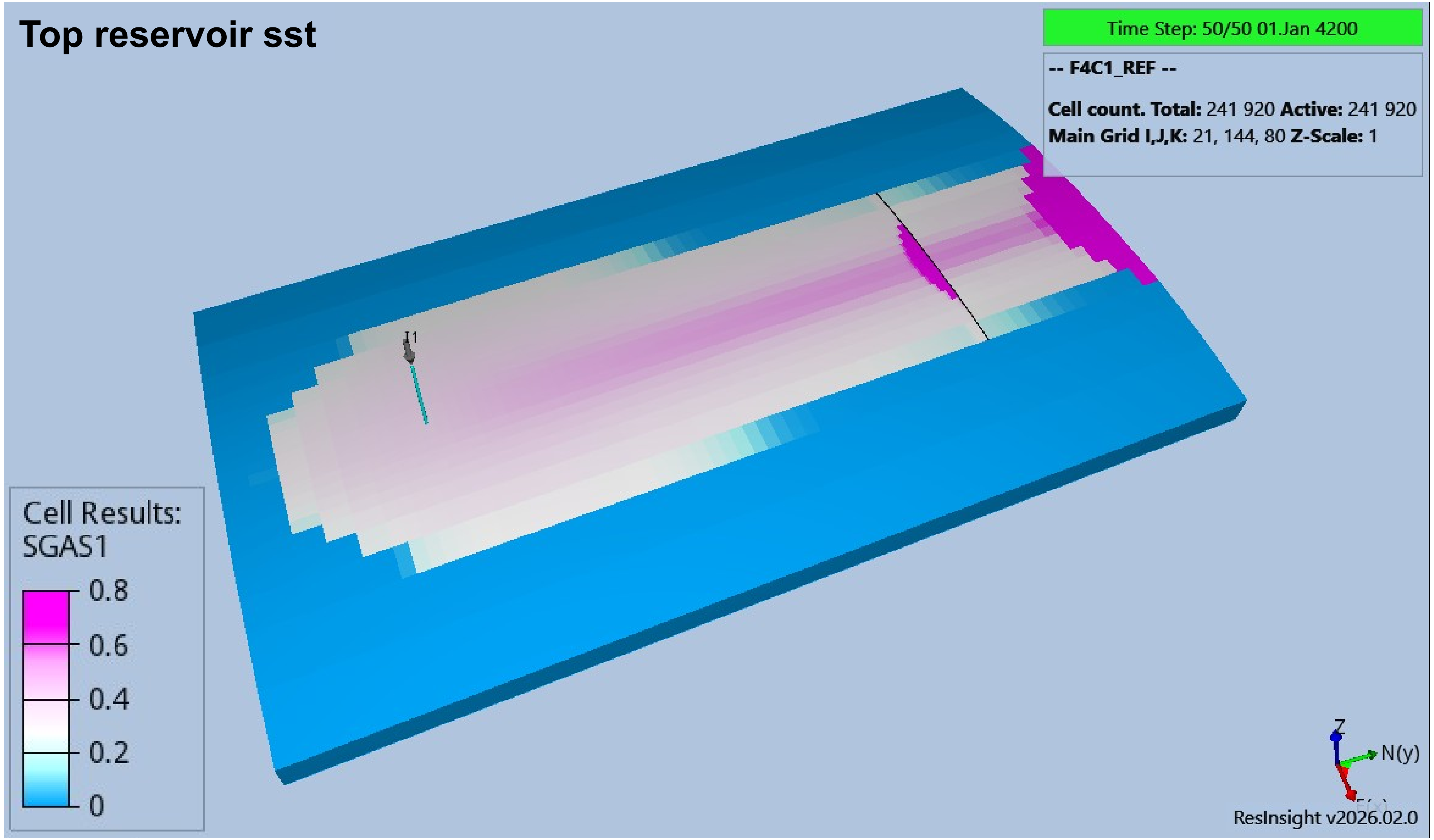
Fault elements

| fault core |
|---|
| altered matrix |
| DB |
| matrix |

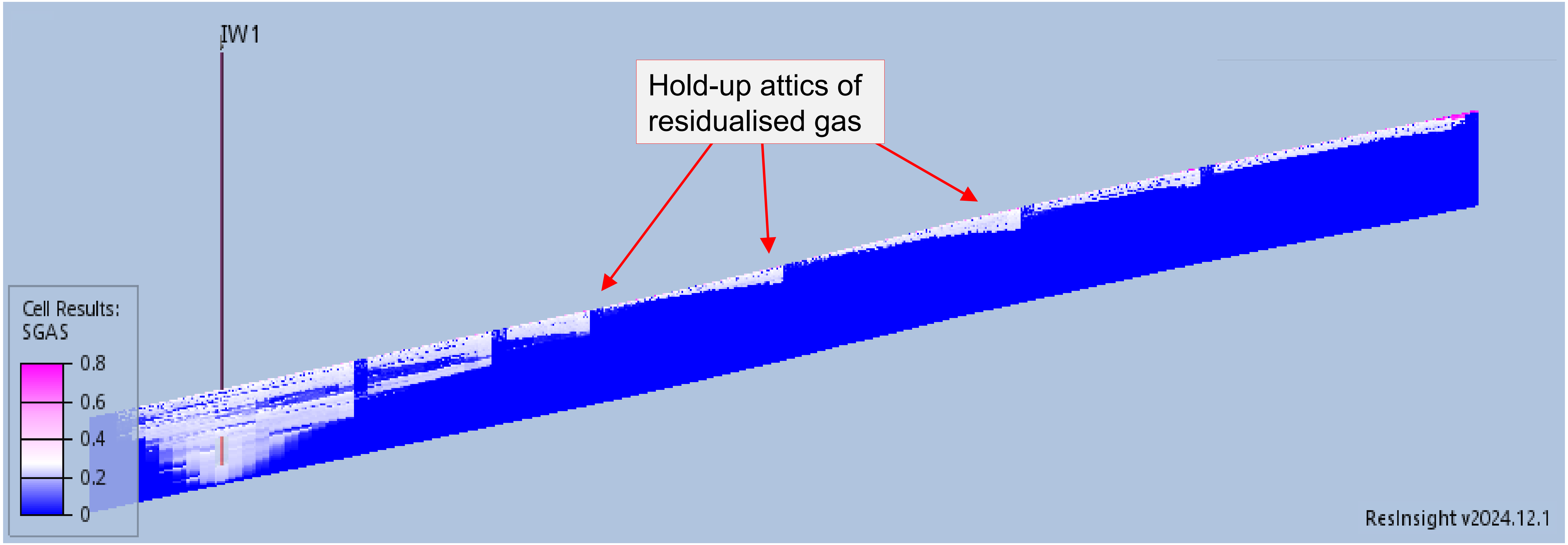
5mm increments



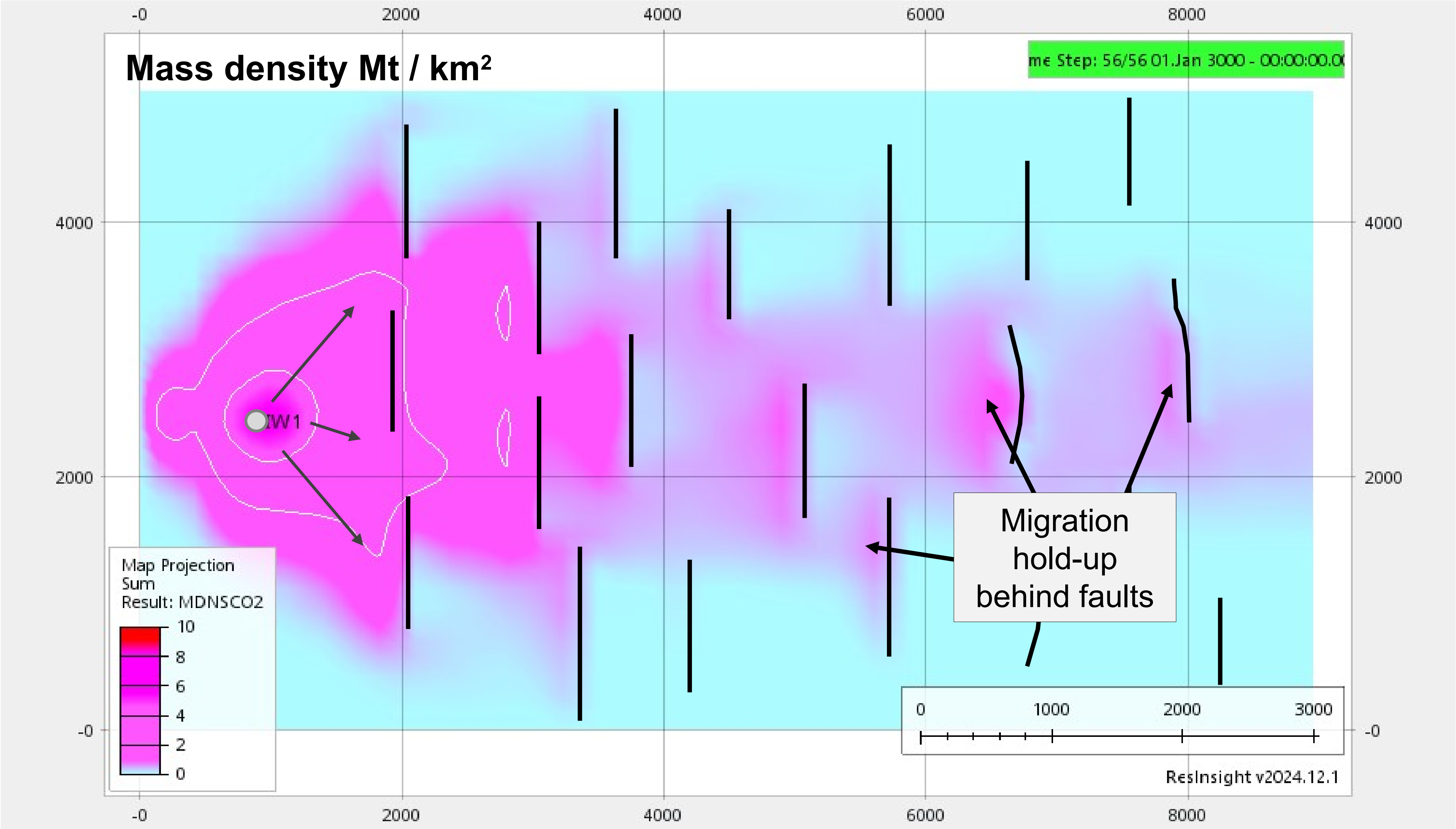
# 3D plume model



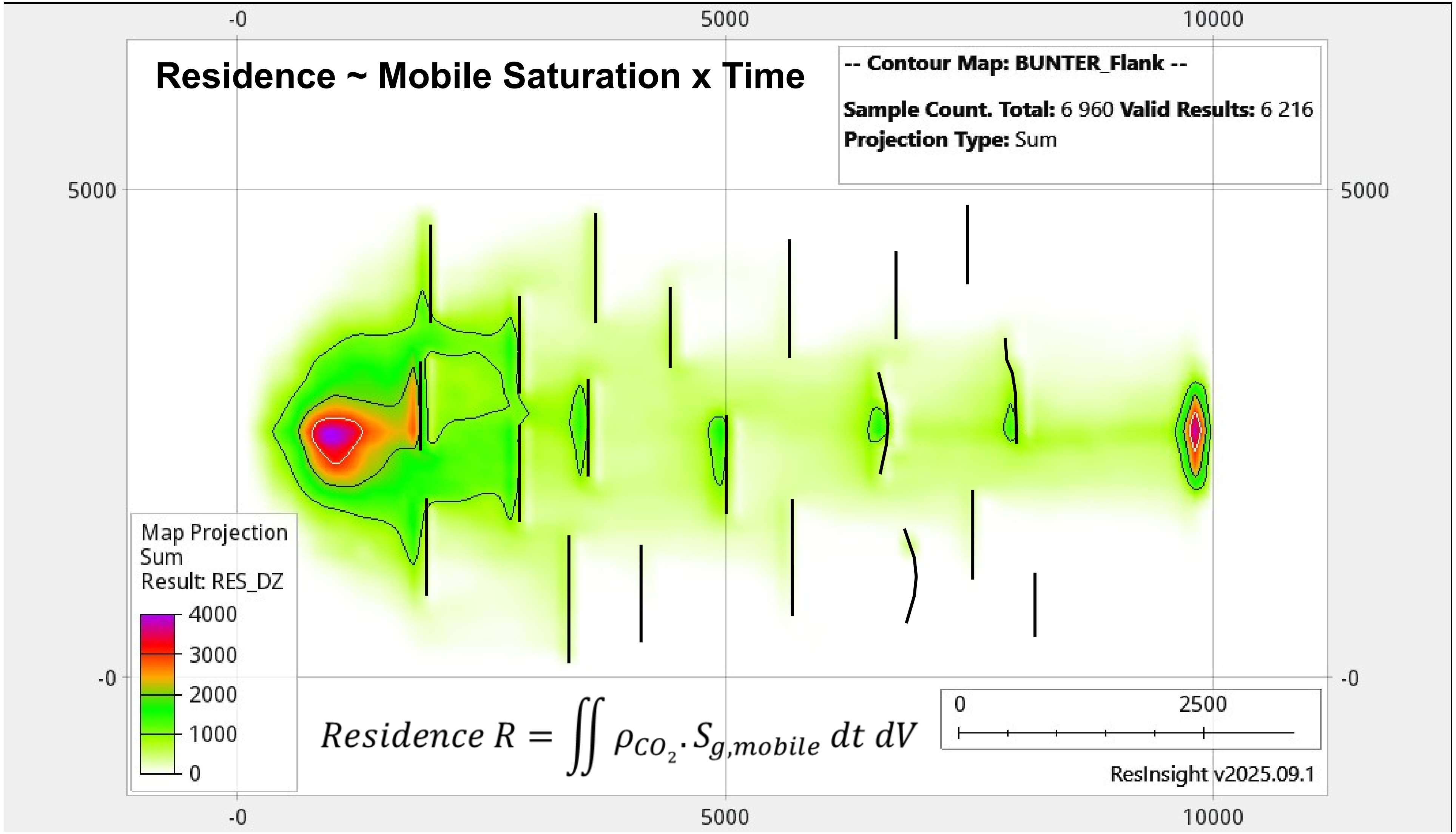
# The ‘salmon ladder’



# Mass density of plume



# Cumulative residence mapping



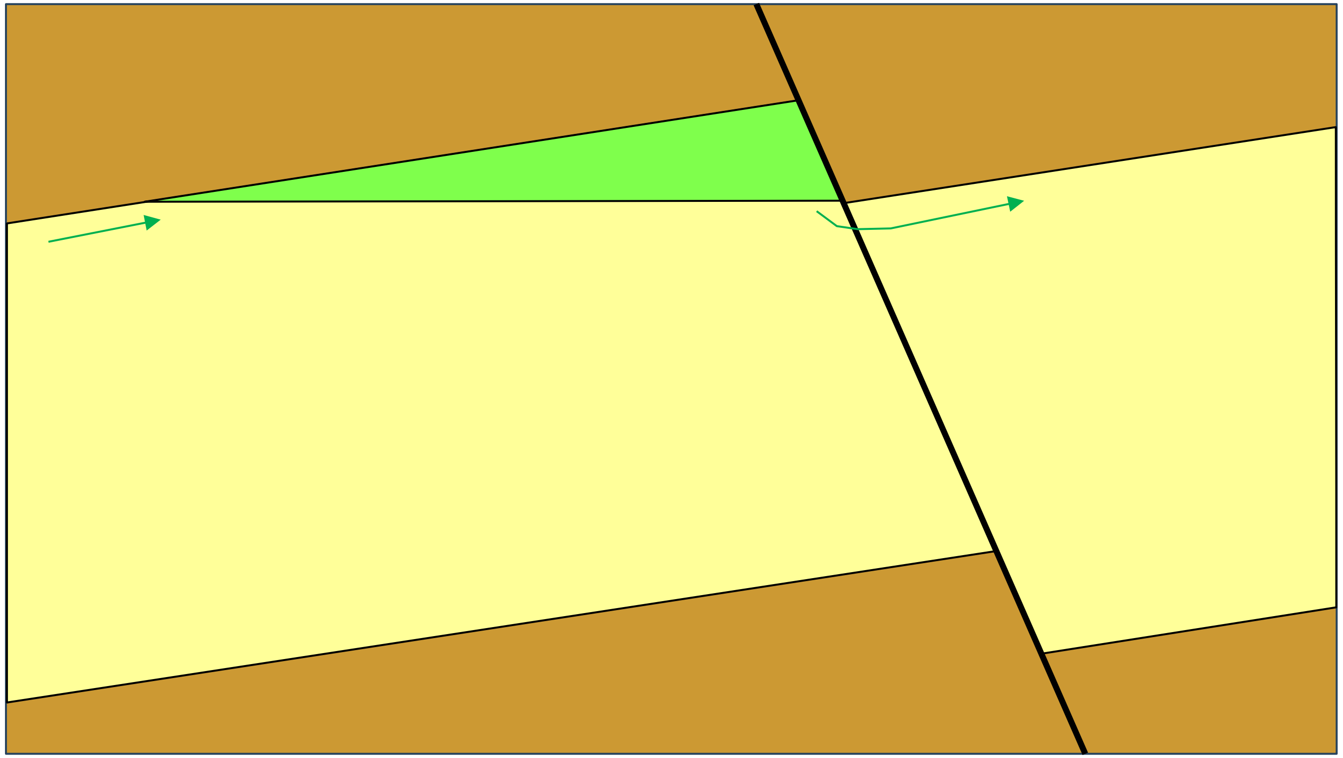

Total residence ~ 2000 Mt.yrs

# Structural trapping effect

Fault displacement offsets porous reservoir sands

$CO_2$ trapped in ‘wedge’

May soak upwards into overburden

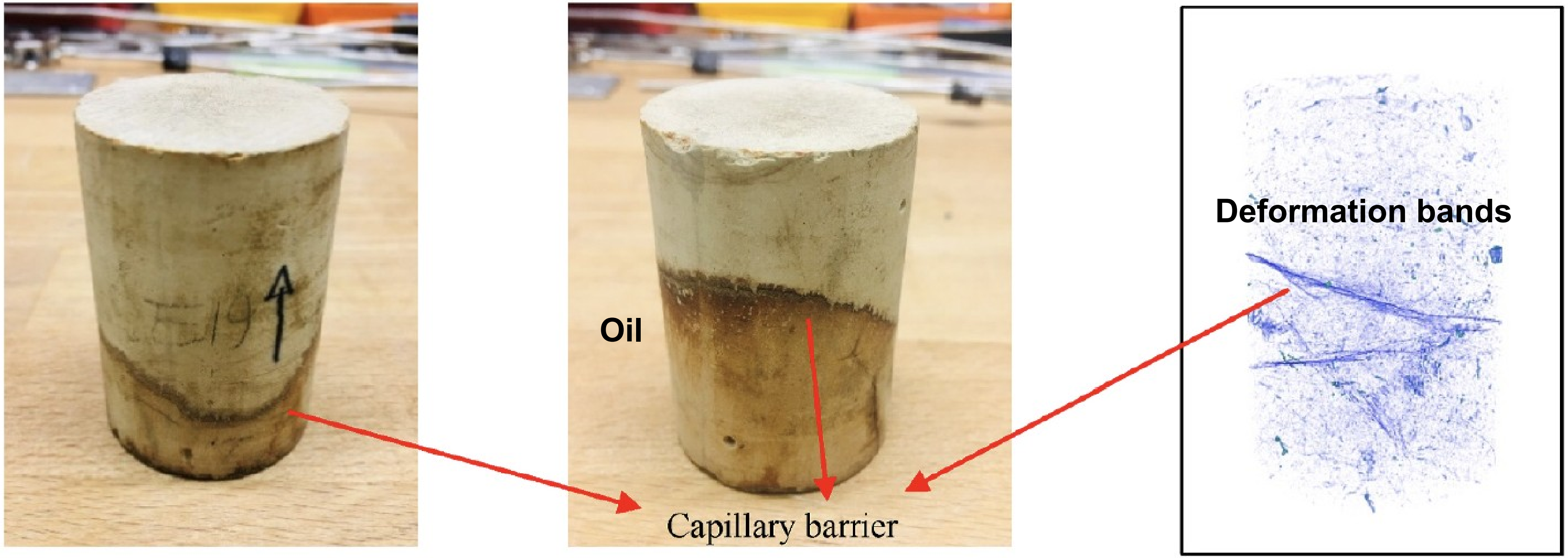


# Capillary trapping effect

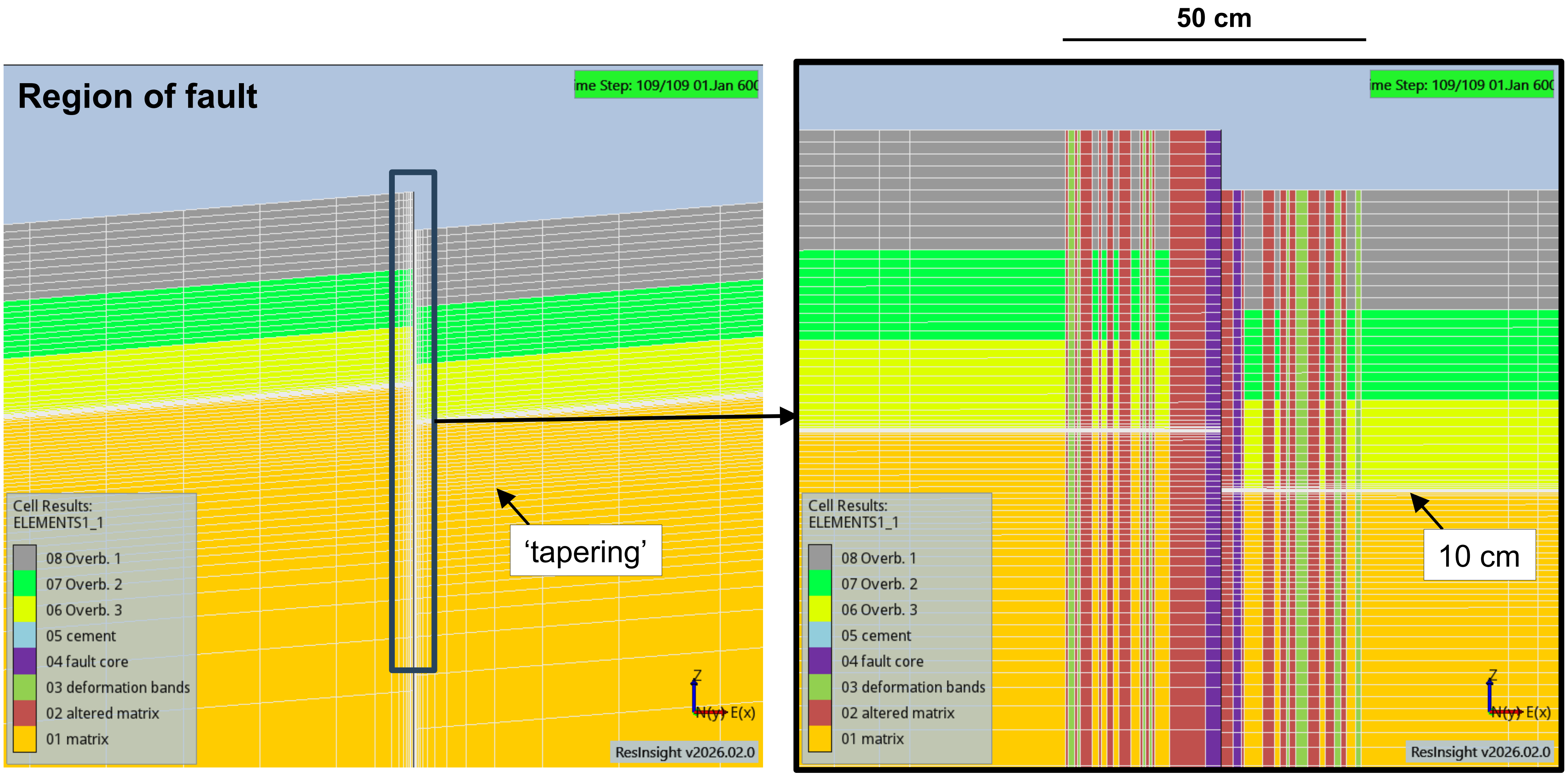
Fault elements (deformation bands, fault core) … lower permeability and/or altered pore structure

Increased capillary entry pressure Pce ~ Sqrt($\phi$/k)

Holds back column of non-wetting fluid such as $CO_2$ (below core plug with oil)

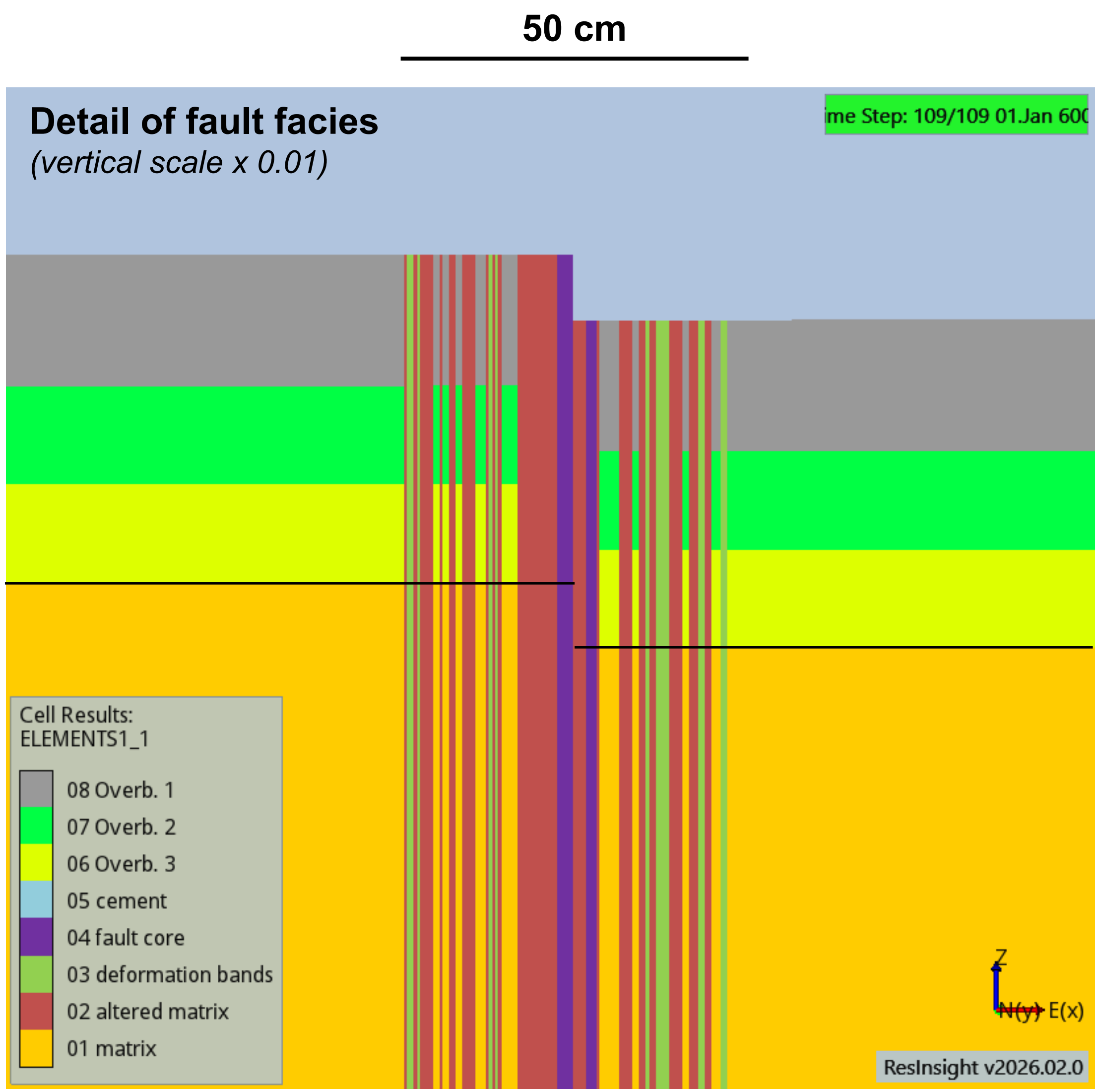


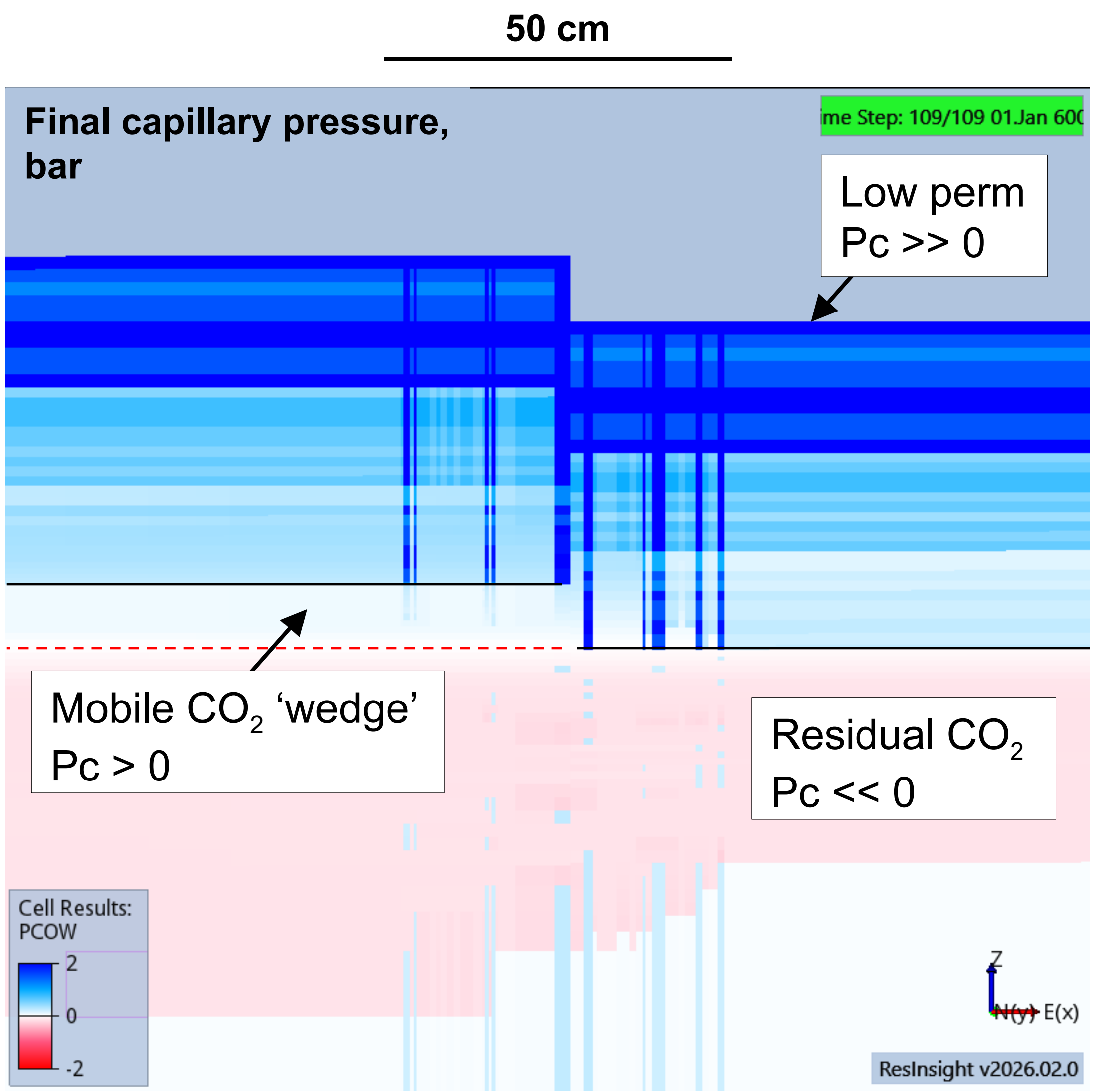
# Grid choice



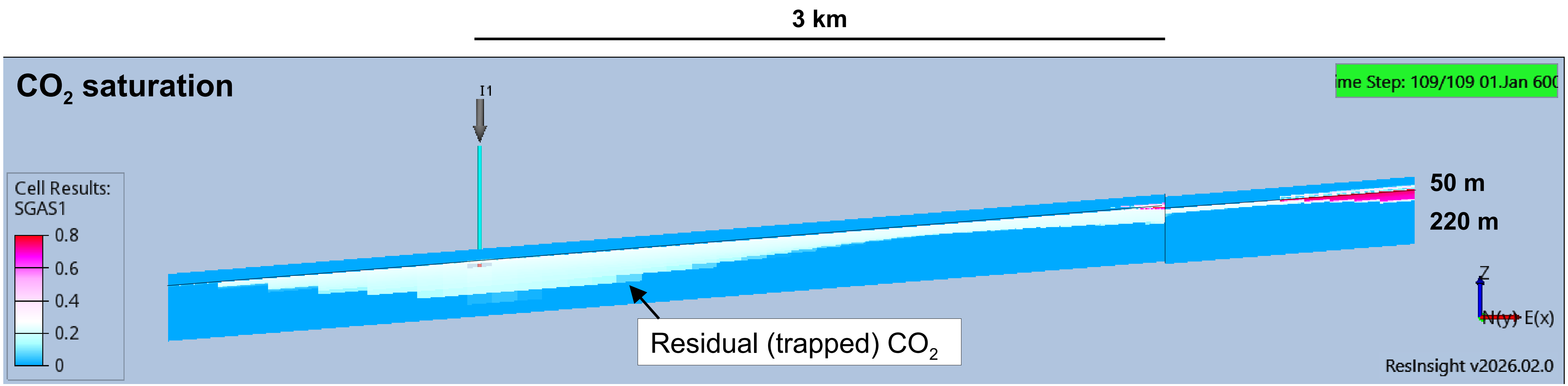
50 cm
Region of fault
me Step: 109/109 01.Jan 600
'tapering'
10 cm
Cell Results:
ELEMENTS1_1
08 Overb. 1
07 Overb. 2
06 Overb. 3
05 cement
04 fault core
03 deformation bands
02 altered matrix
01 matrix
Z
N(y) E(x)
ResInsight v2026.02.0

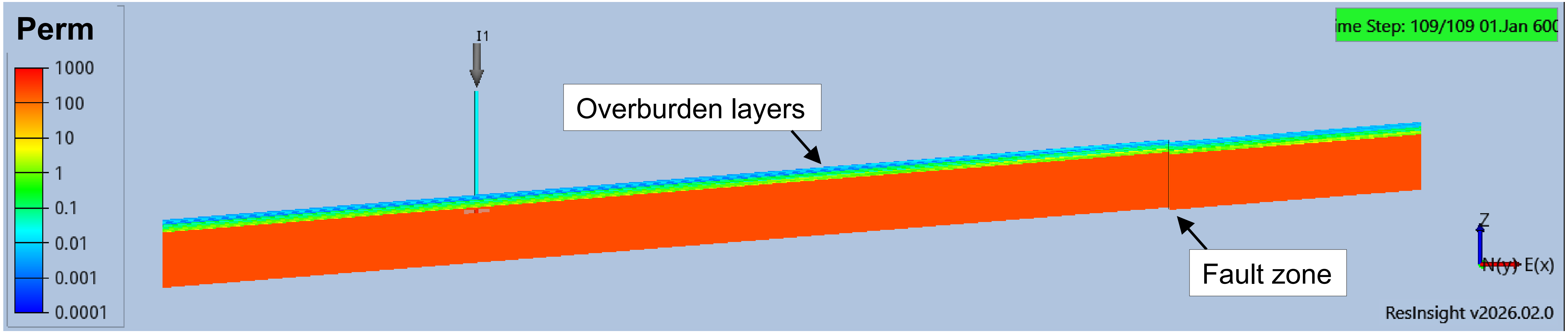
# Capillary pressure within fault zone



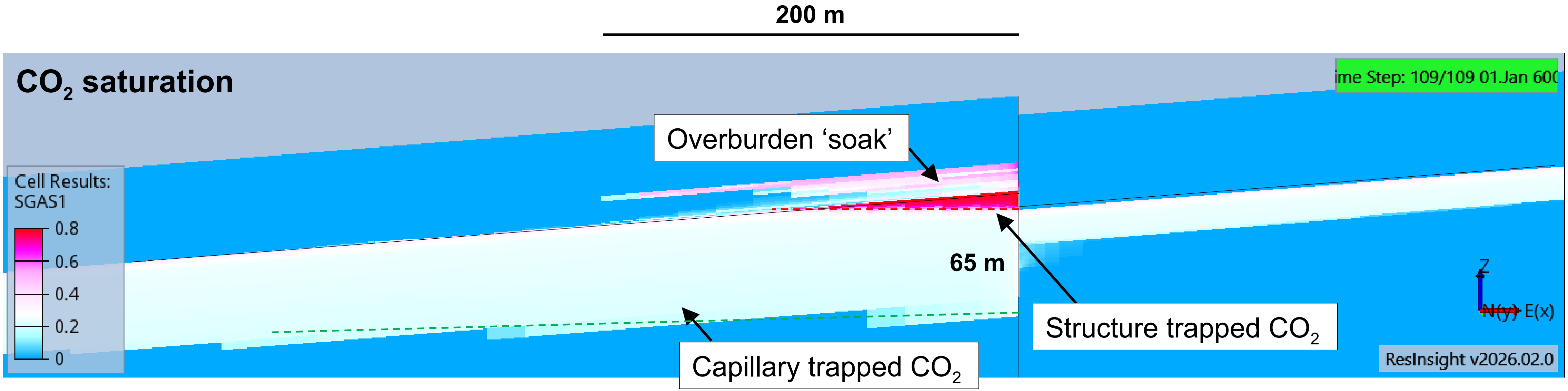



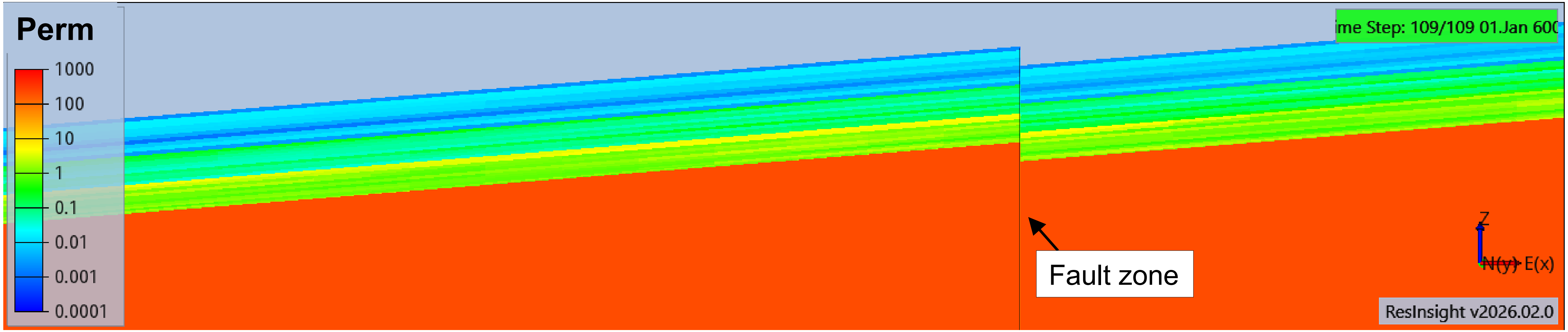
# Plume cross section (1) – overview



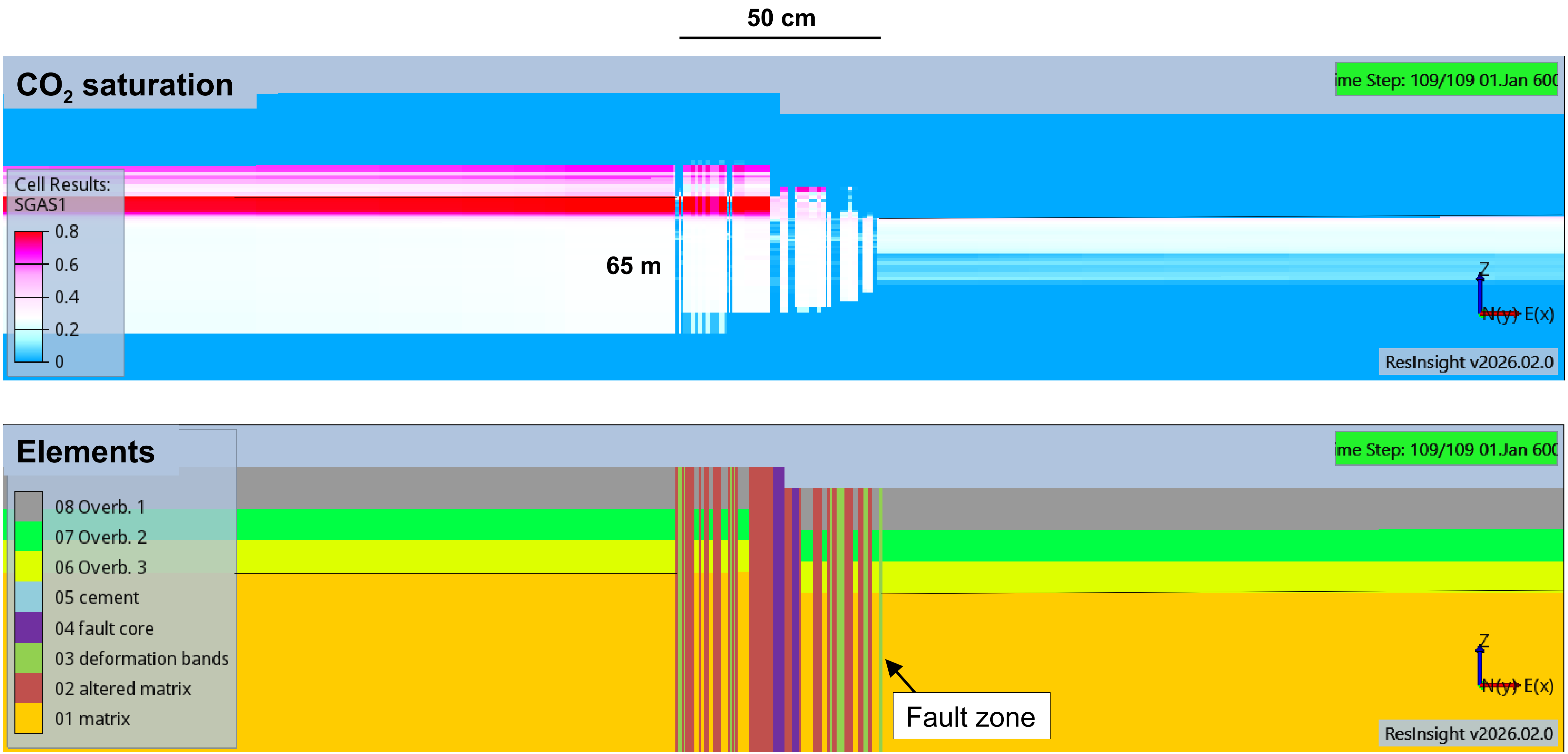



# Plume cross section (2) – close up



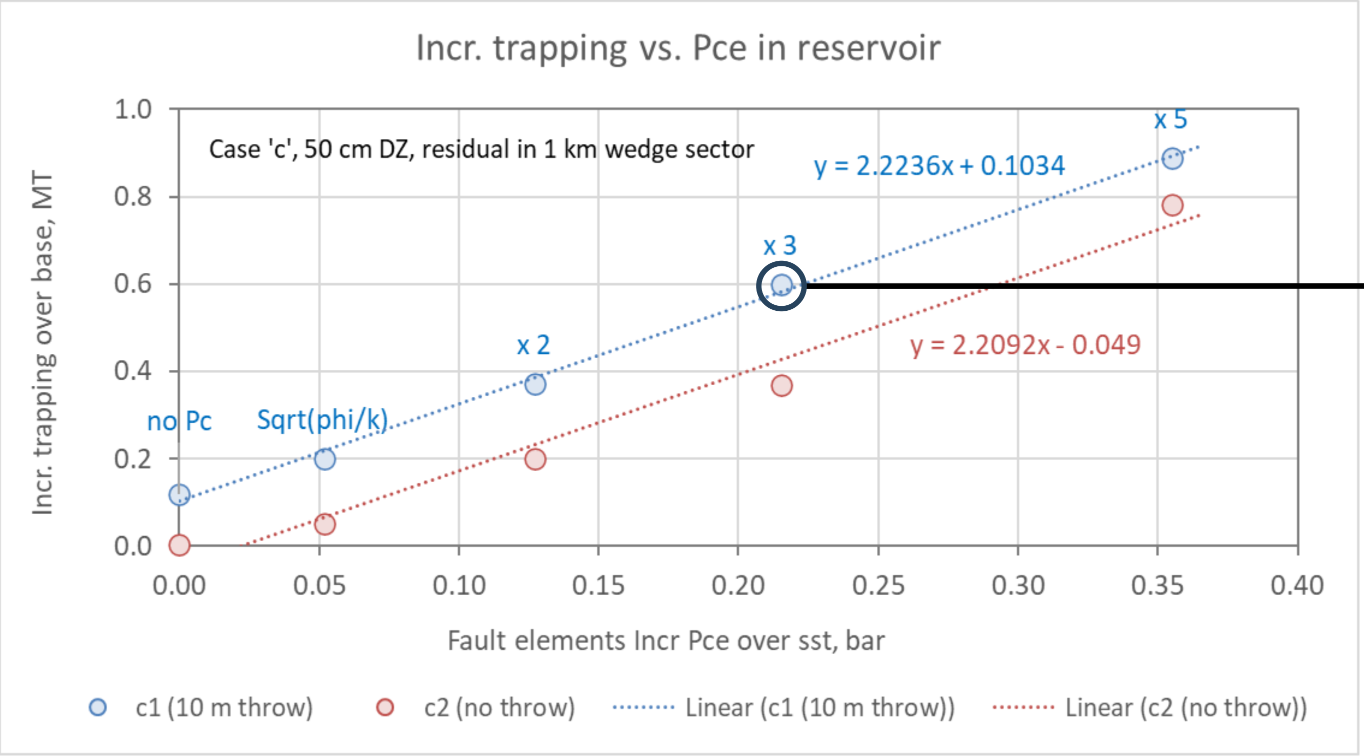



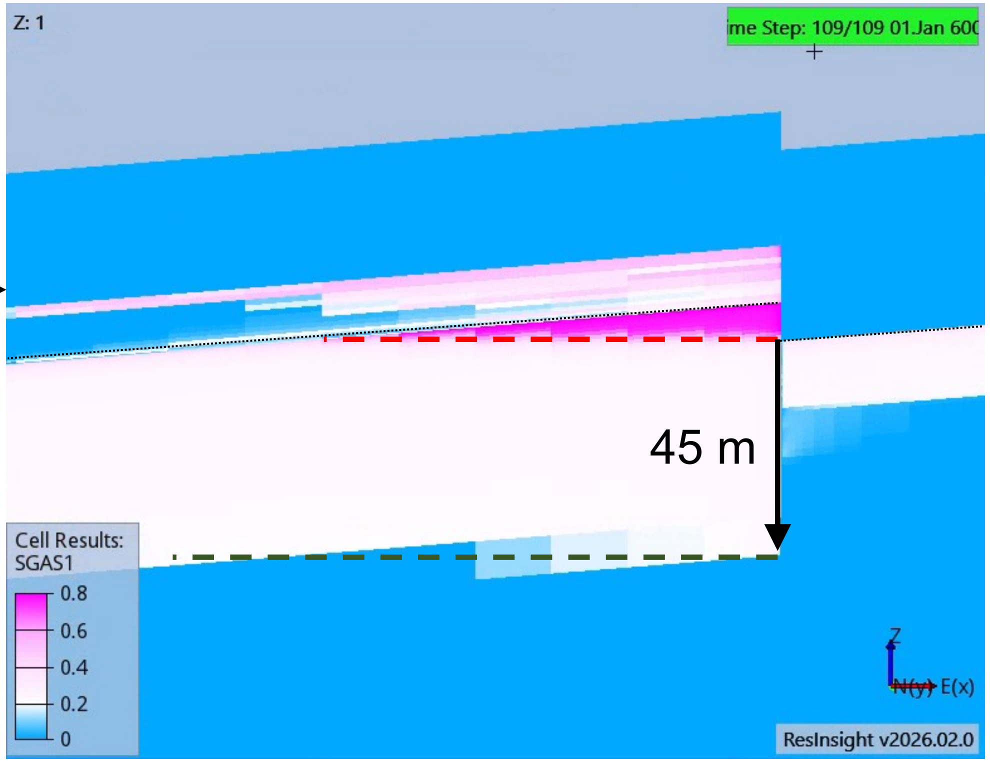
# Plume cross section (3) – extreme close up



# Static and dynamic trapping at fault

Trapping in reservoir – static (structure) + dynamic (capillary entry pressure)



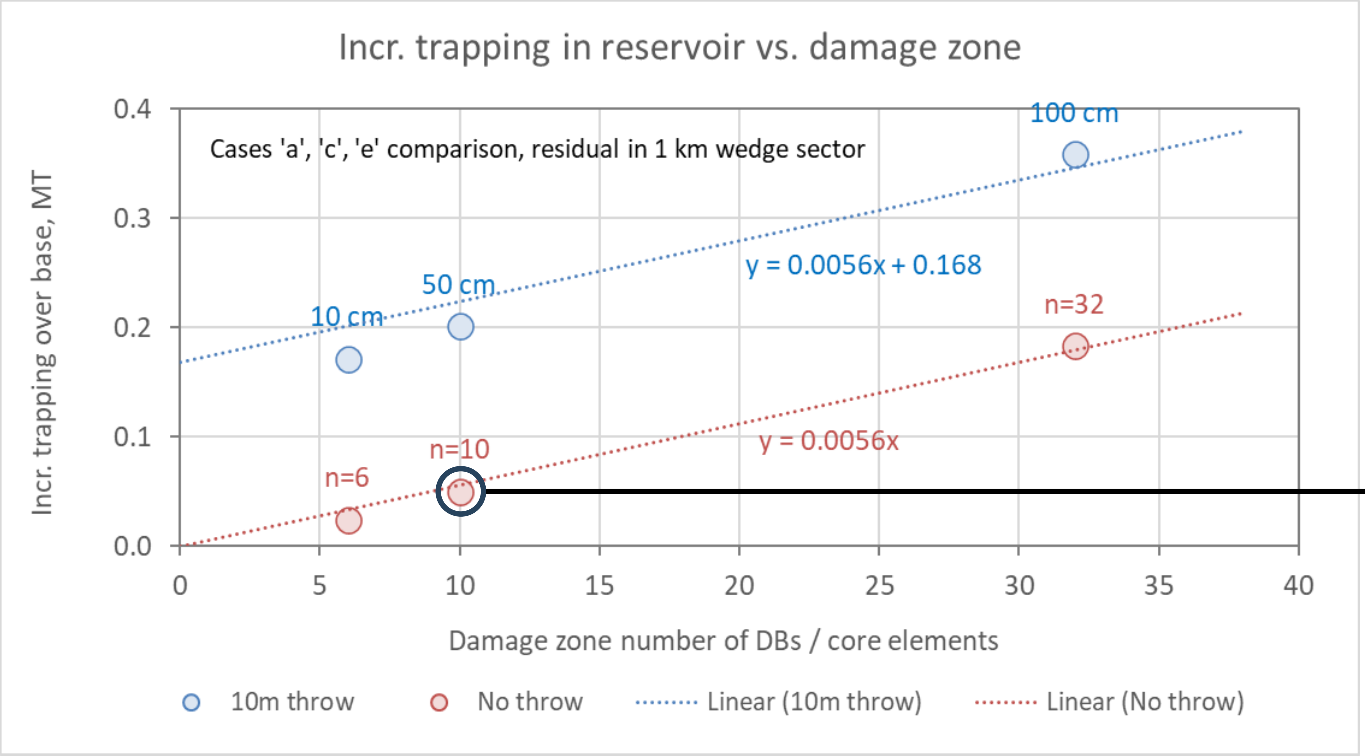



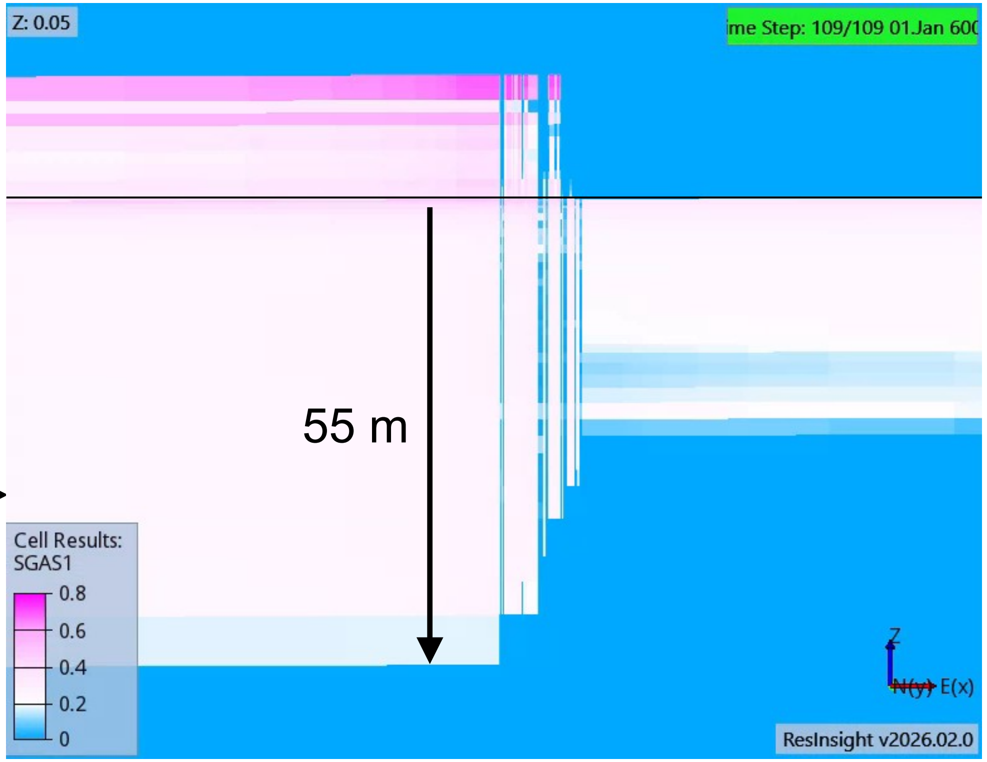

Static trapping (structure) ~ 0.1 Mt for a 10 m wedge

Dynamic trapping (entry pressure) ~ 0.1 Mt per 50 mbar entry pressure

# Effect of damage zone width / complexity

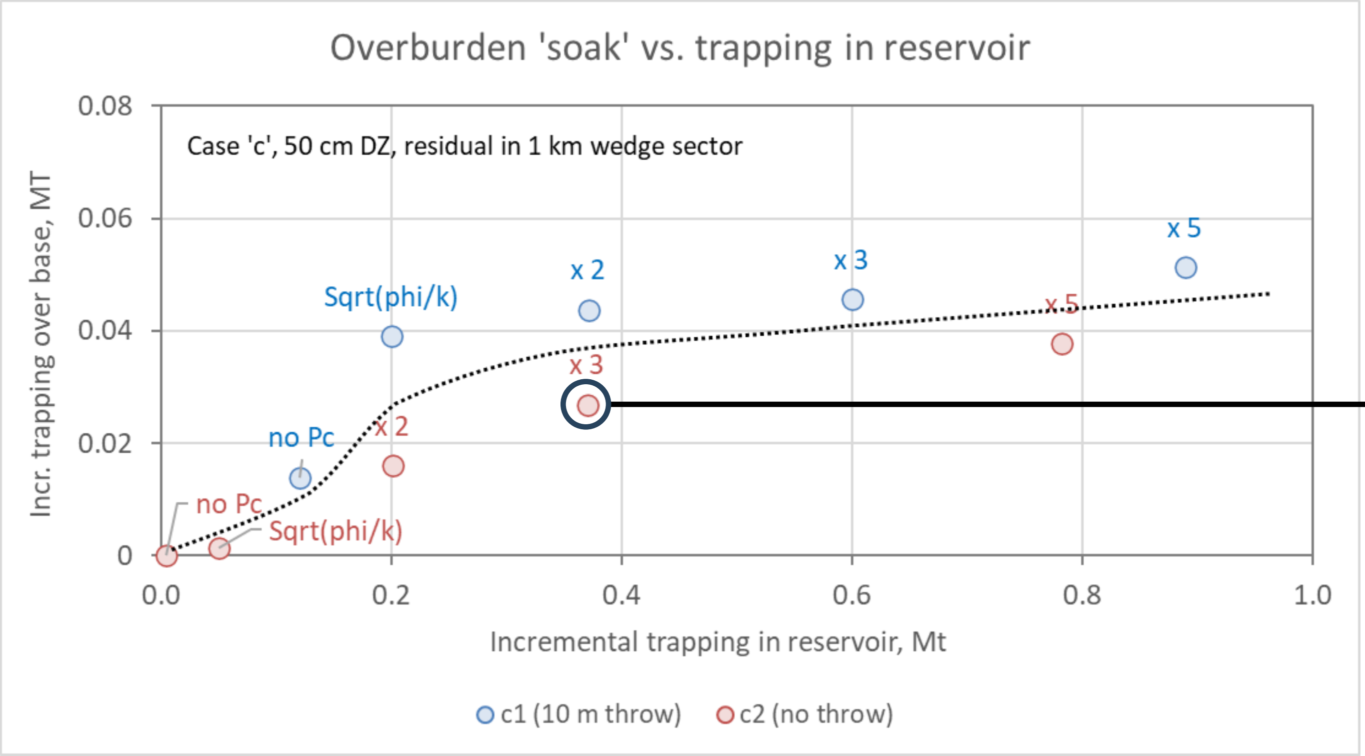
Trapping in reservoir scales with number of baffling fault elements (DBs, fault core)

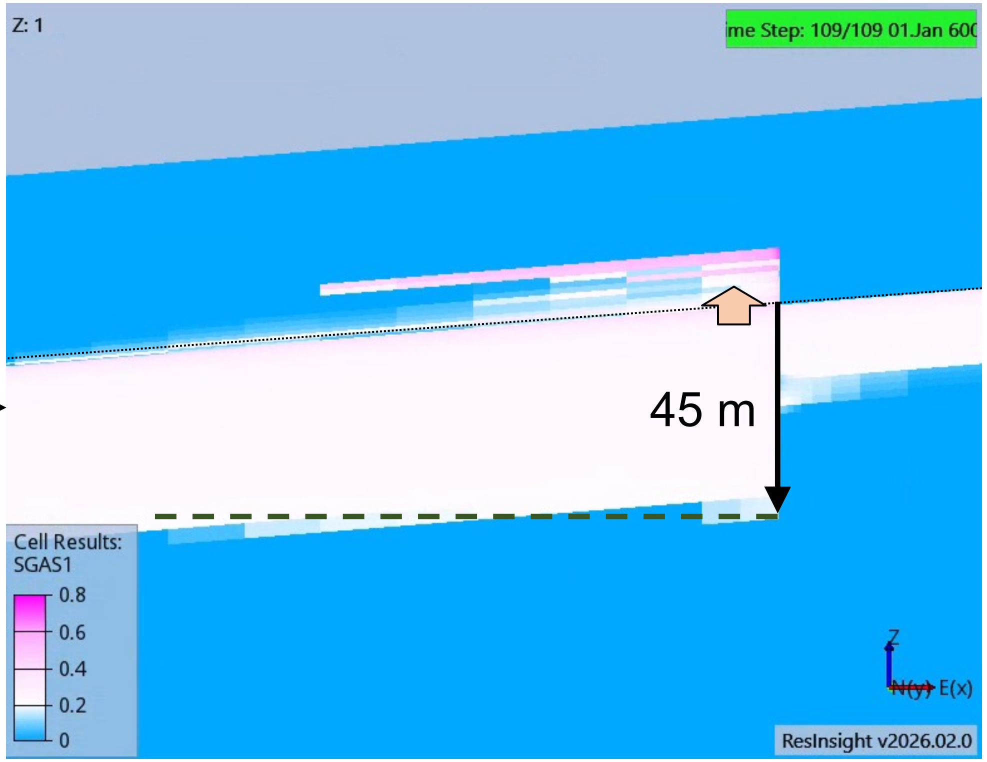


# Overburden ‘soak’

Trapping in overburden … lower but trending upwards with volume trapped in reservoir




Overburden soak ~ available mobile gas x time

# Migration Assisted Storage

## $CO_2$ area mass density

- Mt per km²

## Injector area

- +/- 1.5 km around well
- Storage ~ 10 Mt

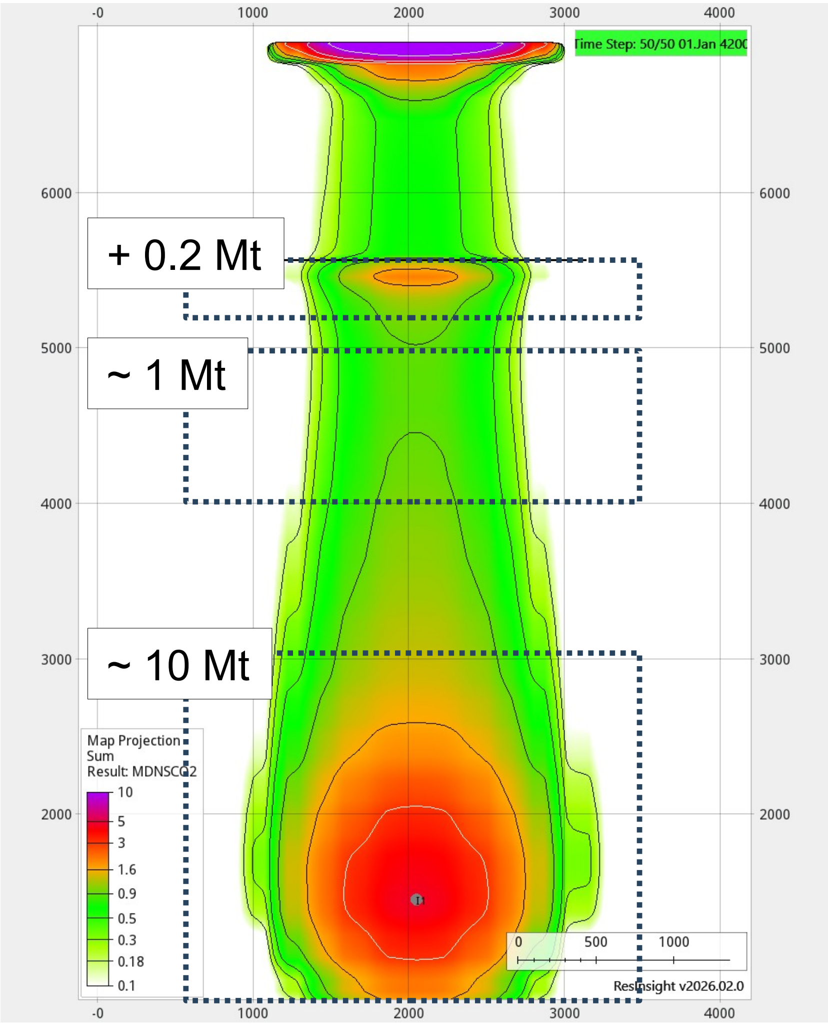
## Plume

- Av. width ~ 1 km
- Storage ~ 1 Mt / km

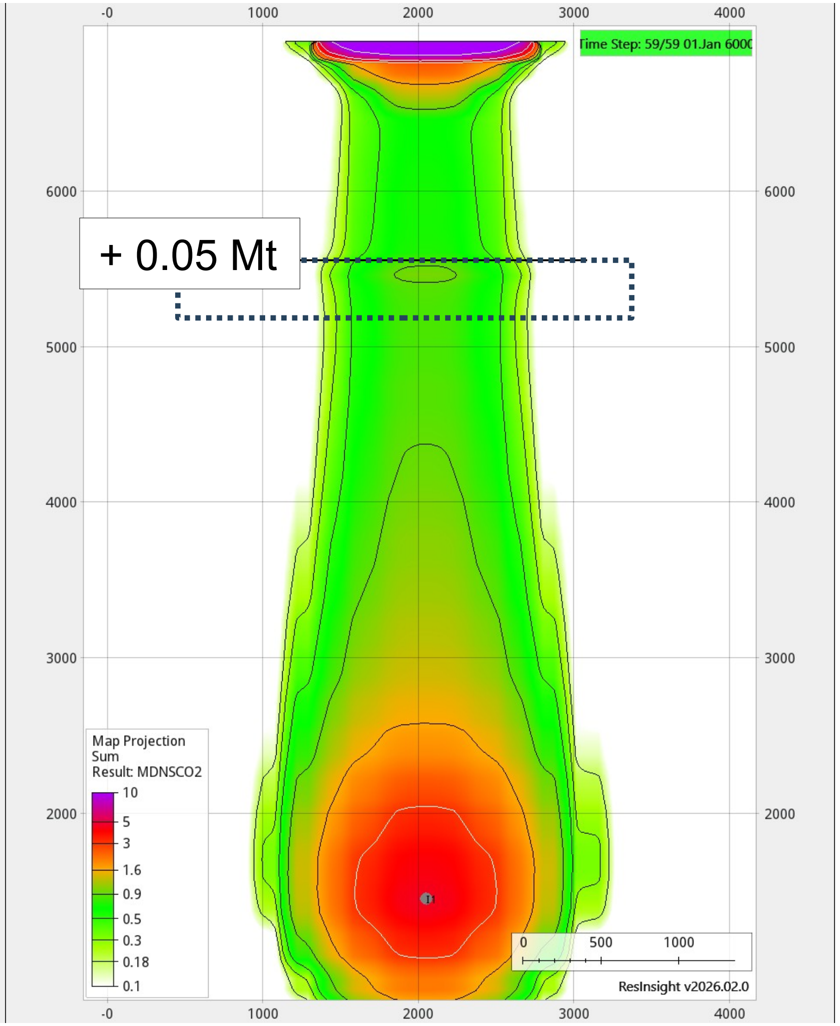
## Faults

- Additional storage
- Model case ~ 0.1 Mt

**Fault trapping, 10m throw, Mt/km²**




**No throw case, Mt/km²**



# Incremental trapping and *residence*

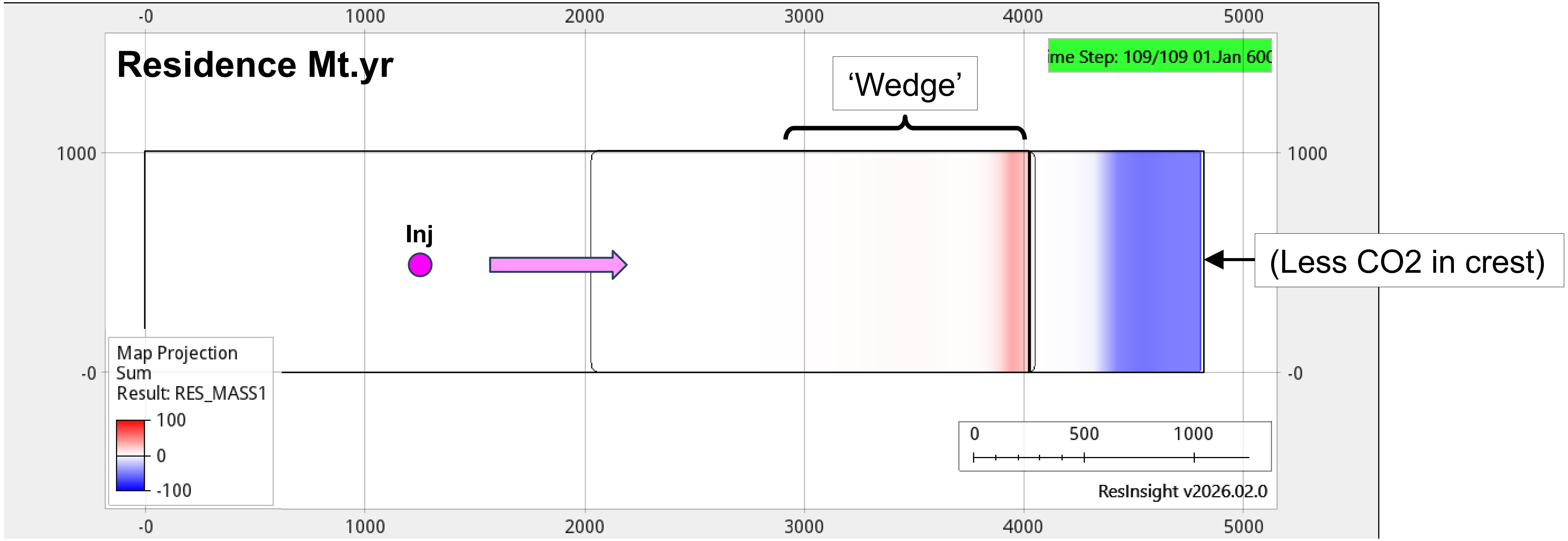
Example from 2D sector model, fault 10 m, structure dip 4°

Incremental over base case – plume with no fault

Mobile $CO_2$ trapped in ~ 1 km 'wedge'

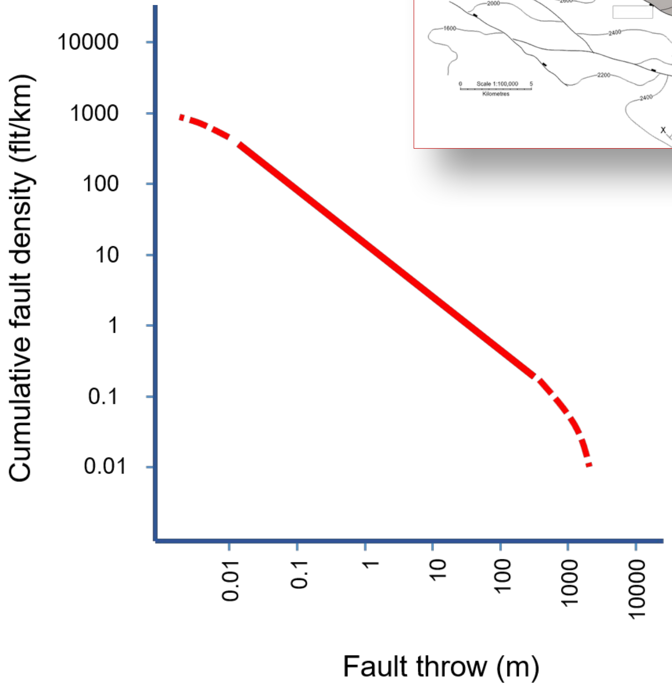
Incr. Trapping ~ 0.2 Mt
Residence ~ 200 Mt.yrs

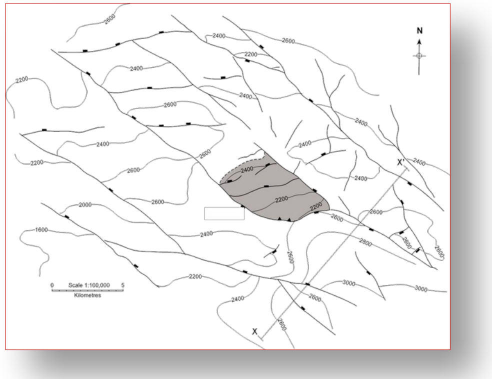
$$Residence\ R = \iint \rho_{CO_2} . S_{g,mobile}\, dt\, dV$$



# … then a thought …

*How many faults are there in a 100km long aquifer … ?*



*See also Nicol, Walsh, Watterson & Gillespie, 1996*

# Scale-up to a regional fault system

## Model calibration

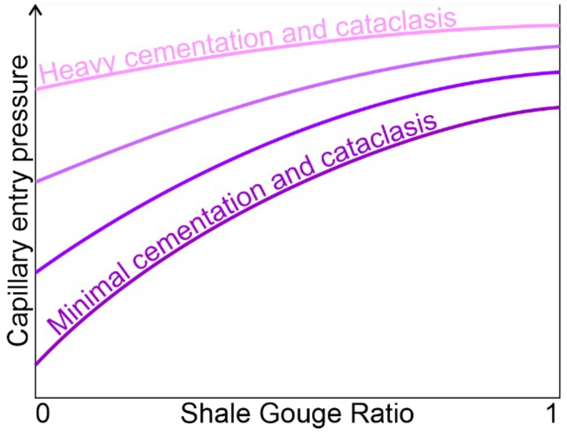
- 'Magnitude' 10 m fault → ~ 0.1 Mt structural effect, ~ 0.1 Mt capillary effect
- Incremental storage scaled to flank faults with range of sizes

## Fault properties vs. magnitude

- Fault frequency / spacing … power law exponent
- Fault DBs / core permeability … no evidence for perm scaling
- Deformation bands … harden and become more numerous with deformation

## Potential for incremental storage on flank

- Integrate 20m (seismic scale) down to ~ 10 cm (strain hardening)
- Structural effect … 0.4 Mt … referenced to 2 km spacing for 10 m fault
- Capillary effect … 0.4 Mt … Pce ~ Sqrt(phi/k), no chemical enhancement
- Overburden soak … adds further 10-20%

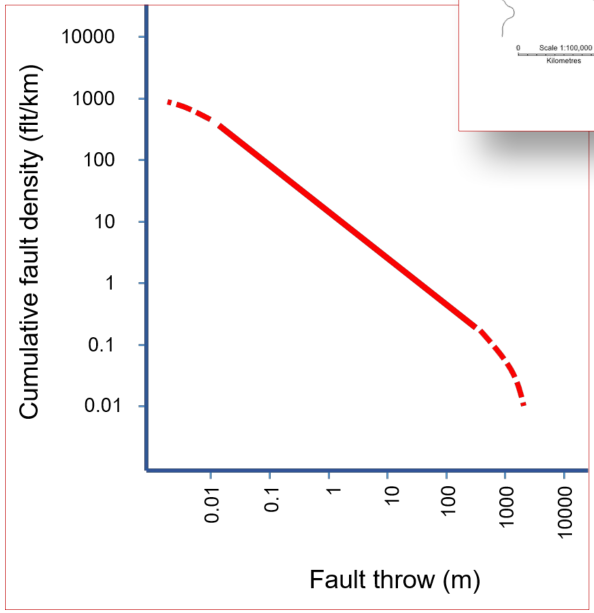



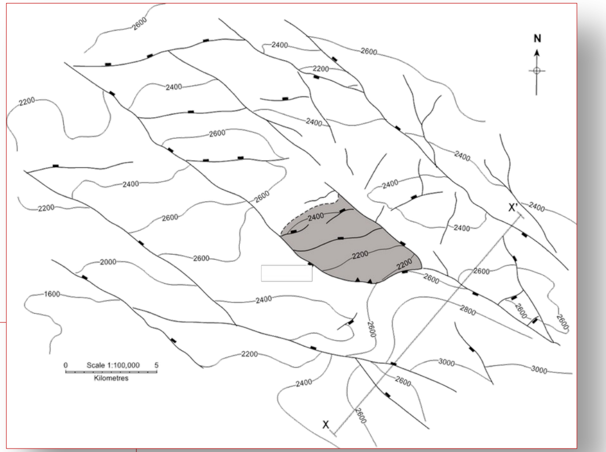

So ……

# Scaling up

## Impact of cumulative residence *(for these cases)*

**~ 1 Mt / km**



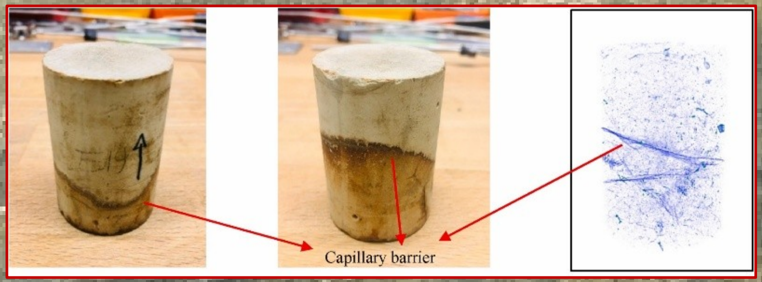



# Workflows for the CCS projects

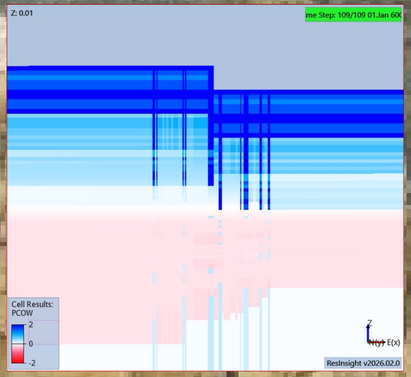
**Still dealing with heterogeneity,**

…. but with different

sensitivities and different tools

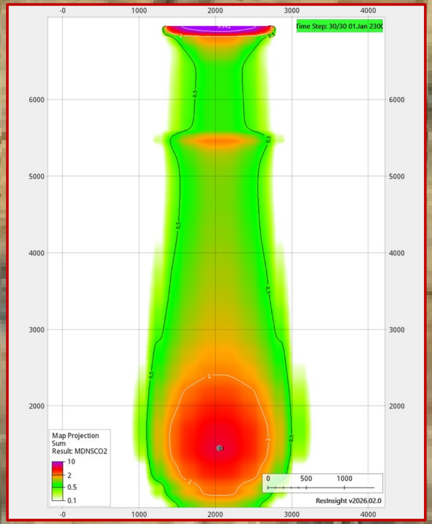







Fine-scale structural model elements *required*

Fault rock property scenarios *needed* to quantify impact




Workflows involve very high resolution models, then scale-up using structural rules

Current (simpler) coarse models are missing some good storage news