

Modelling for Storage

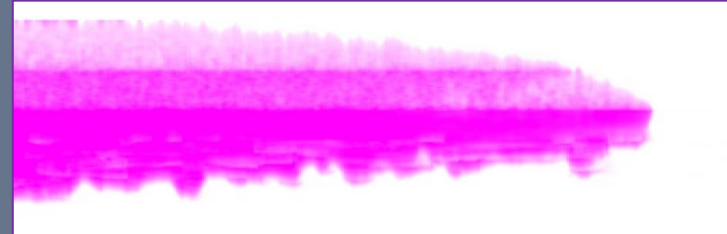
Harder than production

Mark Bentley & Ed Stephens

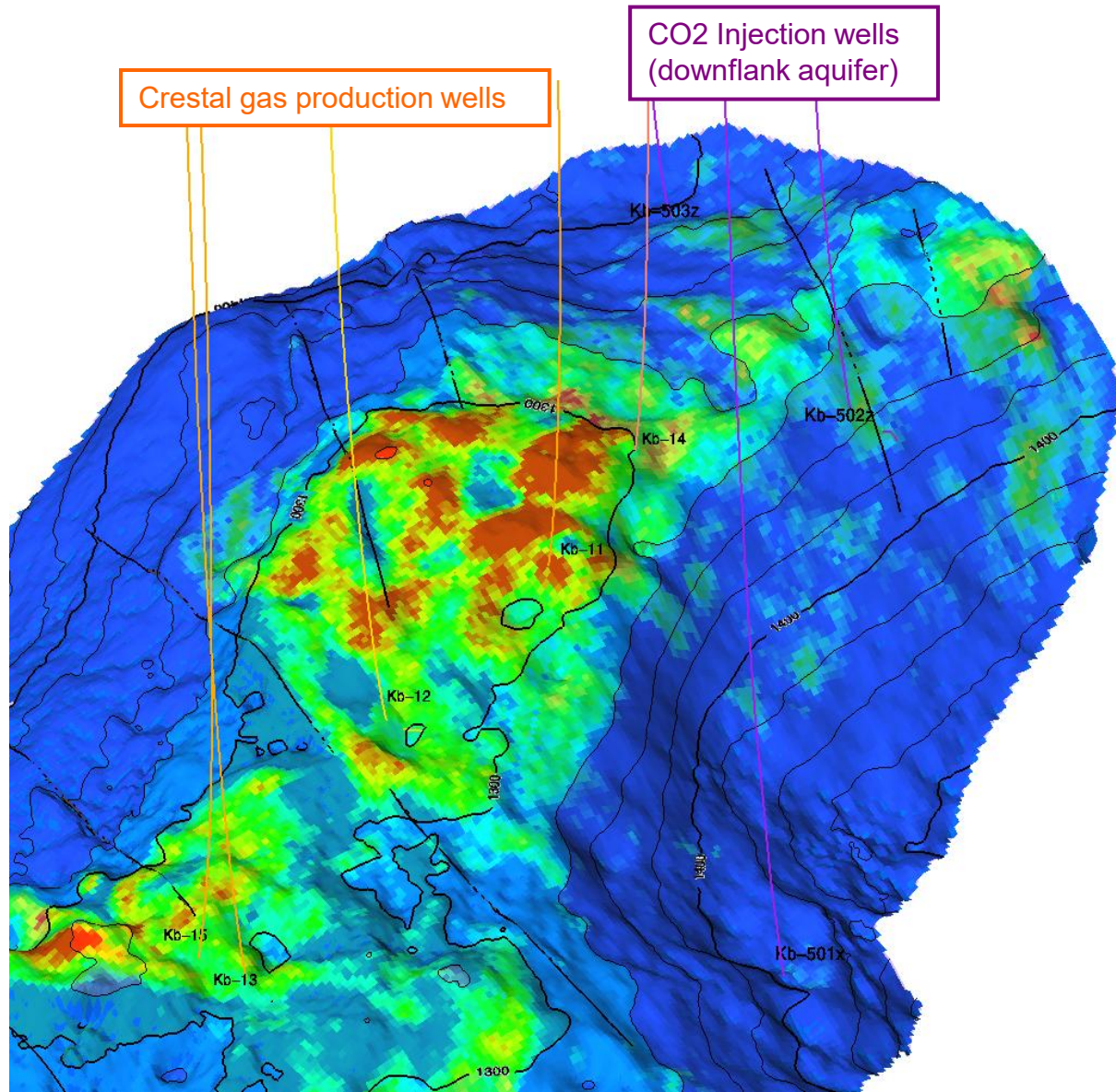
TRACS & Heriot-Watt University

*with contributions from Phil Ringrose NTNU,
and colleagues at TRACS and Heriot-Watt*

FORCE, Stavanger - October 2025



Where we were: “We need a model for CO₂ injection”



An early CCS reservoir model for In Salah

Just a gas injection project!

Easier than production

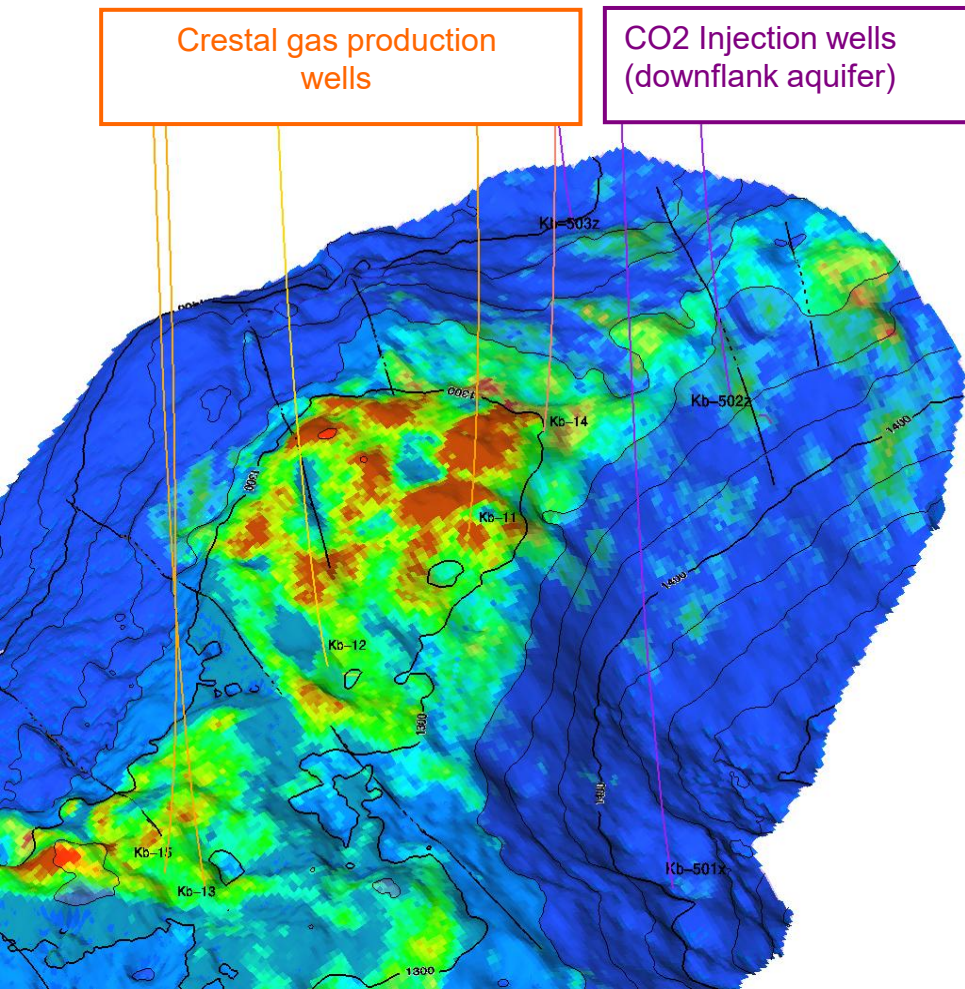
Doesn't need many wells

Reuse old fields

We have the necessary skills

How disappointing 😞

Where we were naïve



Not a gas !

Not a field-scale issue

Not a one well issue either

Old fields not the obvious choice

.. and we don't have *all* the skills

Much more interesting 😊

Models for Storage vs. Production



Study volume

XXL



Fluids and forces

Supercritical



Heterogeneity - matrix

Friend or foe?



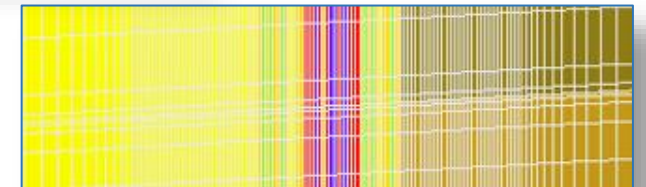
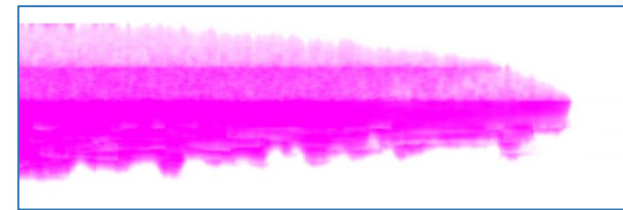
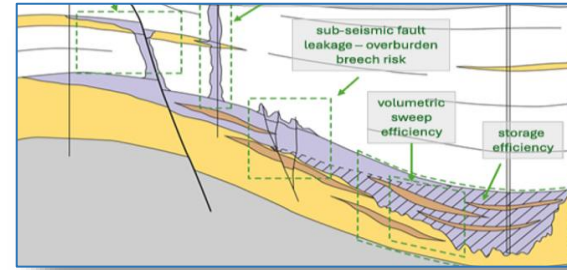
Heterogeneity - structure

Must try harder

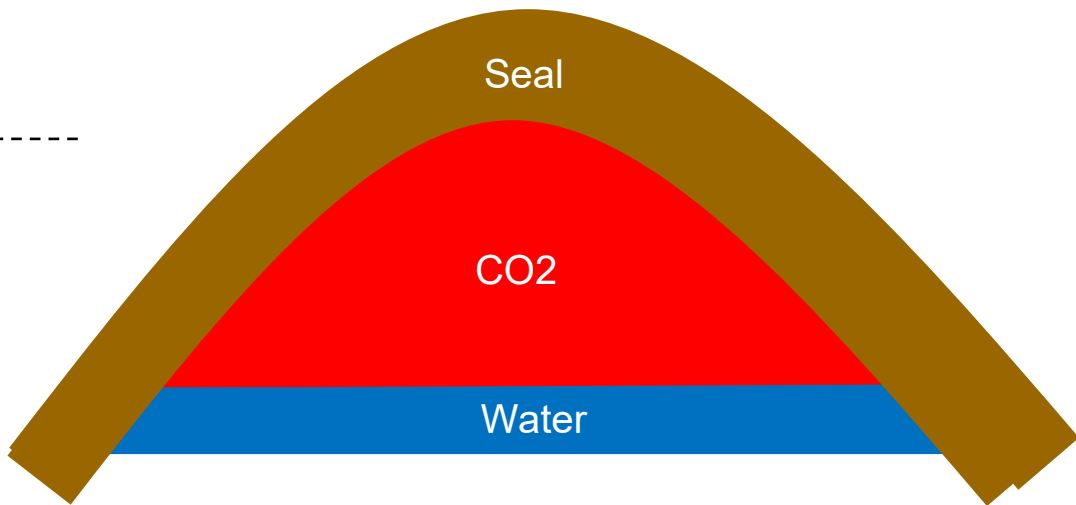
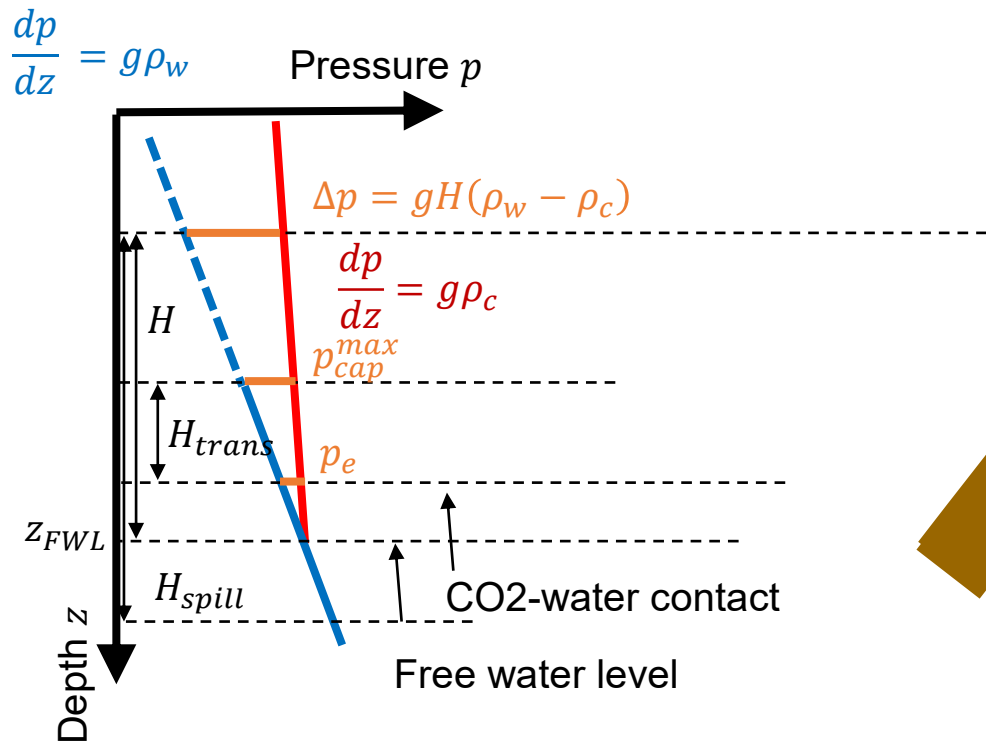


Scale

The big challenge

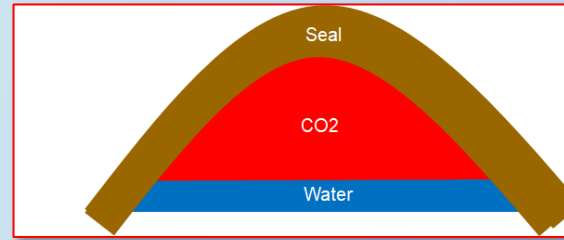


Opening question





Column height



0 response submitted

Scan the QR or use
link to join



<https://forms.office.com/e/gbDY1ksdY4>

Copy link

A - Shorter height than a methane column

B - Similar height to a methane column

C - In-between oil and gas column heights

D - Similar to an oil column height

E - Longer than an oil column height

Treemap

Bar

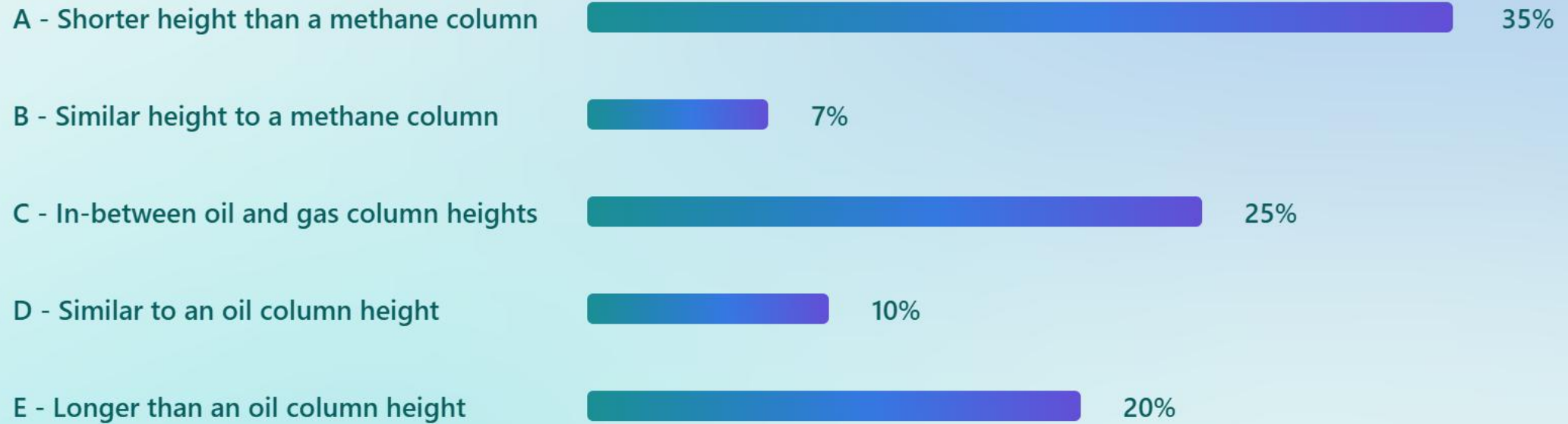


1 of 1



responses submitted

Column height



Treemap

Bar



1 of 1



Seal assessment: exemplary numbers

Spill point $H_{spill} = 200m$

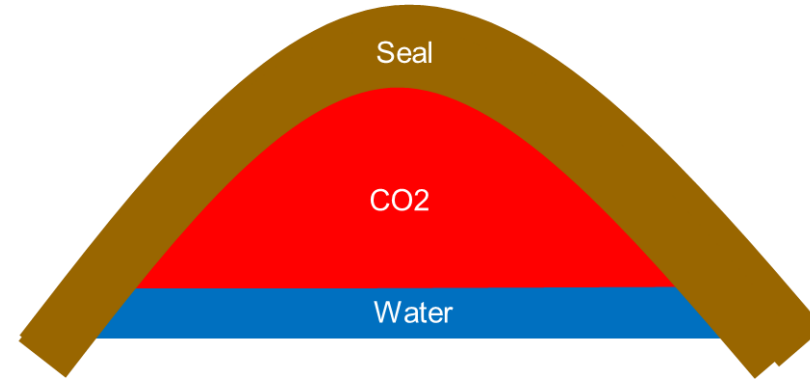
Maximum pore radius seal

$r_{max} = 50 nm$

Strongly water-wet ($\theta = 30^\circ$)

Brine density $\rho_w = 1050 kg m^{-3}$

The interplay between buoyancy and capillarity decides whether a seal is good



	Gas	Oil	CO ₂
Density ($kg m^{-3}$)	400	700	500
σ_{nw} ($mN m^{-1}$)	50	40	25
H_{max} (m)	272	404	161

Quick calculation from Florian Doster, Heriot-Watt

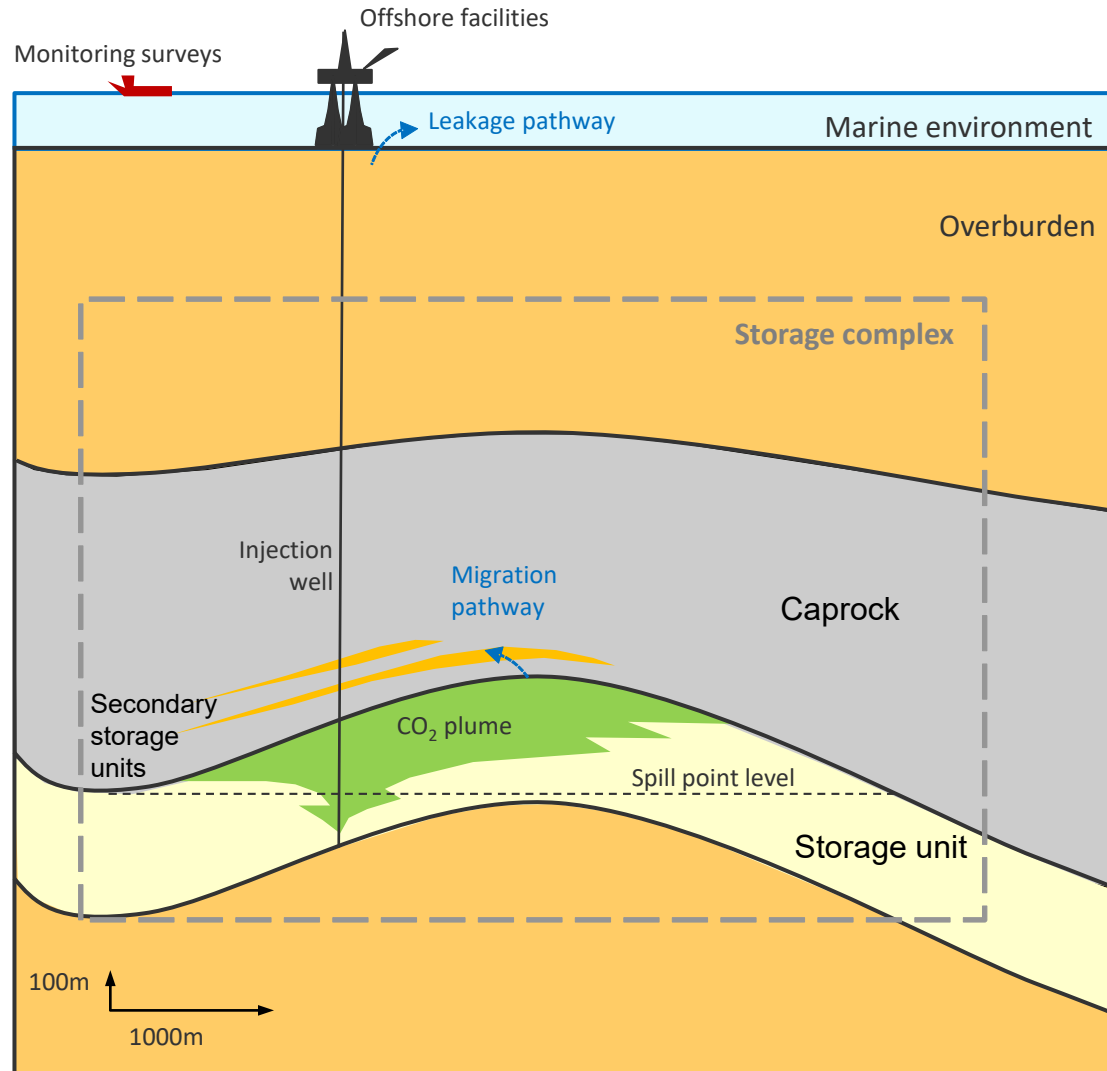
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STUDY VOLUME

It's not reservoir modelling



The 'Storage Complex'

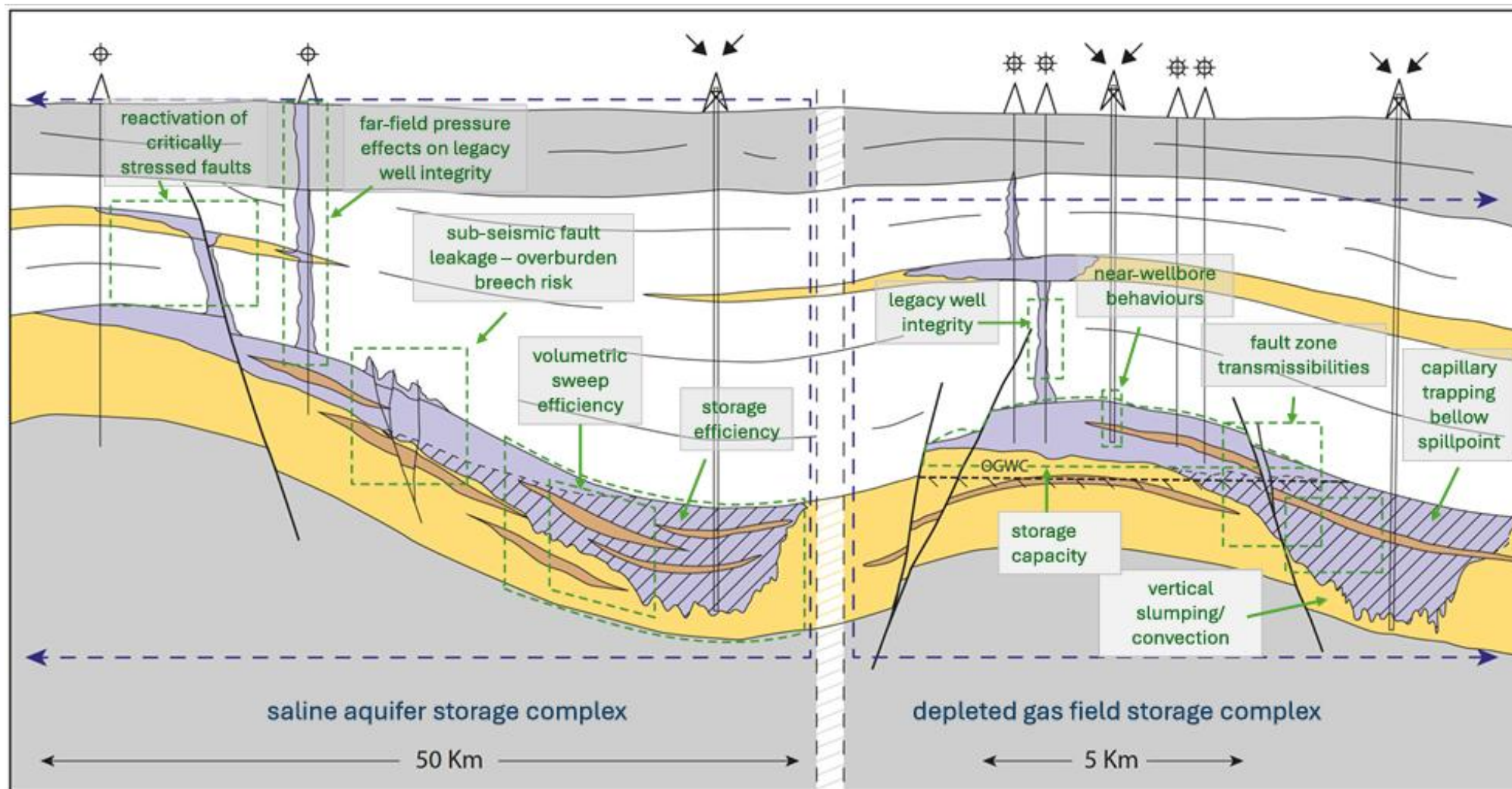


EU CCS Directive (EC 2009; annex 1):

“Sufficient data shall be accumulated to construct a volumetric and 3-D static earth model for the storage site and storage complex, including the caprock, and the surrounding area, including the hydraulically connected areas”

Not reservoir
modelling

The 'Storage Complex' – modelling much more than the reservoir



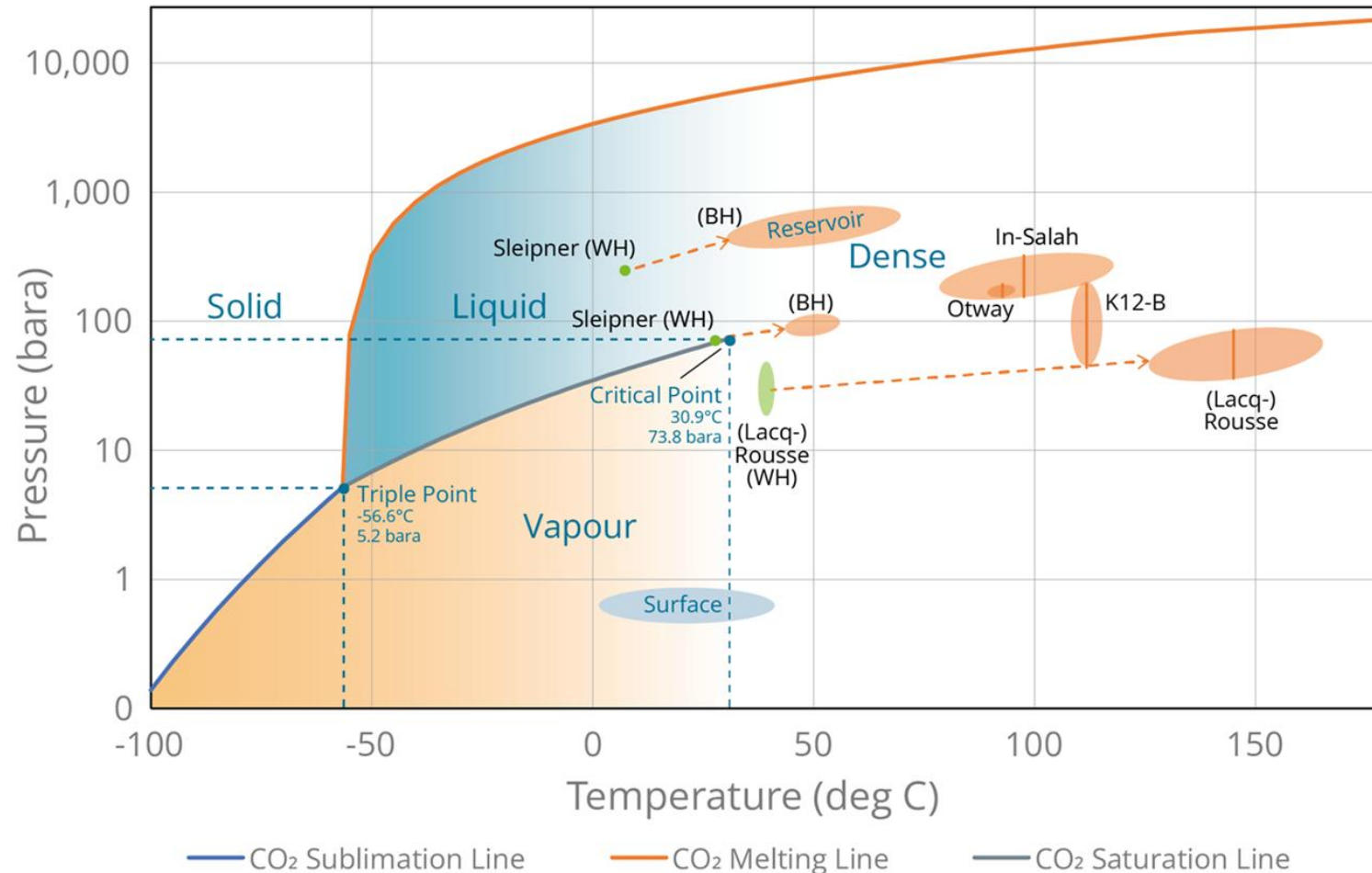
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FLUIDS AND FORCES

Supercritical



Supercritical CO₂ – the Dense Phase



The '4th phase'

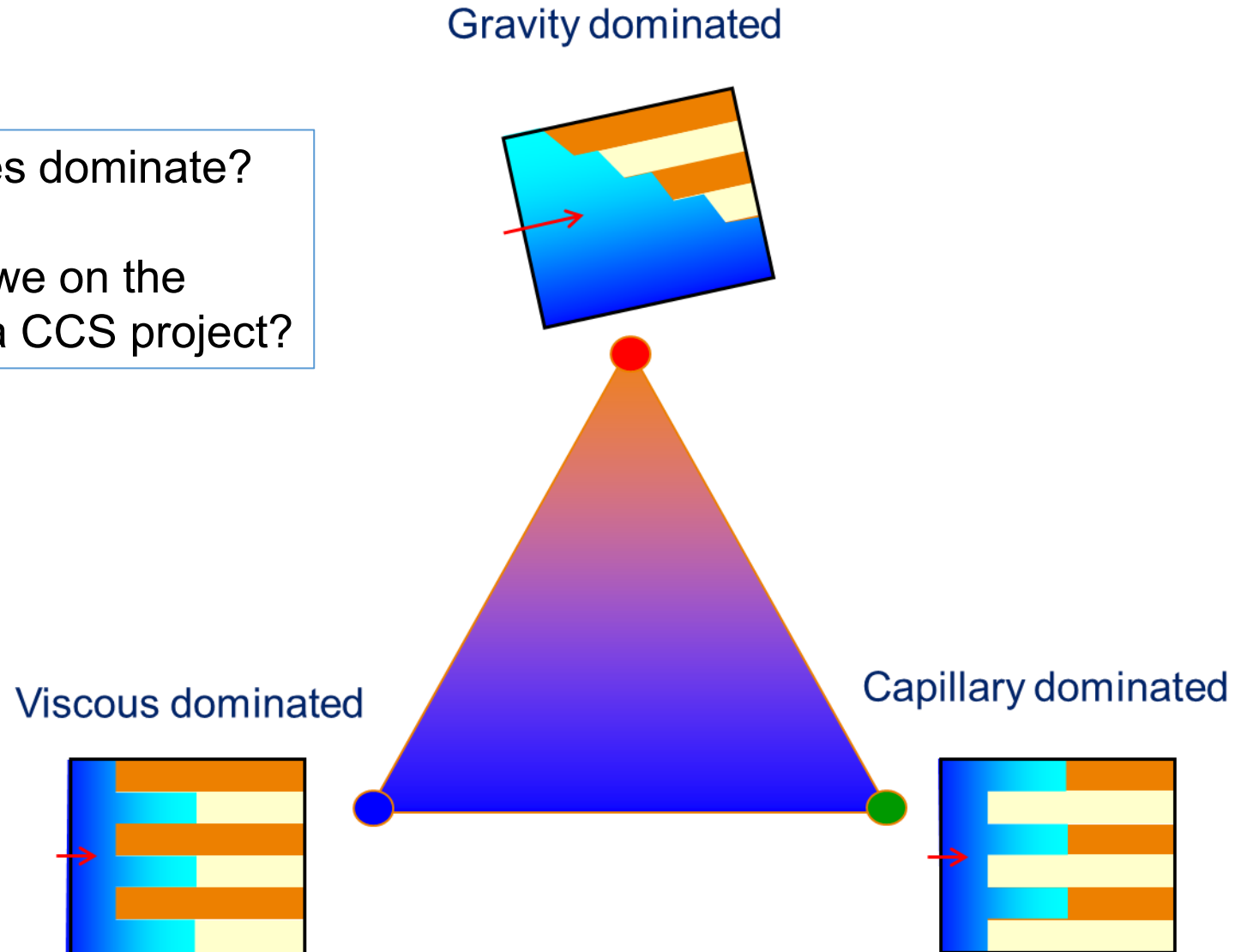
Supercritical CO₂ with **viscosity** similar to a gas, but **density** closer to a liquid, but highly **compressible**



Physics – balance of forces



Which forces dominate?
Where are we on the ternary for a CCS project?





Scan the QR or use
link to join



<https://forms.office.com/e/YjAeR3Q0Ew>

Copy link

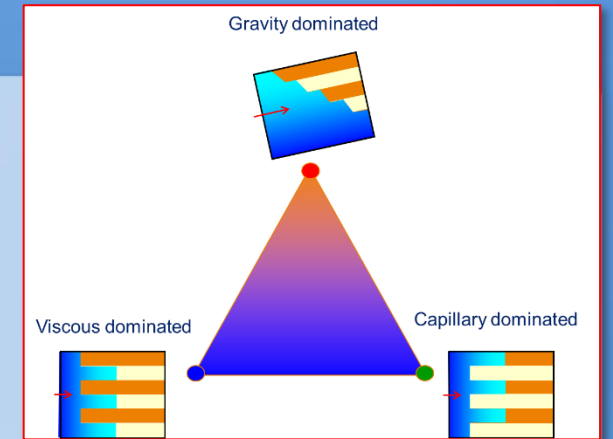
Force balance – which force dominates?

A - Viscous force

B - Gravity force

C - Capillary force

D - All three



Treemap

Bar

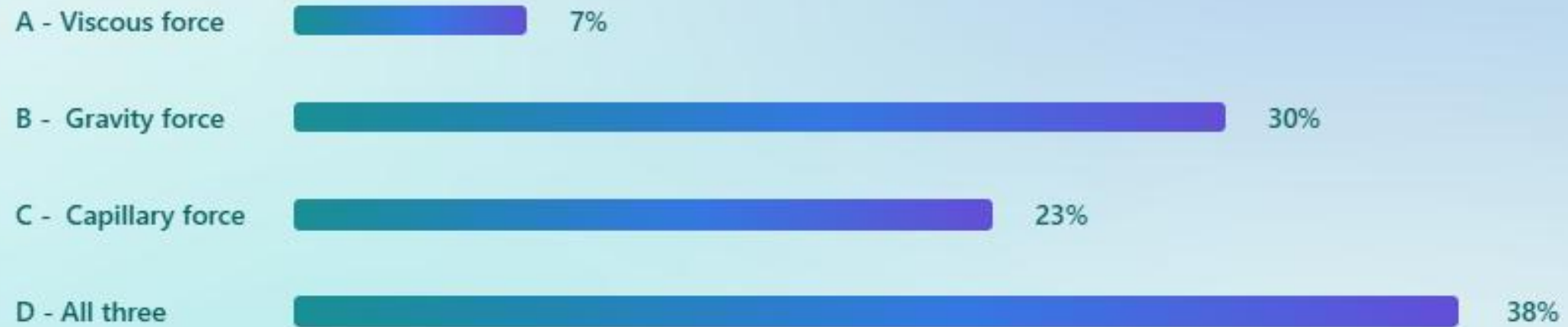


1 of 1



responses submitted

Force balance – which force dominates?



Treemap

Bar

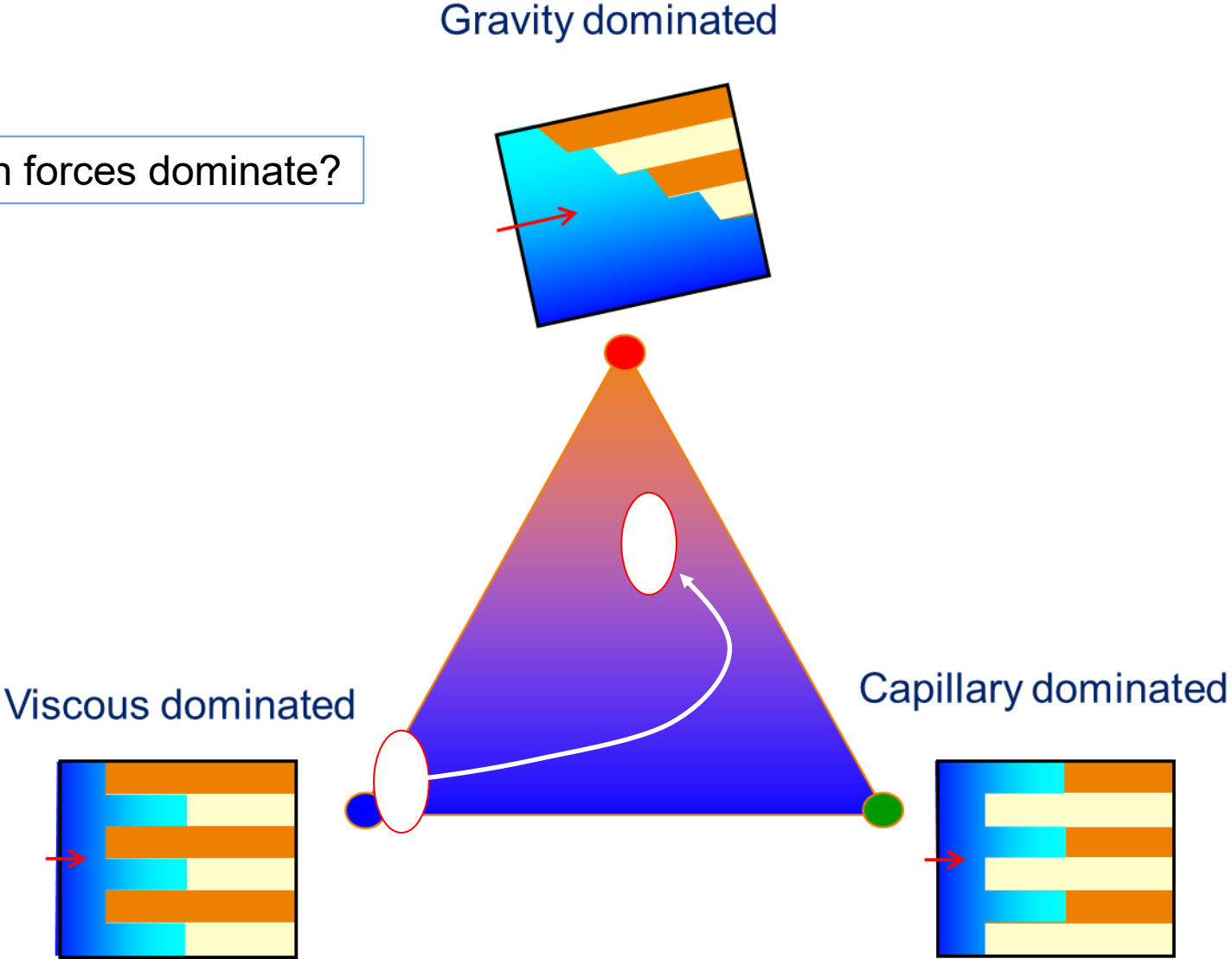


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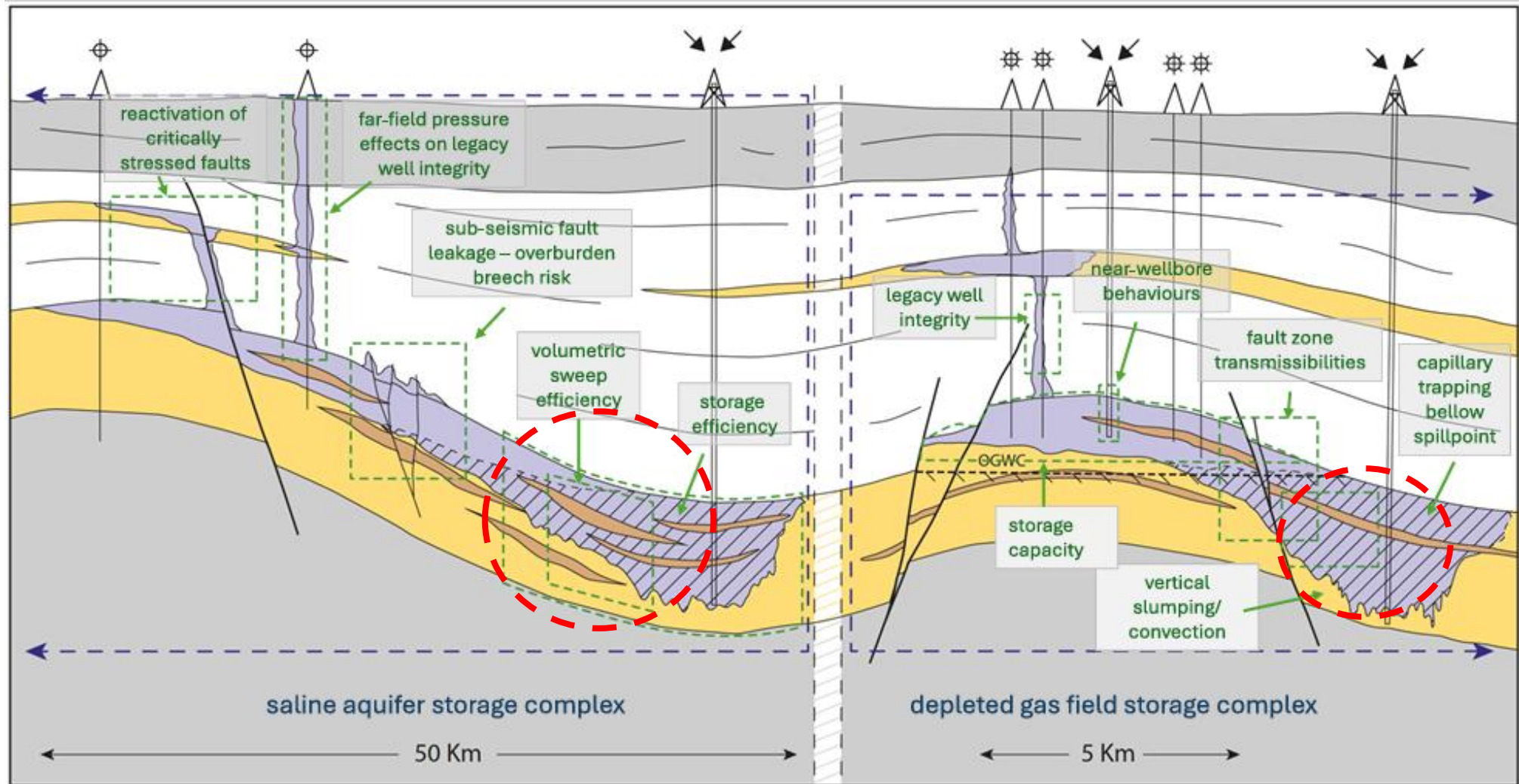


Physics – balance of forces

Which forces dominate?

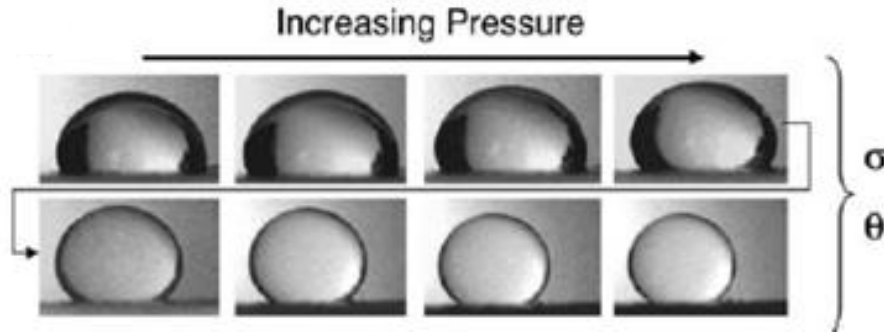


The 'Storage Complex'

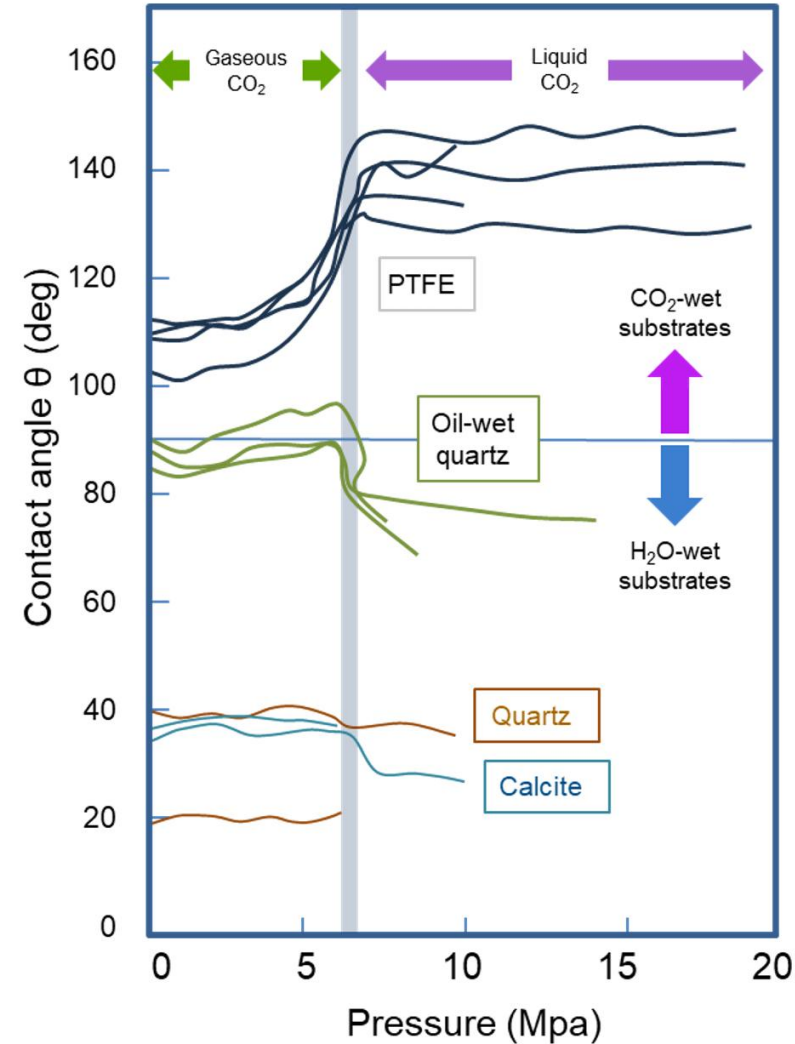
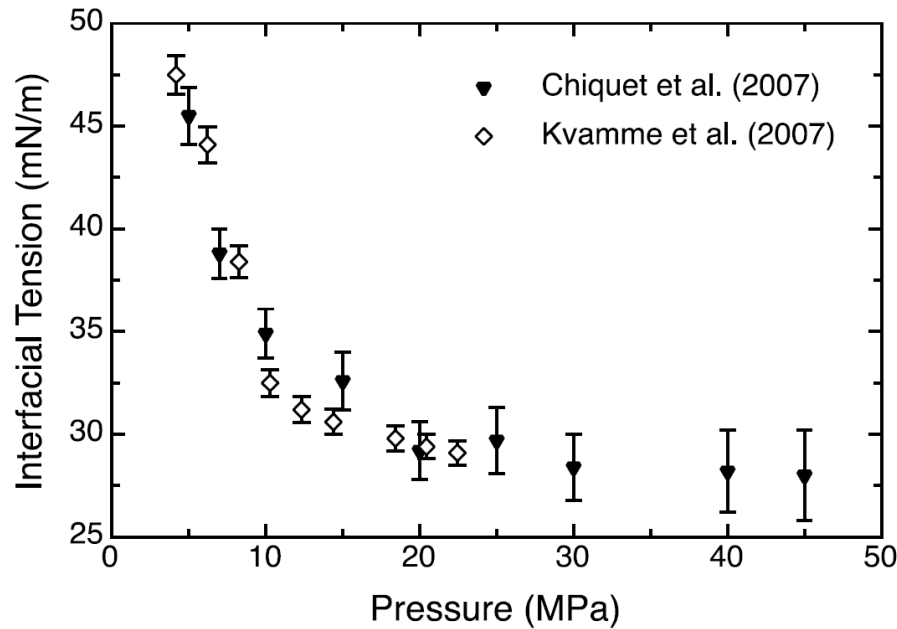


What do know about contact angles?

Droplets of water in supercritical CO₂ on a PTFE substrate



Interfacial tension of water and supercritical CO₂



Contact angle of water droplets on a range of substrates

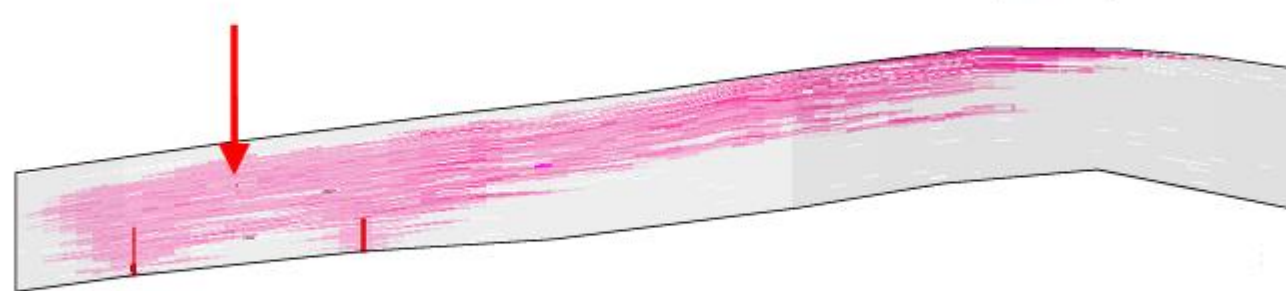


How CCS models go bad

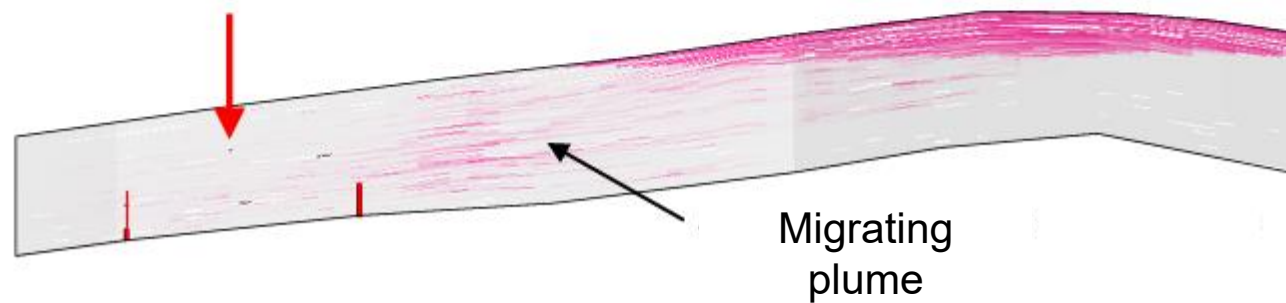
A:
Drainage &
imbibition



B:
Imbibition only



C:
Drainage only





0 response submitted

Use of rel pem curves for aquifer storage

Scan the QR or use link to join



<https://forms.office.com/e/CHF2jfhJet>

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A - Use drainage curves

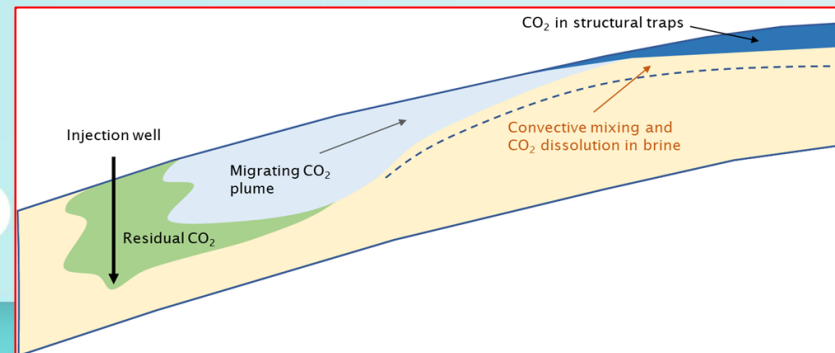
B - Use imbibition curves

C - Use both

D - Use something different

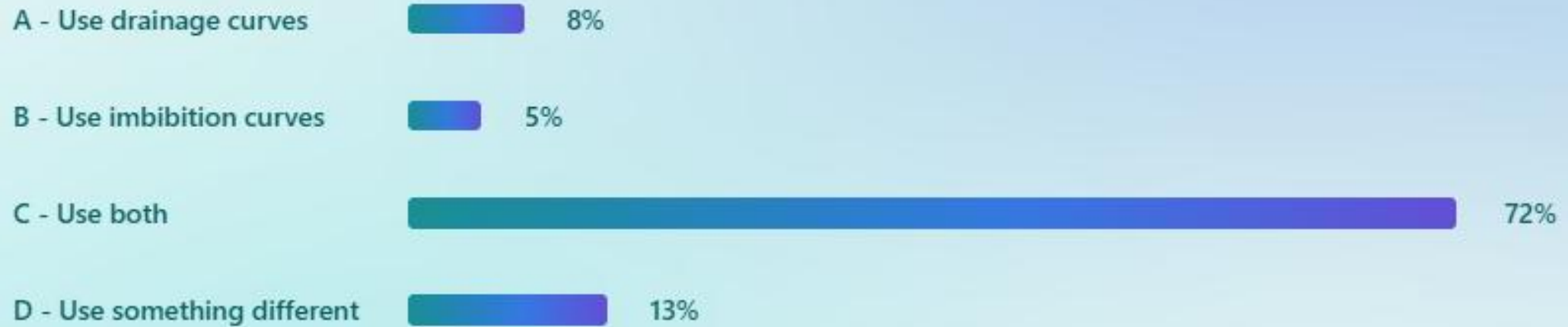
Treemap

Bar



responses submitted

Use of rel pem curves for aquifer storage



Treemap

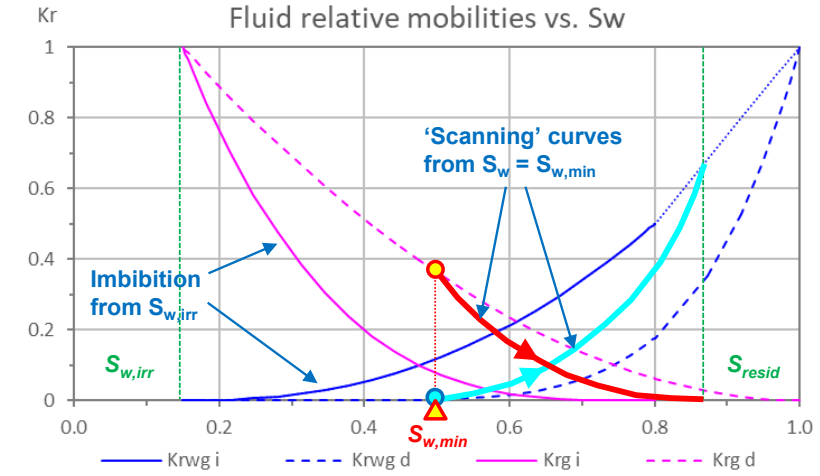
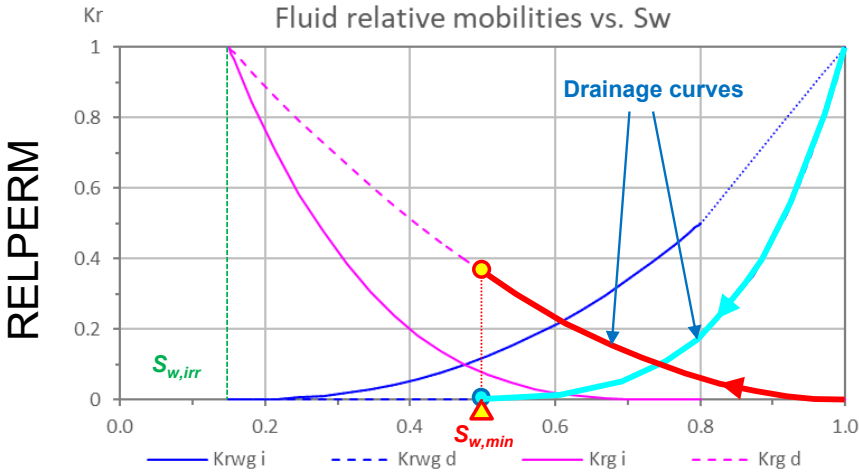
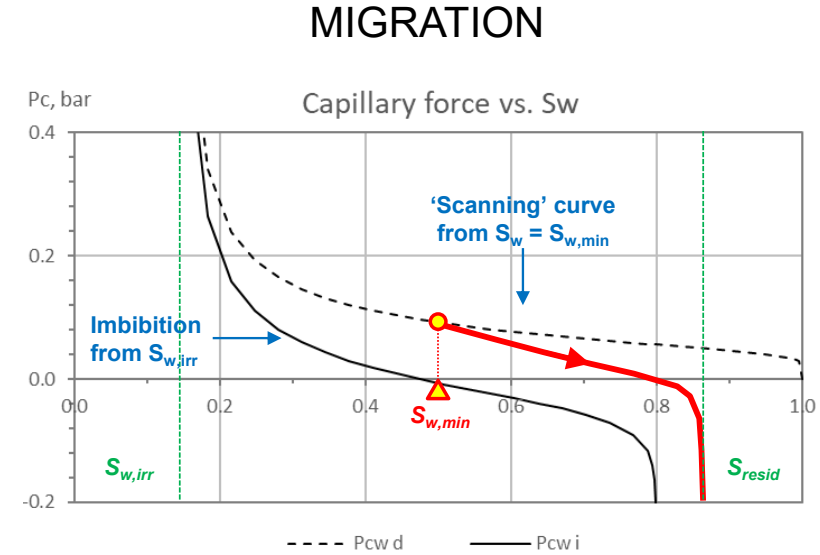
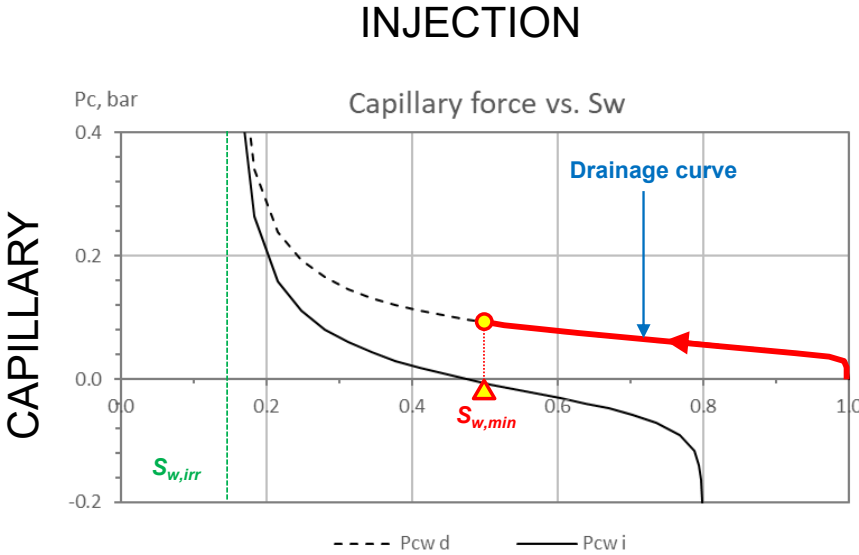
Bar



1 of 1



Drainage and imbibition

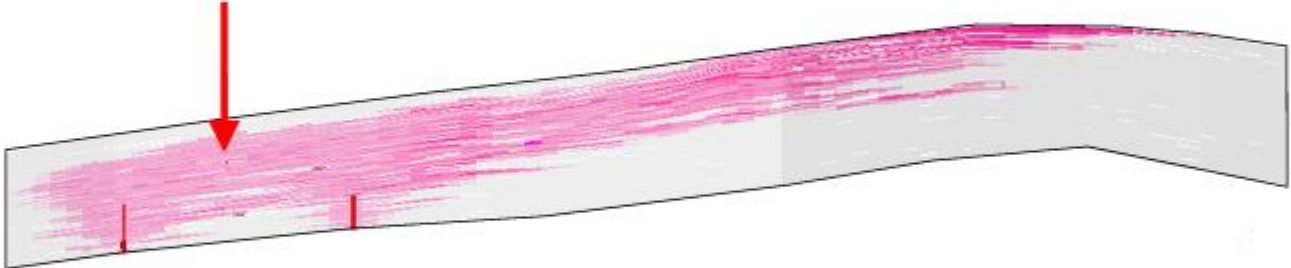


How CCS models go bad

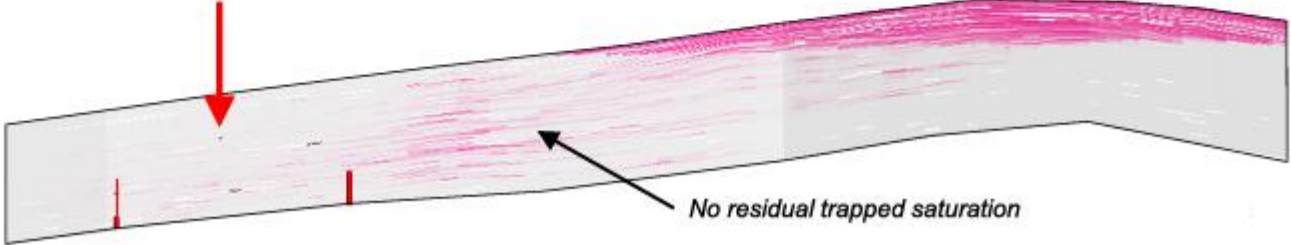
A:
Drainage &
imbibition



B:
Imbibition only



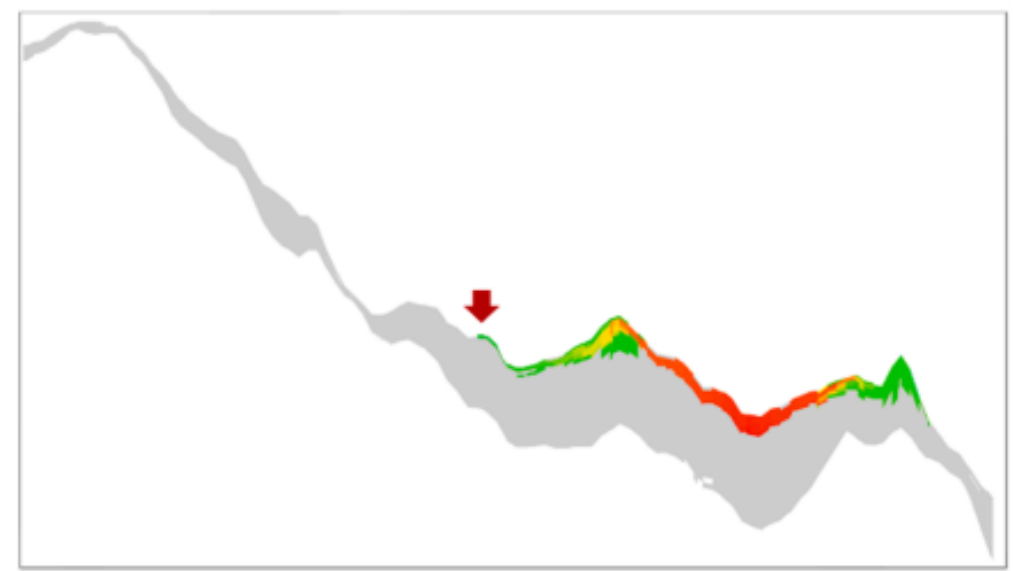
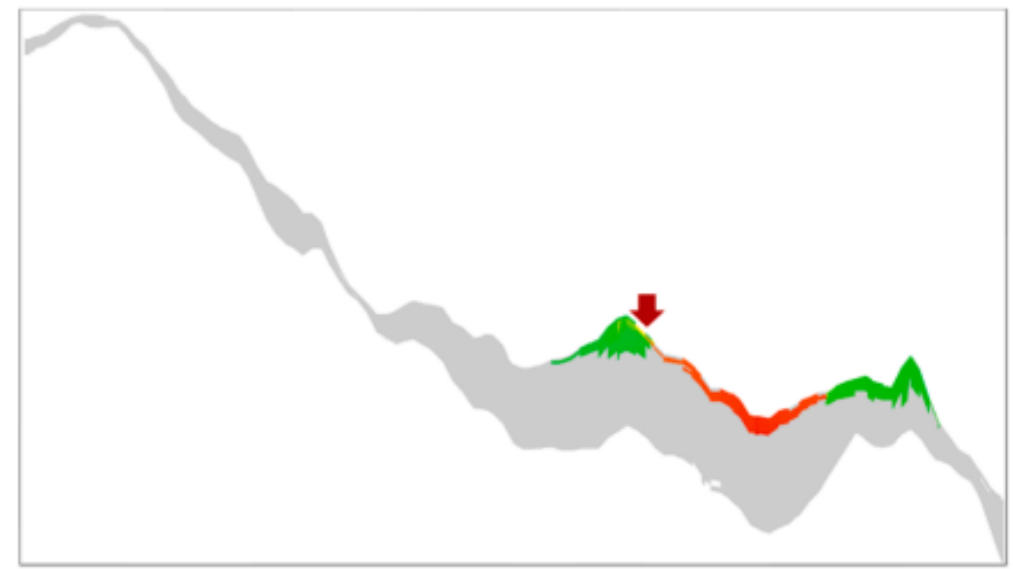
C:
Drainage only



Which gas ends up where?

Gas density varies within the plume

- red = CO₂-rich
- green = methane rich)

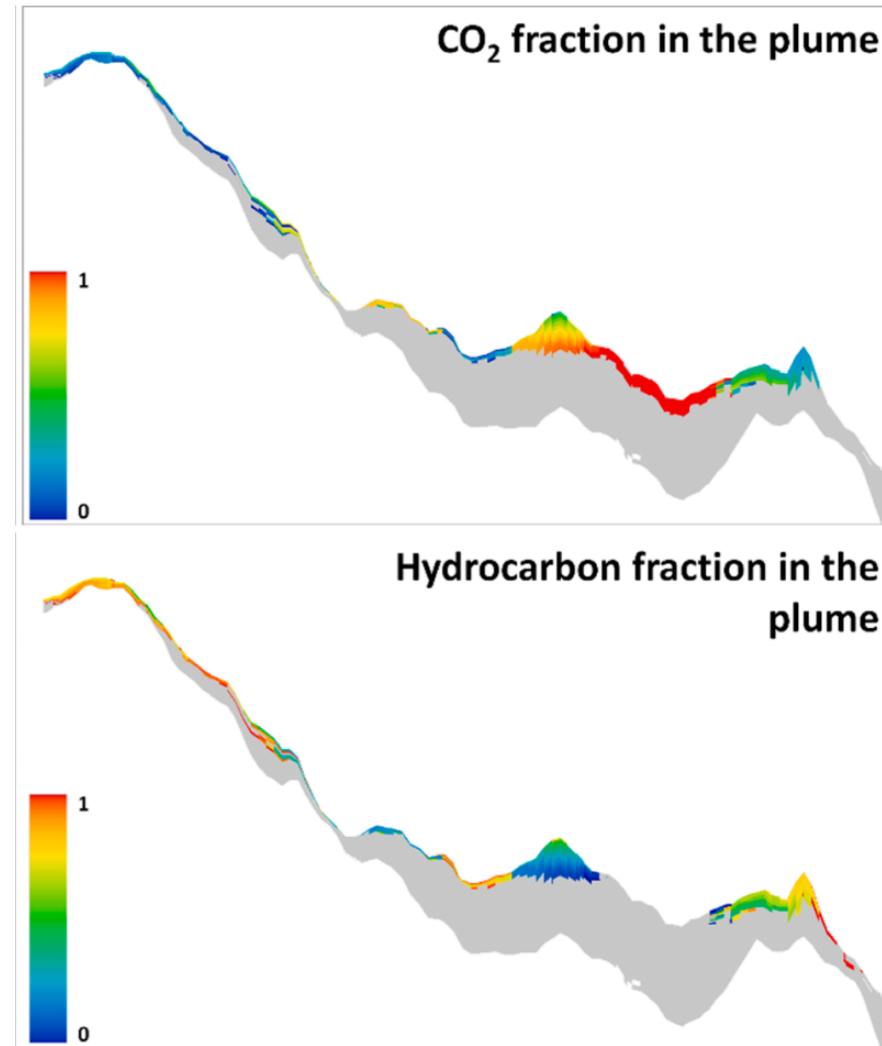


Saaed Ghanbari, Eric Mackay, Niklas Heinemann, Juan Alcalde, Alan James, Michael Allen, 2021

Which gas ends up where?

1000 years later

- Buoyancy takes over
- Remobilised methane ends up at the trap margin more quickly than forecast
- Overall storage capacity is reduced



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HETEROGENEITY – MATRIX

Friend or foe?



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?



0 response submitted

Sensitivity to permeability heterogeneity (orders of magnitude)

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Copy link

A - Greater than 3 orders

B - 3 orders

C - 2 orders

D - 1 order

E - Less than 1 order

Treemap Bar

< 1 of 1 >

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

responses submitted

Sensitivity to permeability heterogeneity (orders of magnitude)



Treemap

Bar

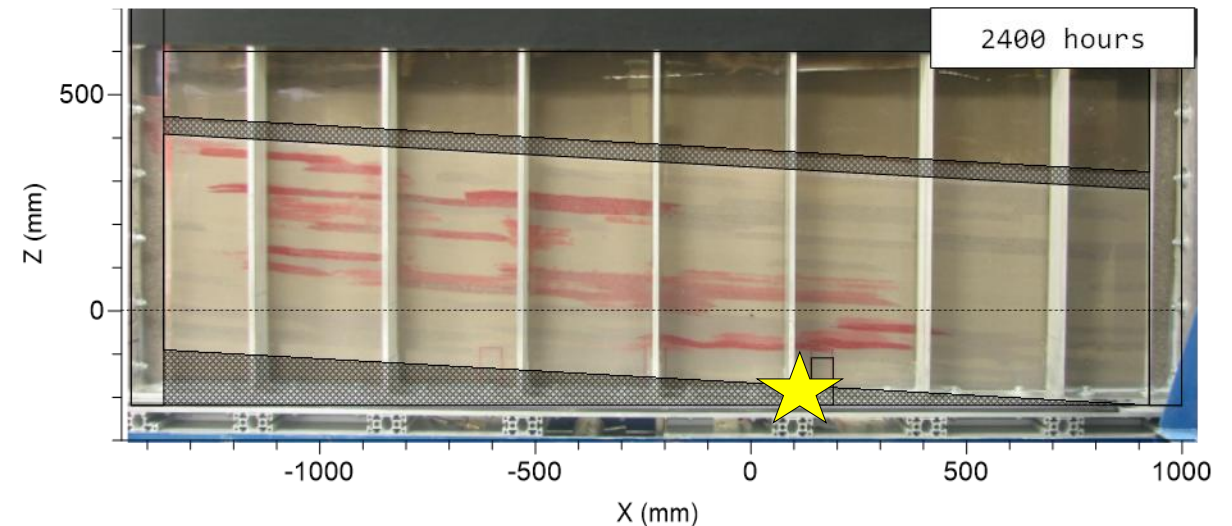
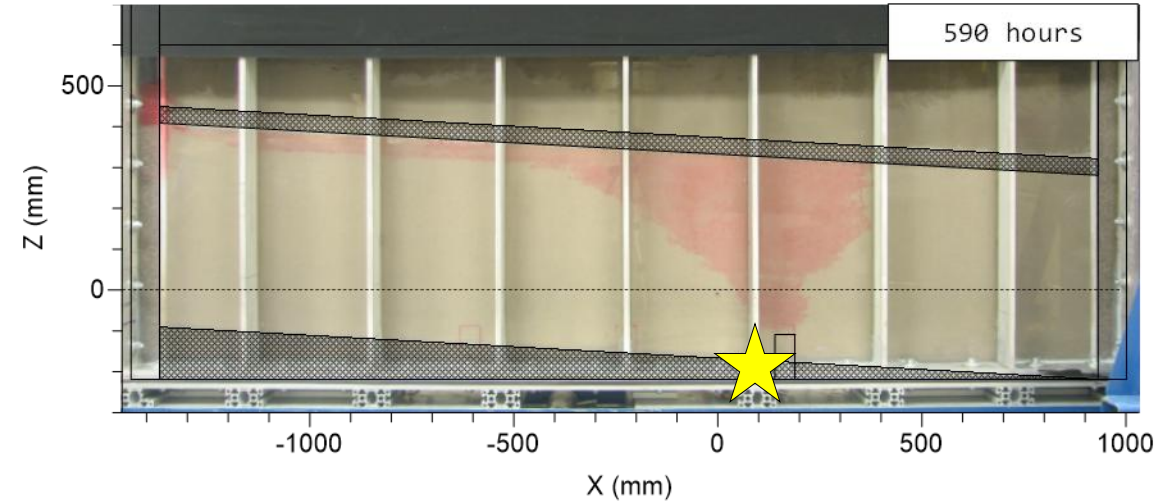


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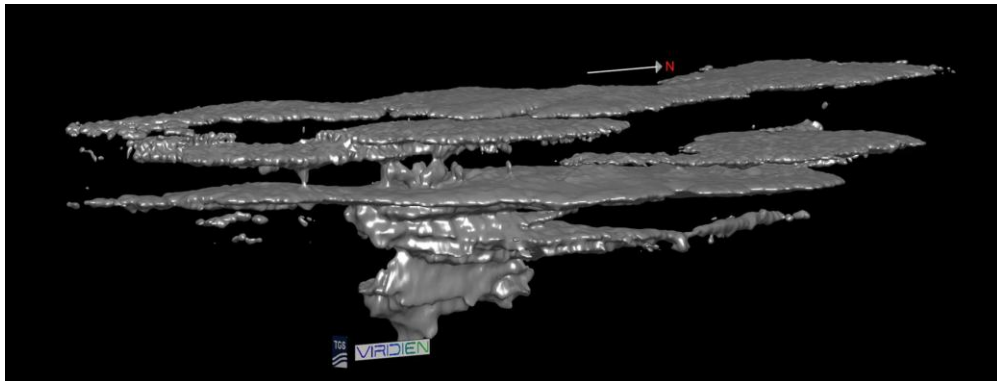


Simple sand box experiments

The injection point (★) for a plume of red injection fluid in a homogeneous reservoir sand (upper picture) vs. a heterogeneous reservoir sand (lower picture)



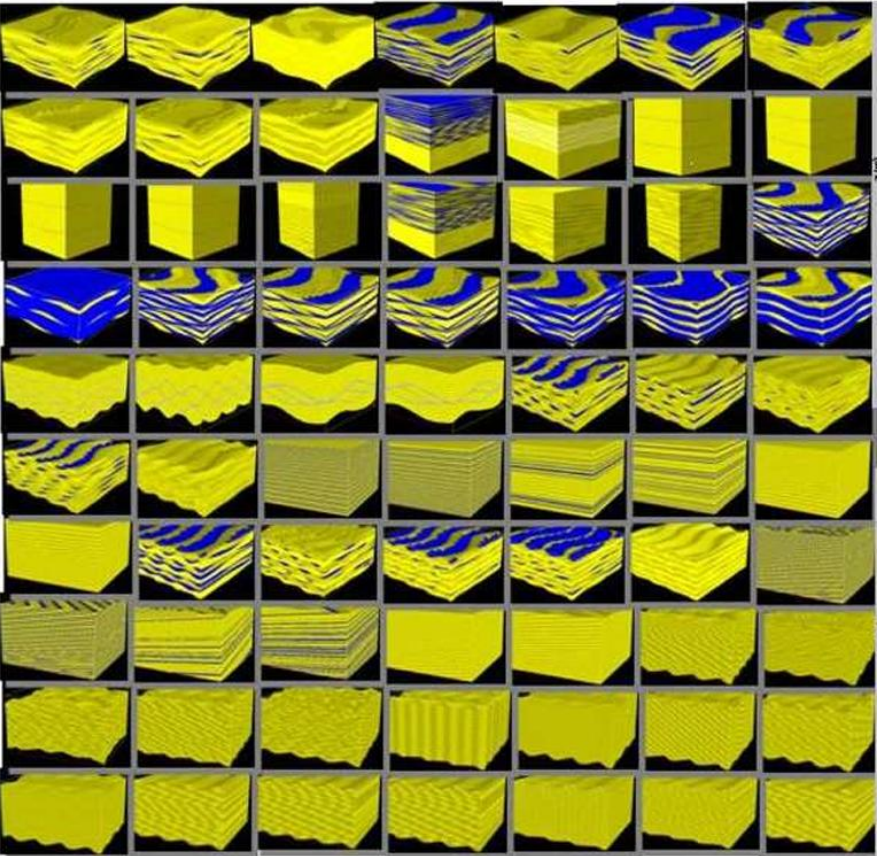
Comparable patterns to those picked up on 4D seismic at Sleipner – multiple stacked capillary traps:



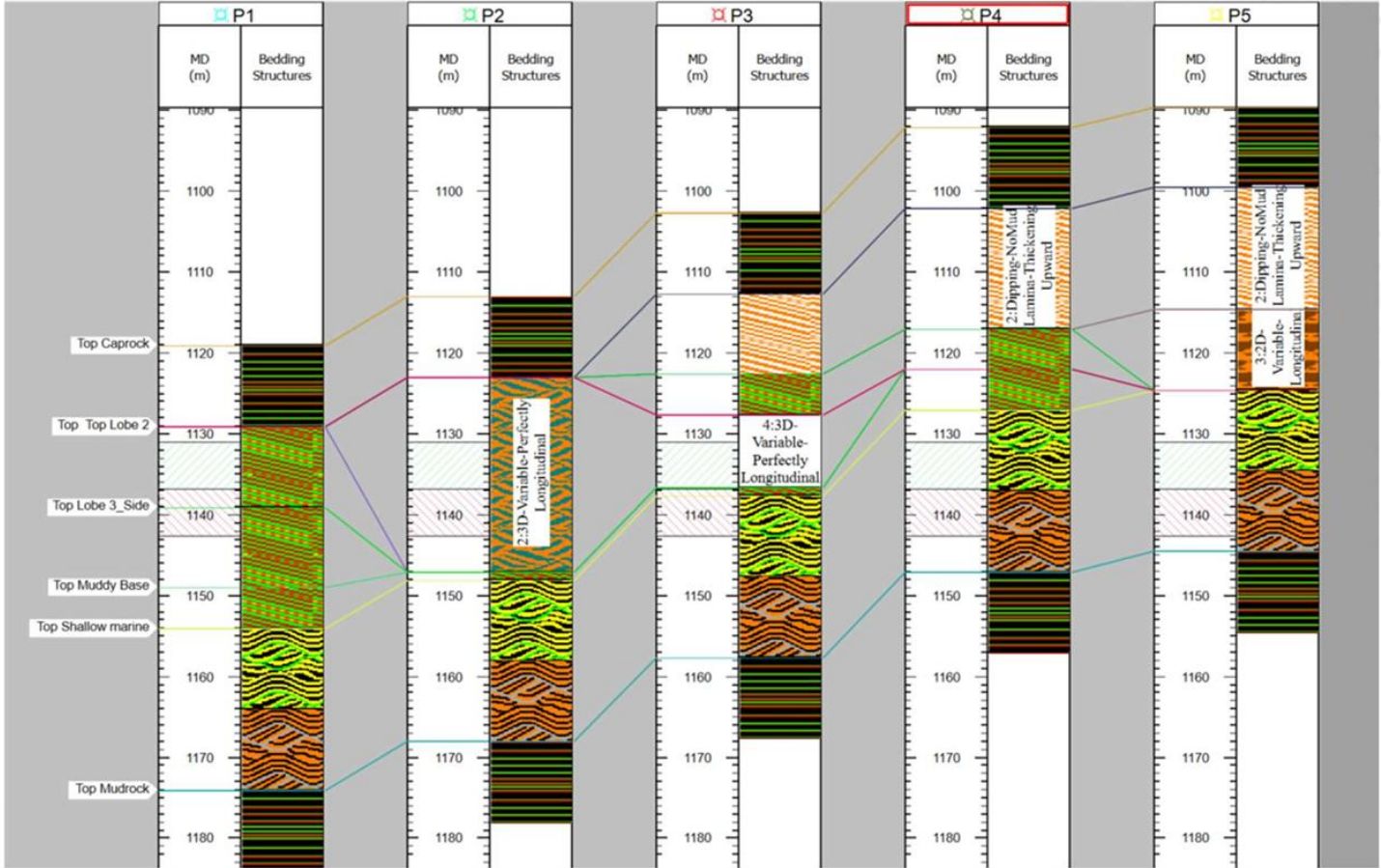
Martinez et al., 2025; Ringrose et al., 2025

Capturing heterogeneity – addressing the multi-scale question - SMALL

Sedimentary bedding template library

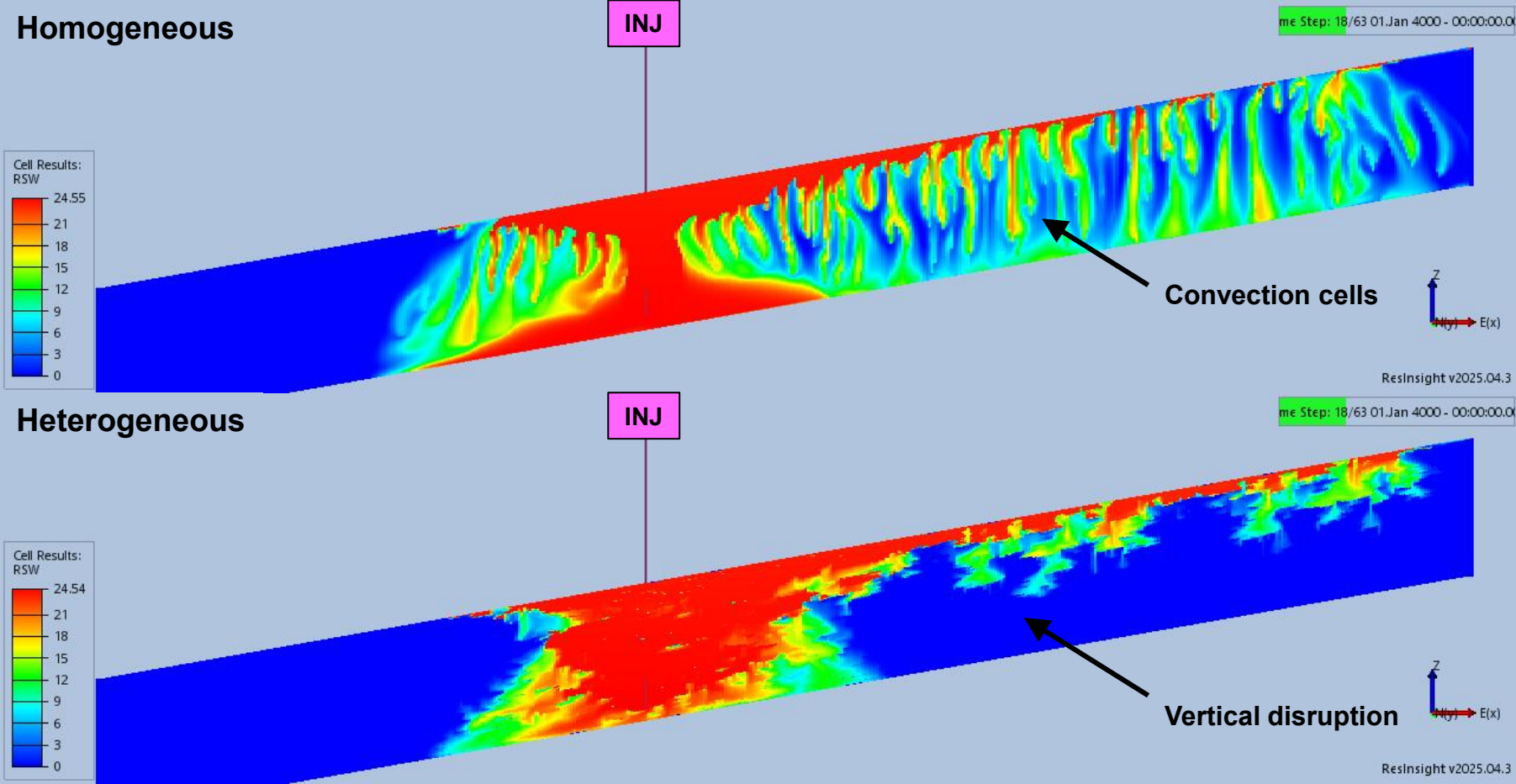


Application to Pano outcrop model (well correlation was done manually)



Capturing heterogeneity – addressing the multi-scale question - BIG

Bunter sst, UK SNS
Snapshot at t=2000 years



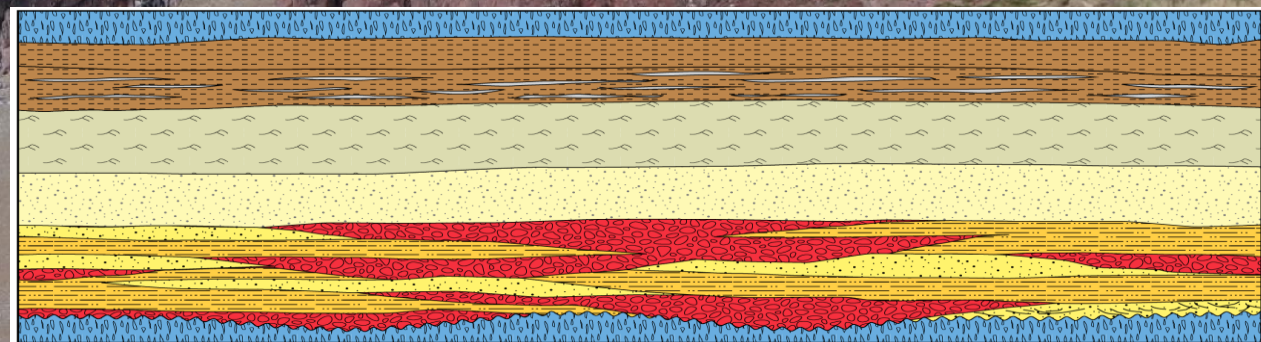
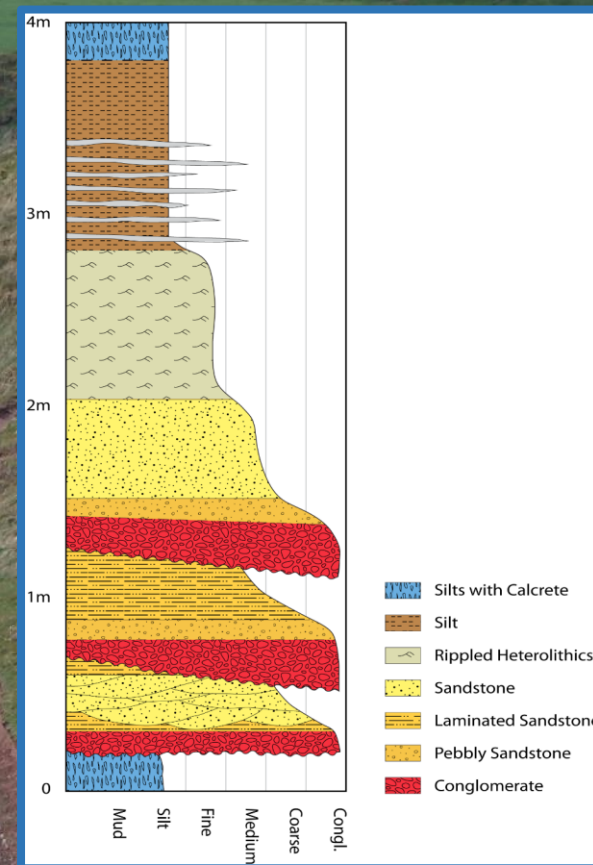
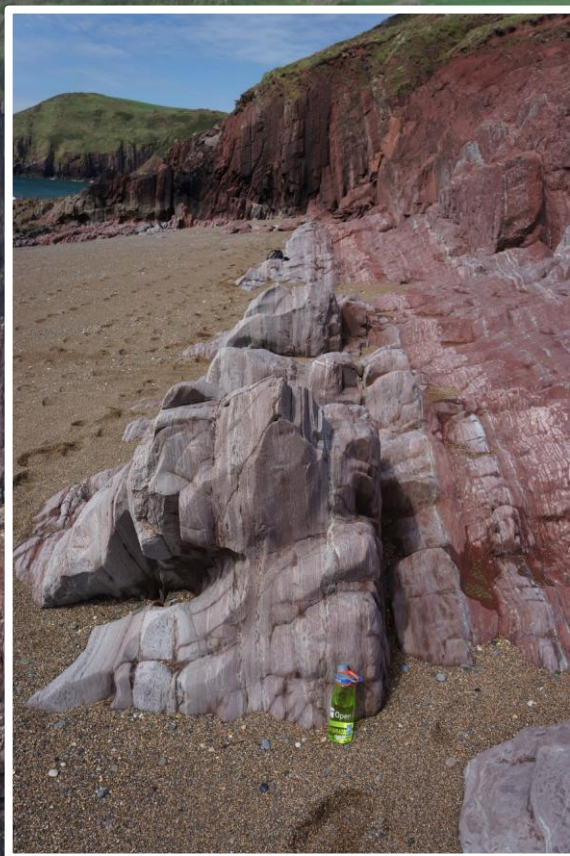
“Truth Models”



Resolve at the scale of the data



Model at the scale of the question

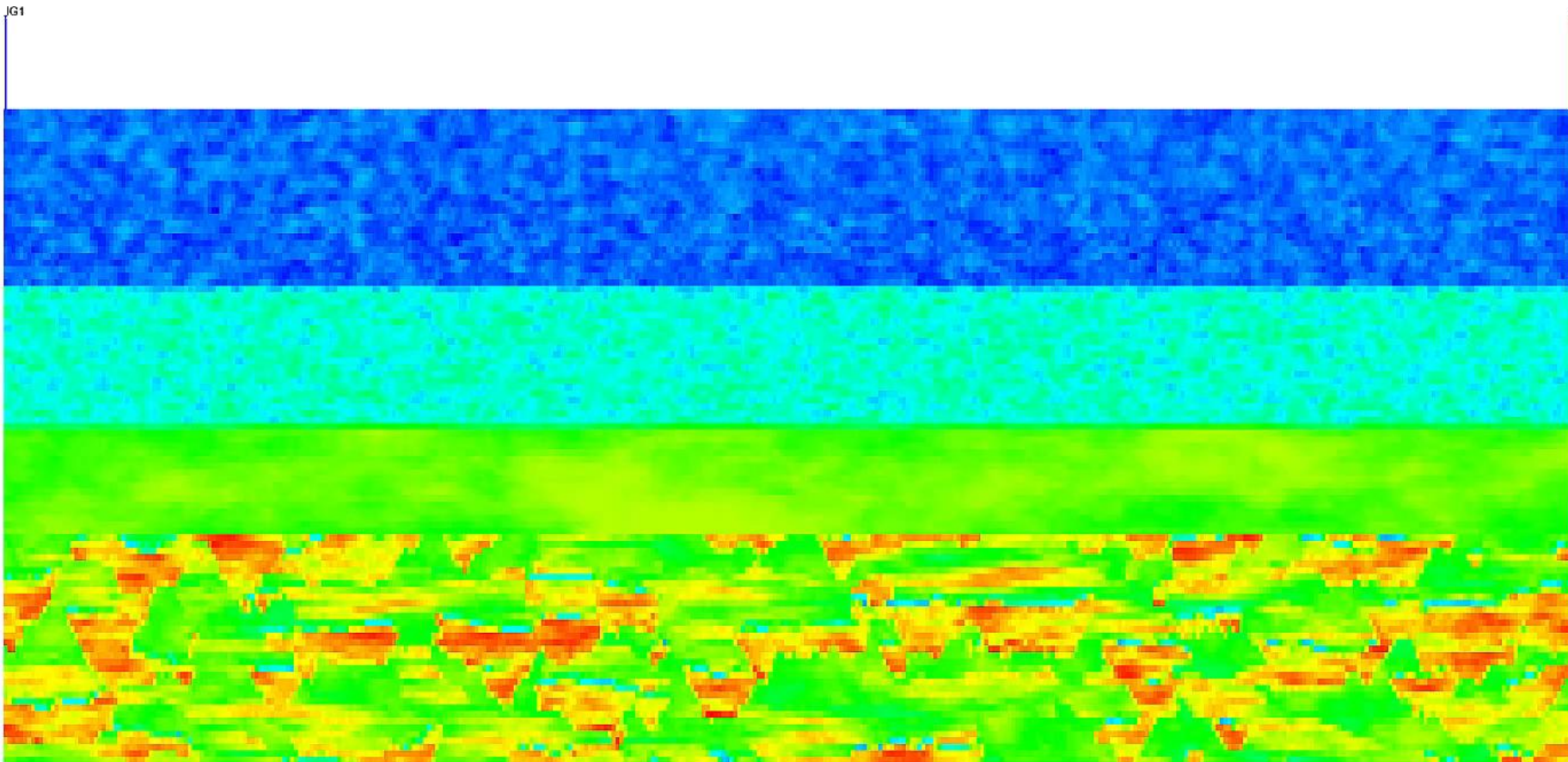
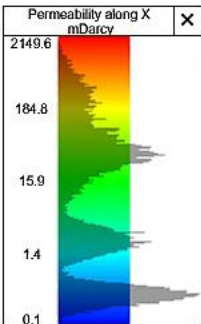


2D 3D Histogram

Definitions

Grid Properties

- Initial
 - Block size along X
 - Block size along Y
 - Block size along Z
 - Depth
 - Tops
 - Net to Gross Ratio
 - Porosity
 - Permeability along X
 - Permeability along Y
 - Permeability along Z
 - Std pore volume at P(ref)
 - Min. Water Saturation
 - Min. Water Saturation (Imbibition)
 - Crit. Water Saturation
 - Crit. Water Saturation (Imbibition)
 - Max. Water Saturation
 - Max. Water Saturation (Imbibition)
 - Min. Gas Saturation
 - Min. Gas Saturation (Imbibition)
 - Crit. Gas Saturation
 - Crit. Gas Saturation (Imbibition)
 - Max. Gas Saturation
 - Max. Gas Saturation (Imbibition)
- Calculated
 - Pressure
 - Temperature
 - Saturation of Water
 - Saturation of Gas
 - 1 / FVF for W
 - 1 / FVF for G
 - 1 / Viscosity of Water
 - 1 / Viscosity of Gas
 - Mass Density of Water
 - Mass Density of Gas
 - Rel. Perm. of Water
 - Rel. Perm. of Gas
 - Cap. Press. of Gas-Water
 - Pore Volume at Res. cond.
 - Water potentials
 - Gas potentials
 - Component 'WATER'
 - Component 'GAS'
 - Fluid-in-place
 - Regions
 - User Cuts
 - User Maps
 - Vector Fields
 - Interblock Flows



- Graphs
- Graph Templates
- Waterflood
- 2D Histogram
- Fluid Properties
- Schedule

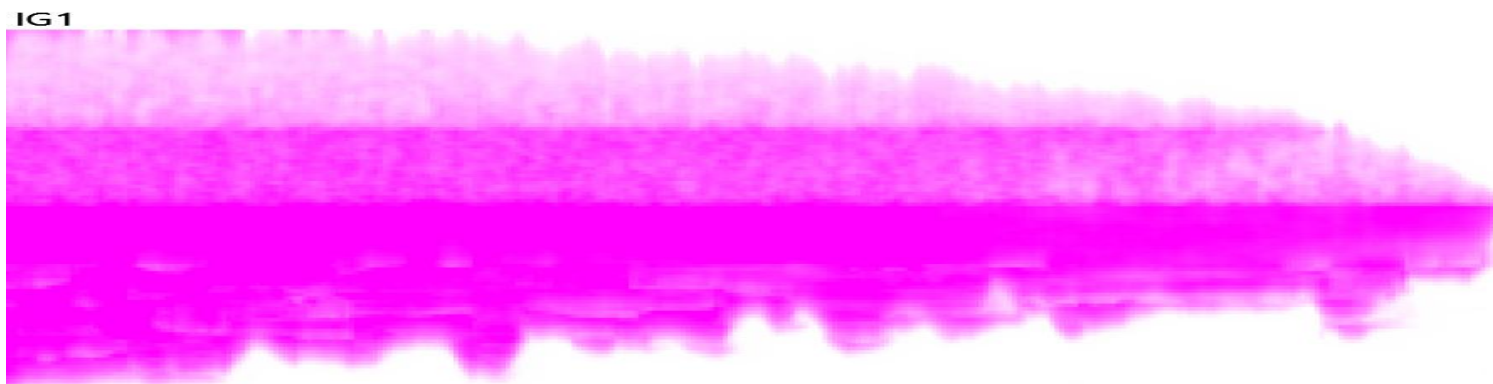
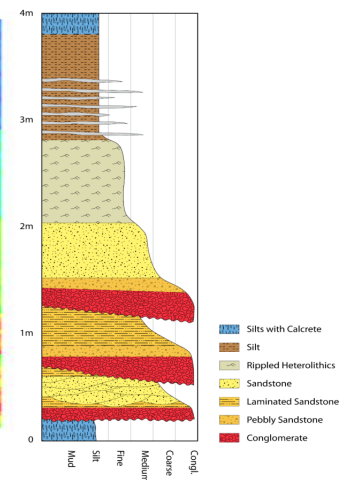
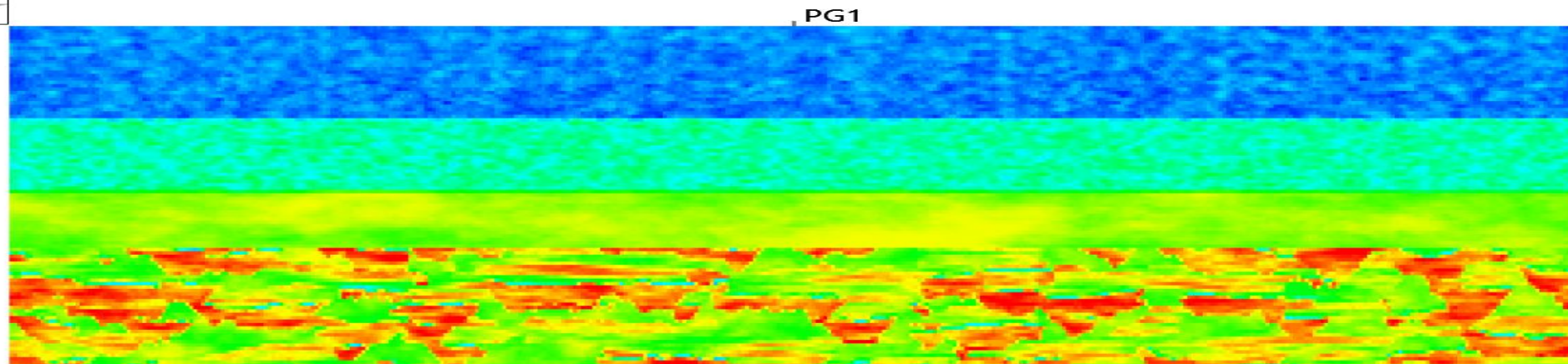
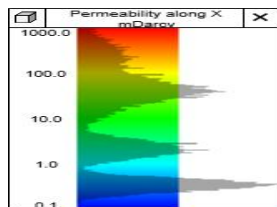
Ed Stephens, TRACS and Rock Flow Dynamics

Z scaling: 41.6667

0% Paused

Model read errors: 0, warnings: 136 208 16 136 0

CO₂ truth model – 4m x 500m bed



How sensitive is CCS to reservoir heterogeneity?

Critical order of magnitude perm contrasts – “Flora plus”

Critical permeability contrast



Fluid fill



Mechanism



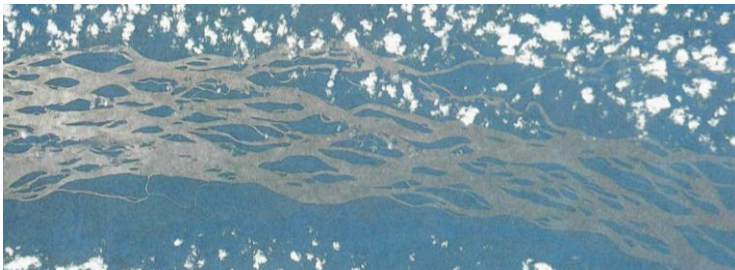


Storativity & storage – what is the storage efficiency factor?

A
Middle-Upper
Shoreface



B
Fluvial channel



C
Aeolian (dunes)



D
High density
gravity flow



E
Low density
gravity flow



F
Carbonate
build-up



G
Highly faulted
reservoirs



0 response submitted

Best reservoirs for storage (assume all porous and permeable)

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link to join



<https://forms.office.com/e/NtTB7qubF3>

 Copy link

A - Shoreface
sands

B - Braided fluvial

C - Aeolian

D - High density
gravity flows (deep
marine)

E - Low density
gravity flows

F - Carbonates
(reefs)

G - Highly faulted
reservoirs

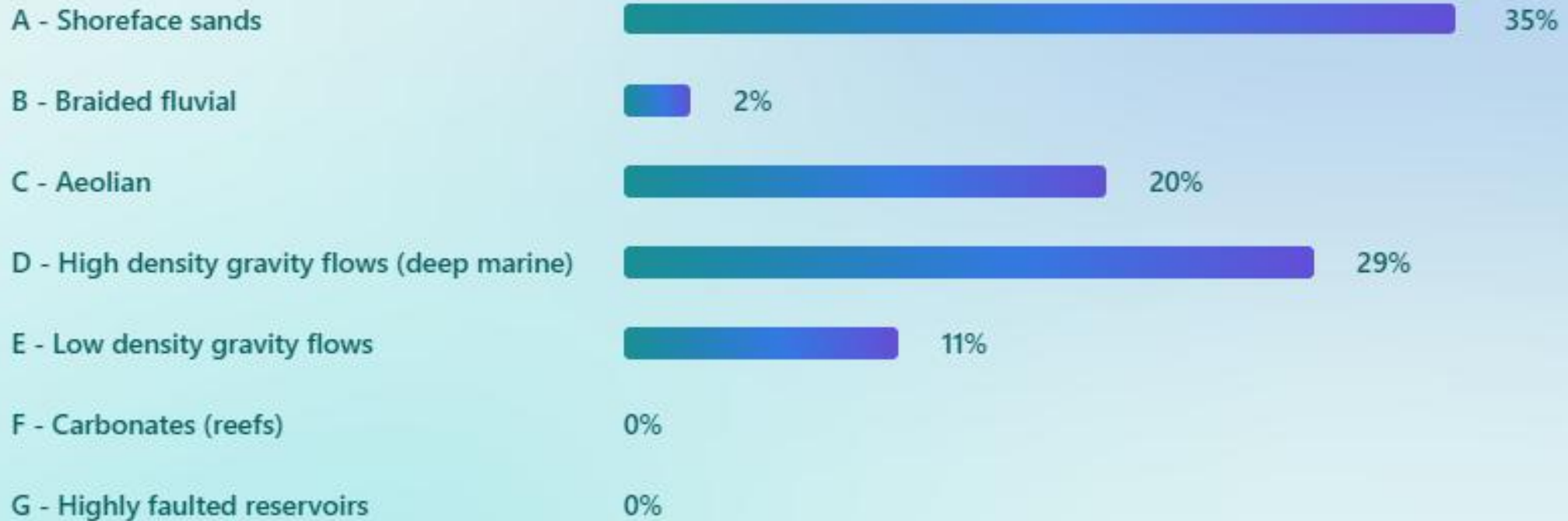
Treemap

Bar



responses submitted

Best reservoirs for storage (assume all porous and permeable)



Treemap

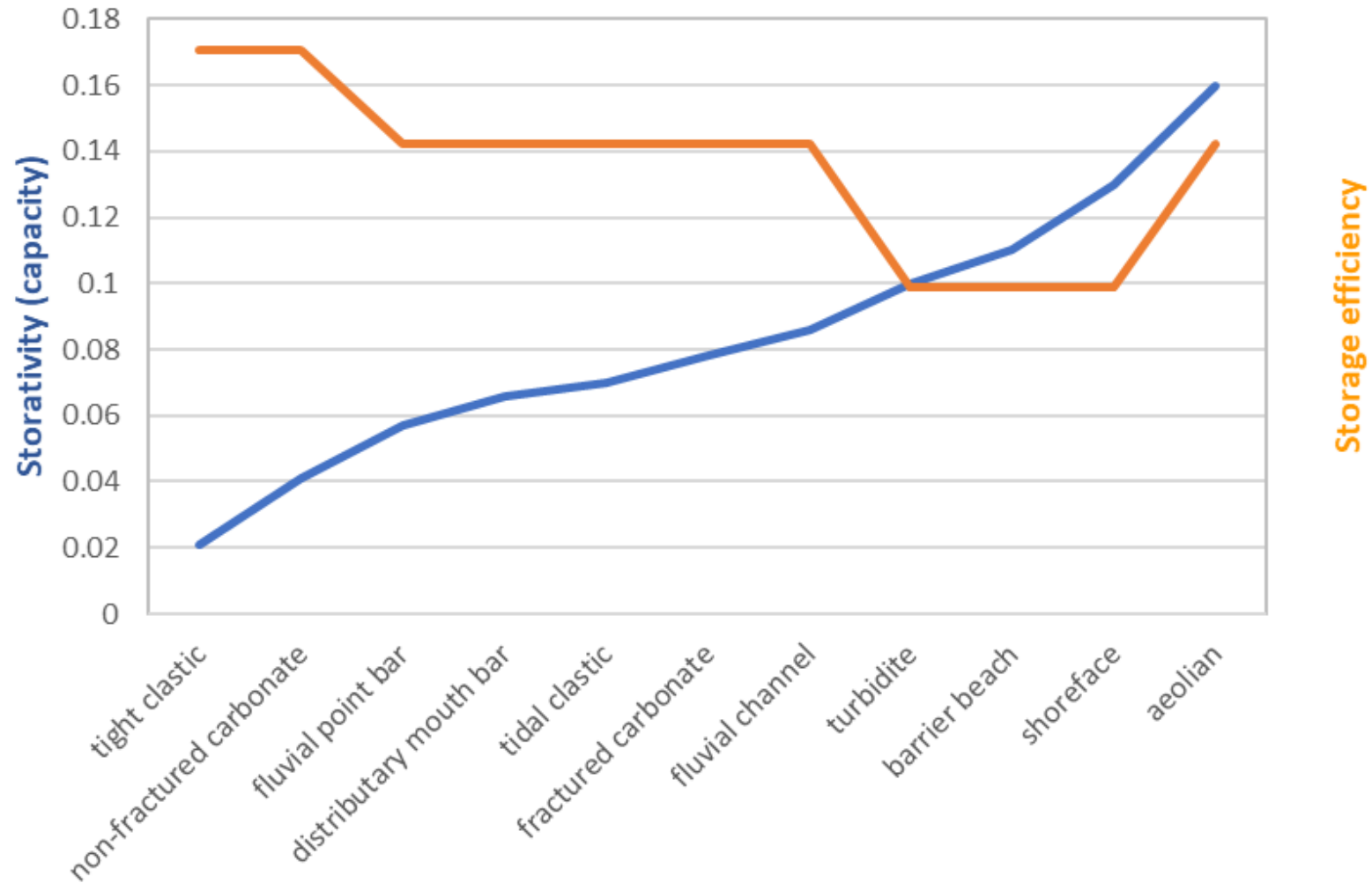
Bar



1 of 1



Storativity & storage – what is the storage efficiency factor?



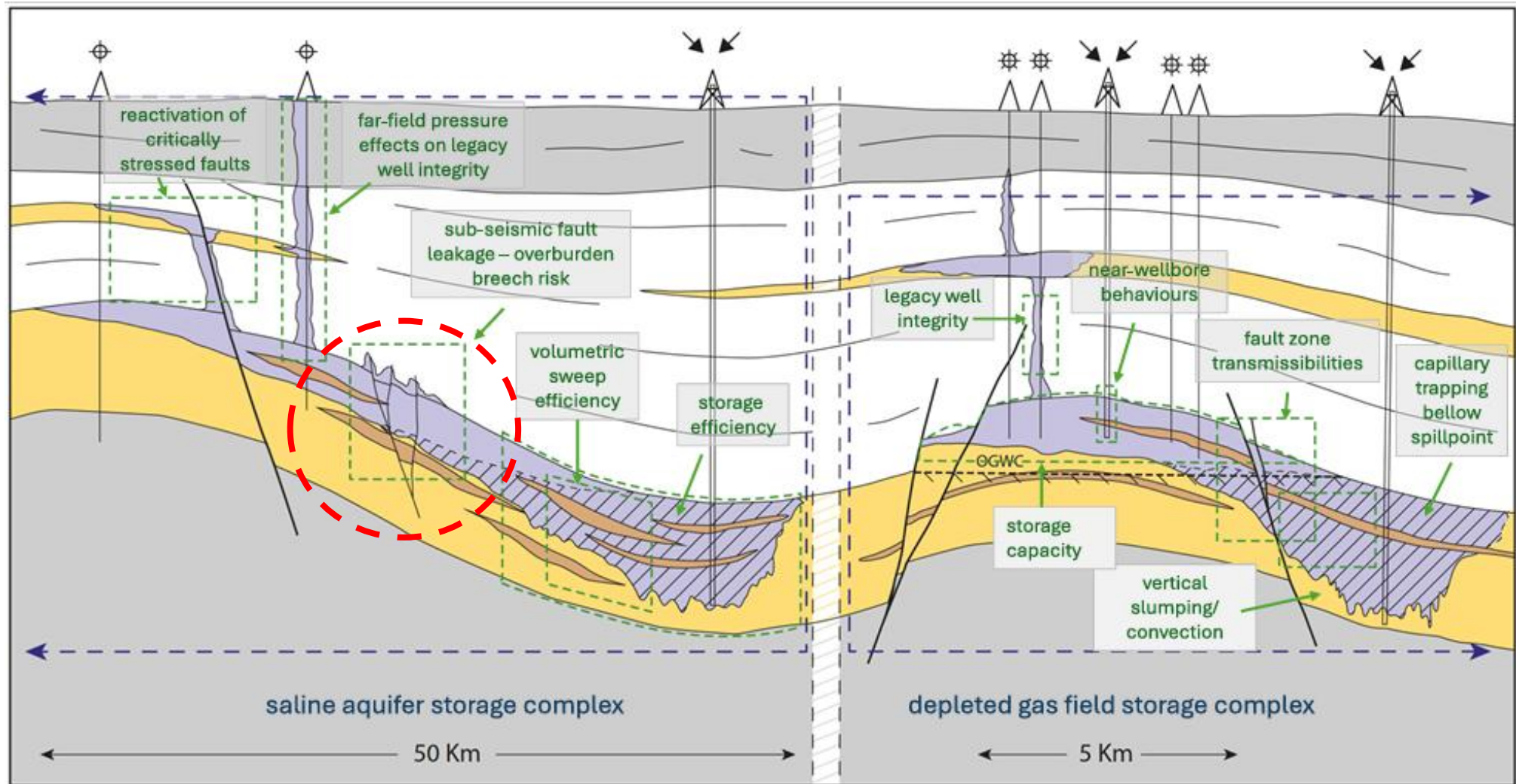
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HETEROGENEITY – STRUCTURE

Must try harder



The 'Storage Complex'





Sub-seismic faults in aquifers are mostly ...



Scan the QR or use
link to join



<https://forms.office.com/e/ShQQnB0Ghf>

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A - Important as
barriers (fault seal)

B - Important as
baffles (because of
transmissibility
multipliers)

C - Important as
baffles (because of
residence)

D - Relatively
unimportant

Treemap

Bar



1 of 1





responses submitted

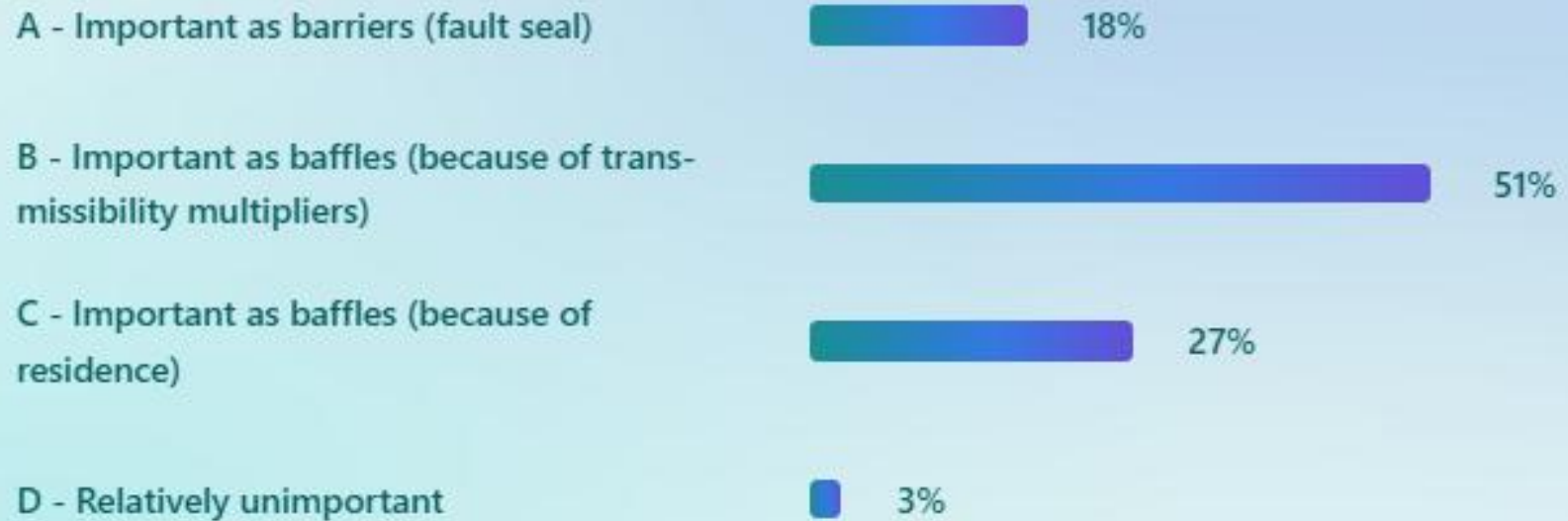
Sub-seismic faults in aquifers are mostly ...

Scan the QR or use
link to join



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Treemap

Bar



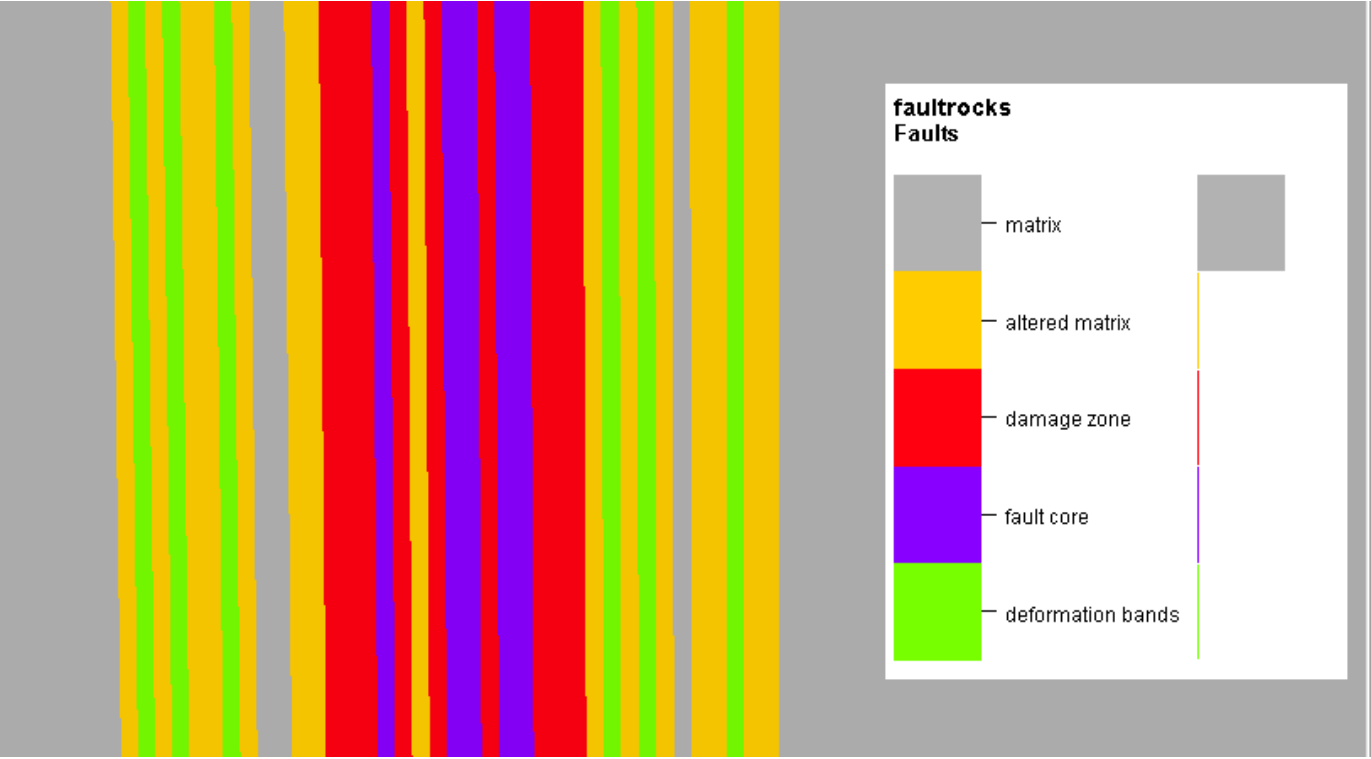
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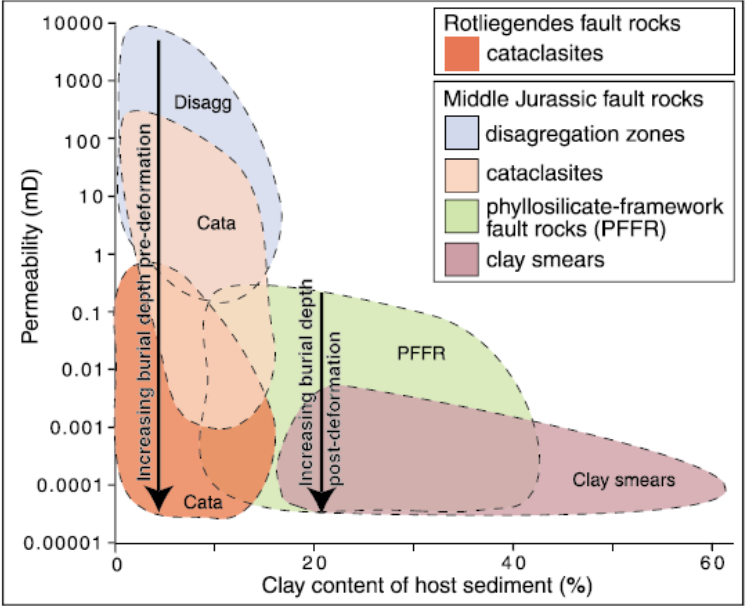


Let's do structure 😊

Damage zone truth model

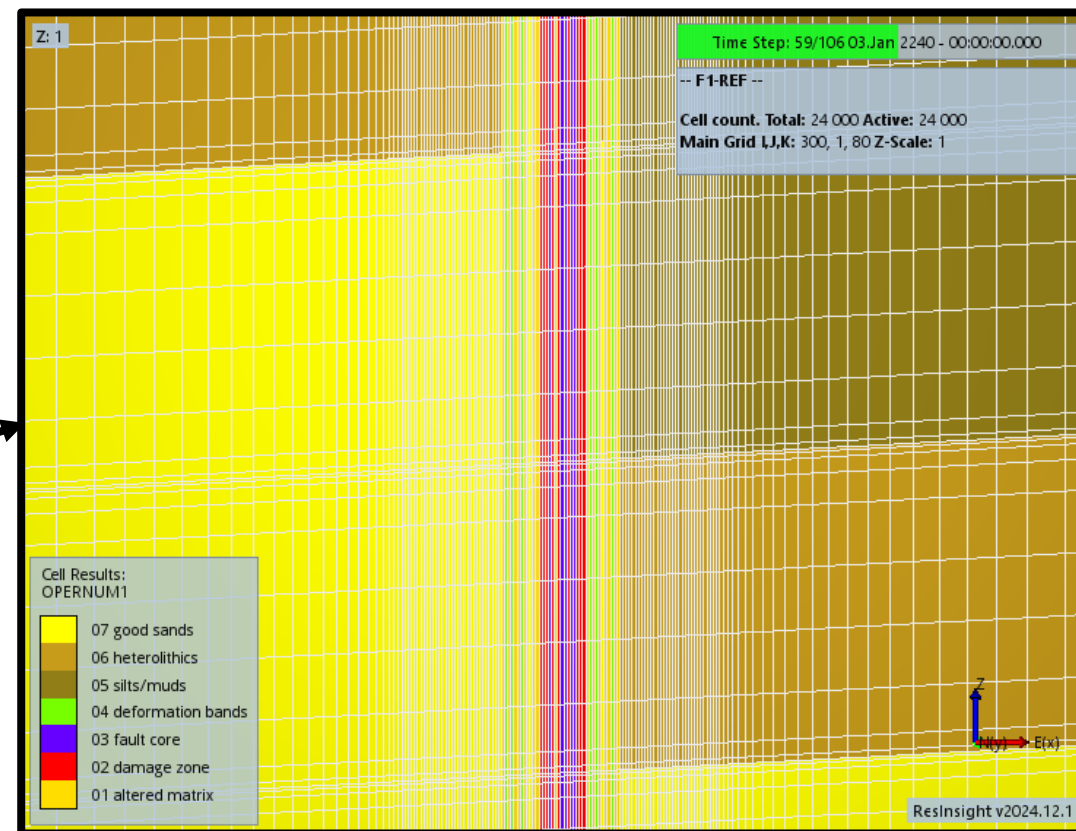
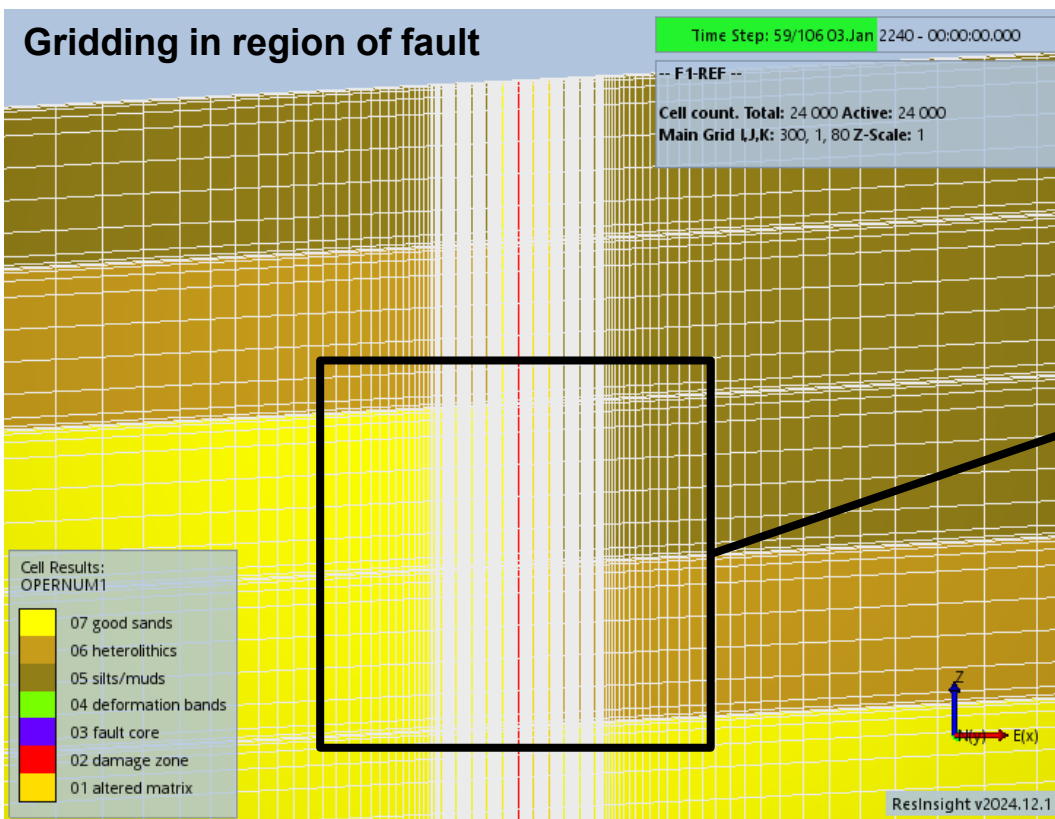


4m

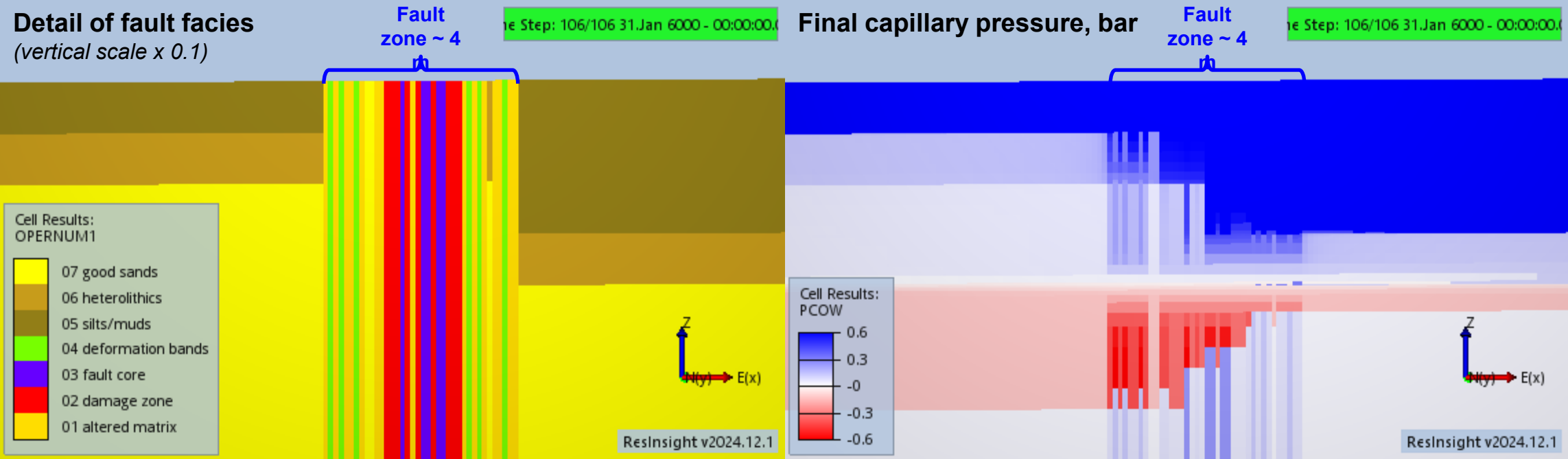


Knipe & Fisher, 2001

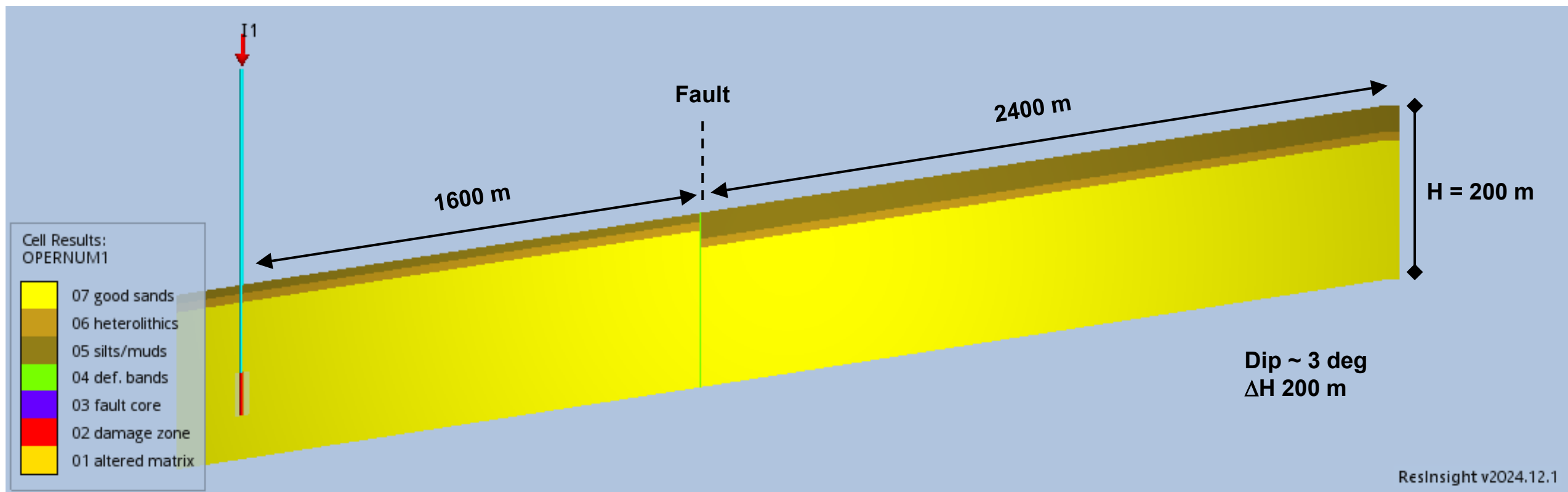
Tartan gridding in region of fault



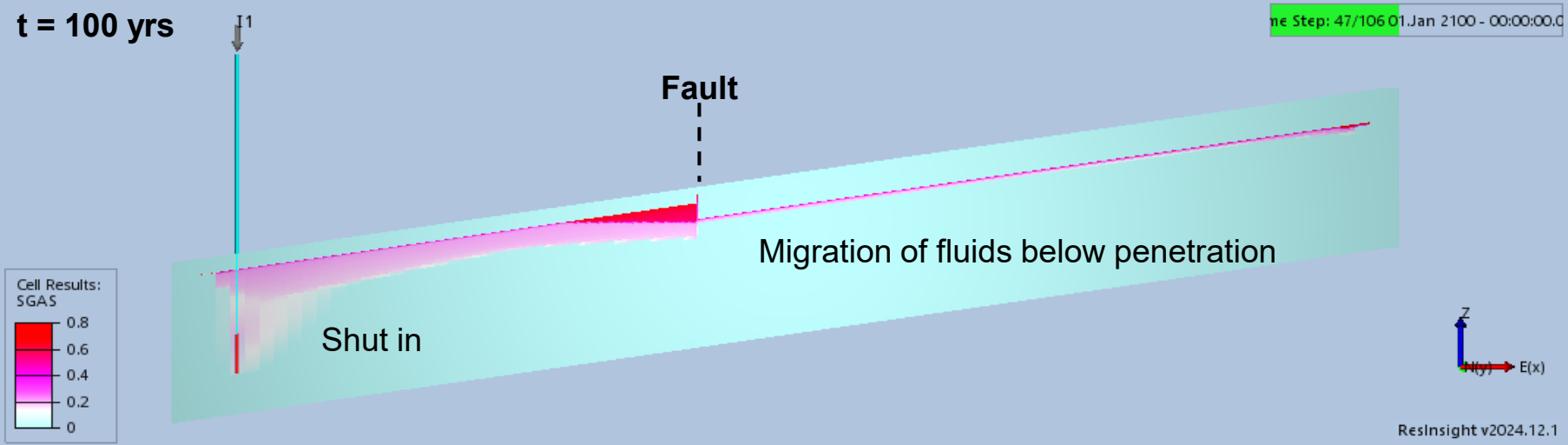
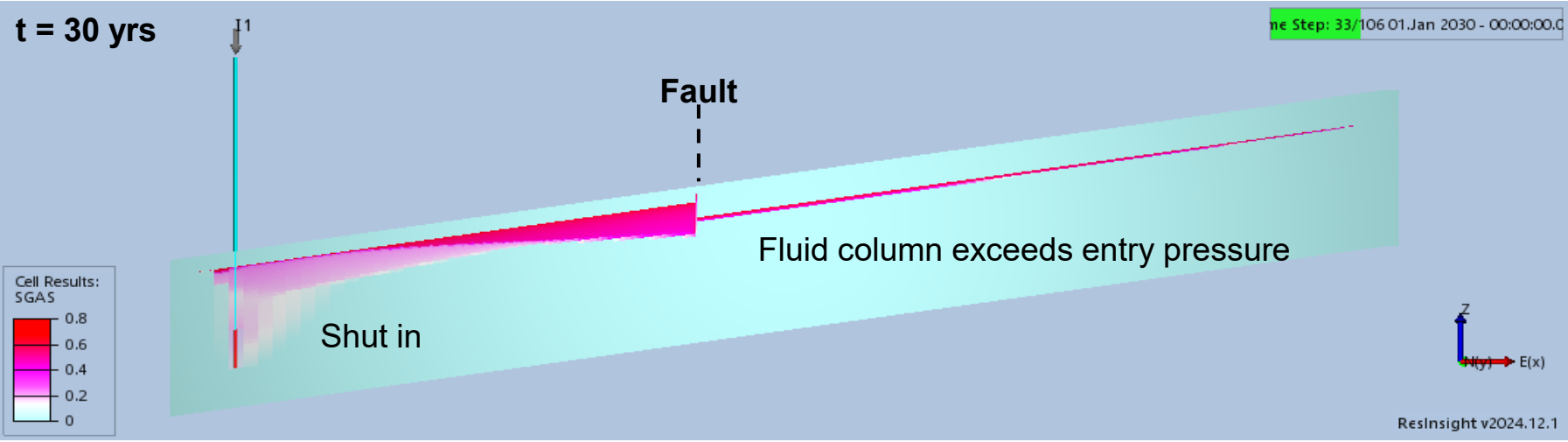
Capillary pressure within fault zone



The passing plume – initial model

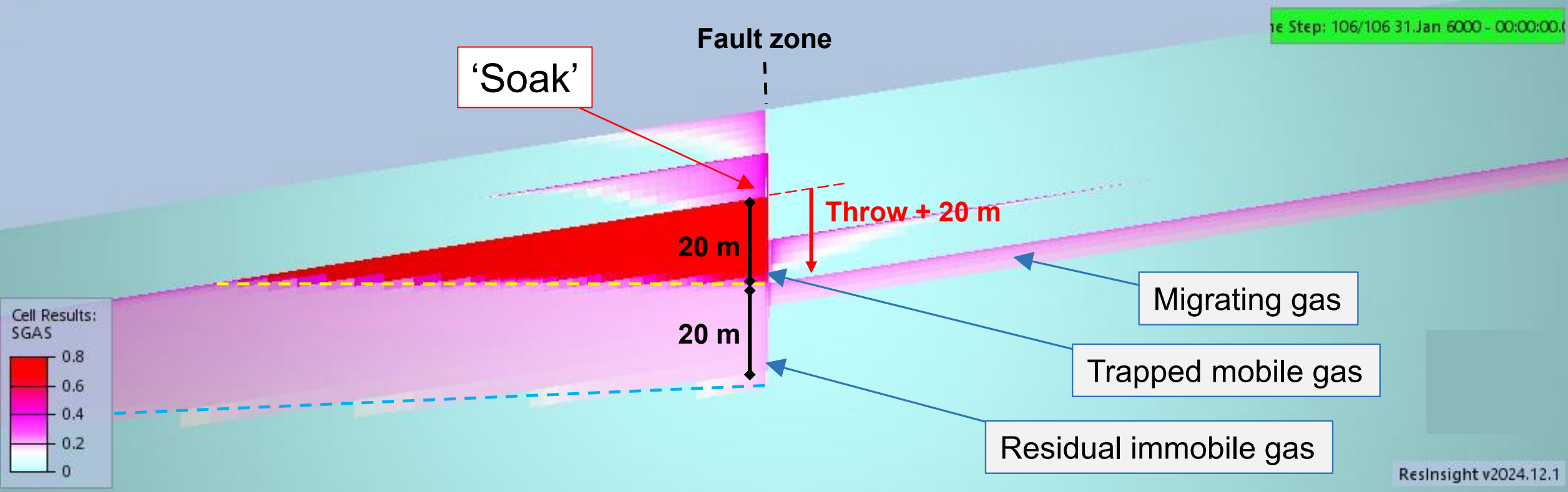


CO2 plume migration after injection shut-in



Close up of saturation at fault zone

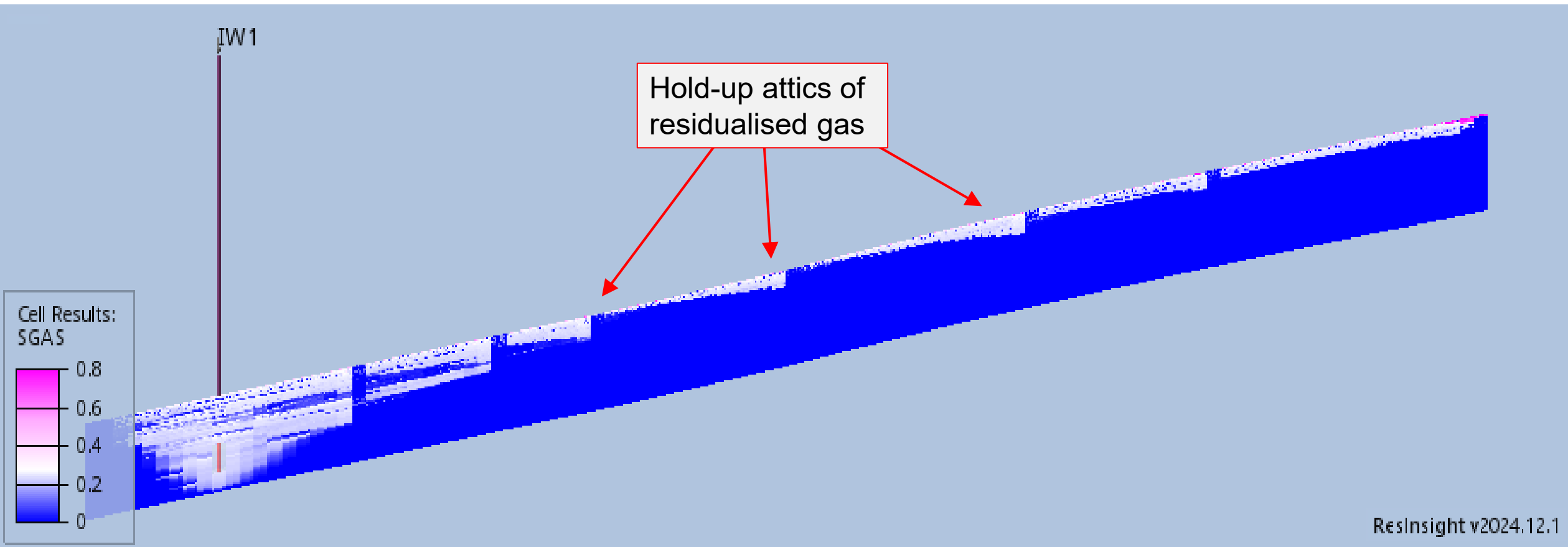
Step: 106/106 31.Jan 6000 - 00:00:00.0



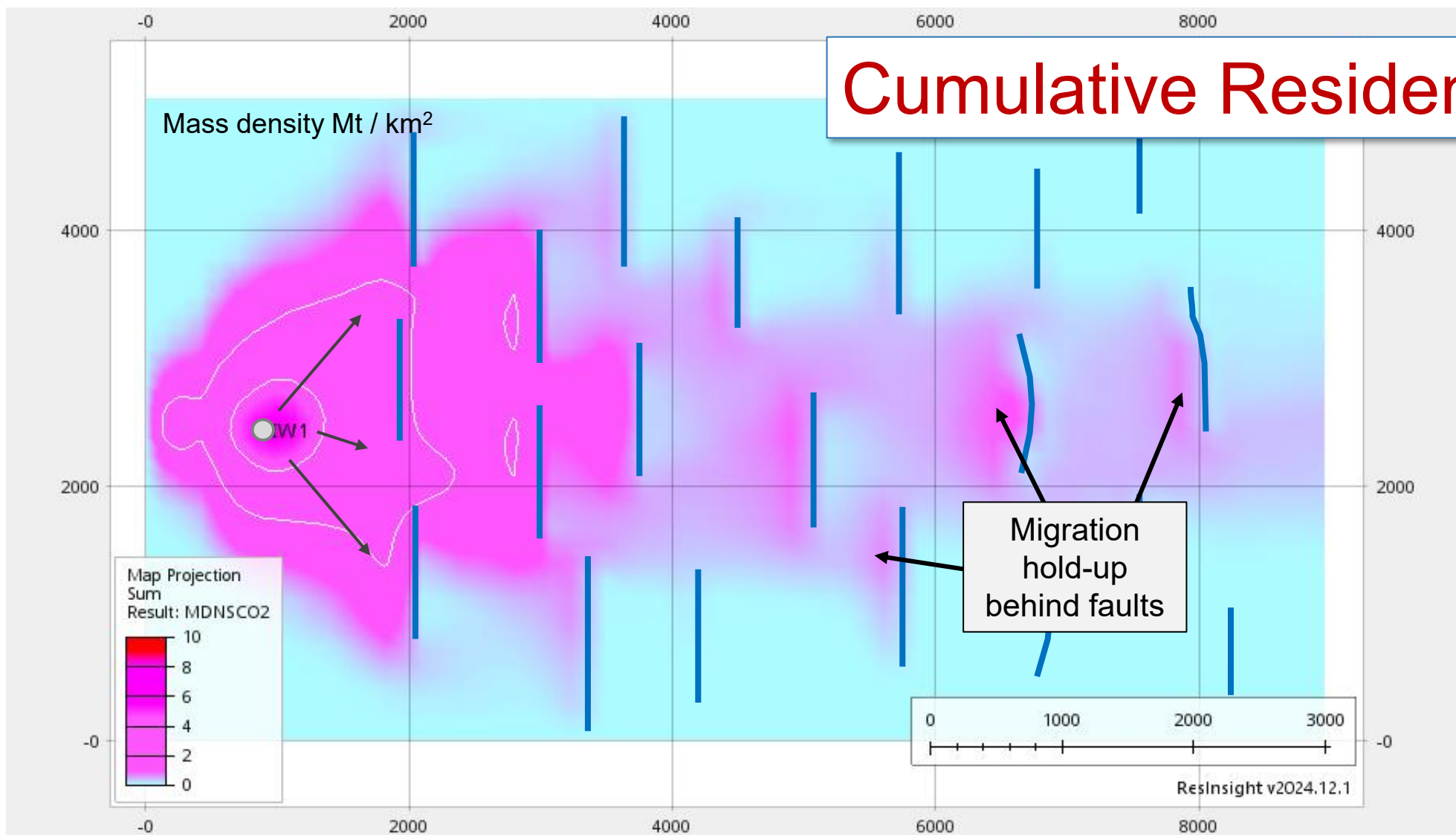
Residence

$$Residence R = \int S_{g, mobile} dt \quad (\text{years})$$

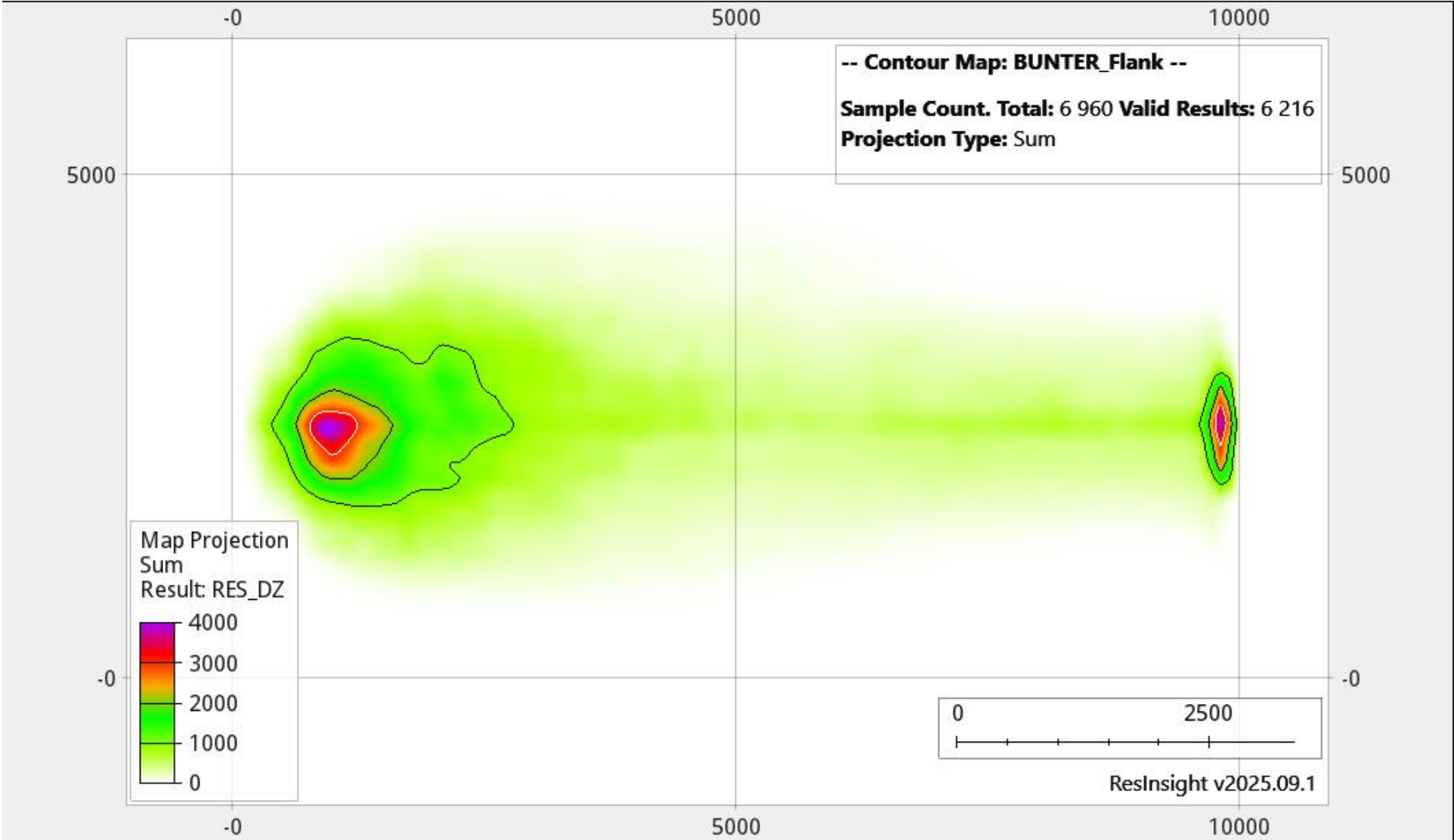
There will be more than one fault



The 'salmon ladder'



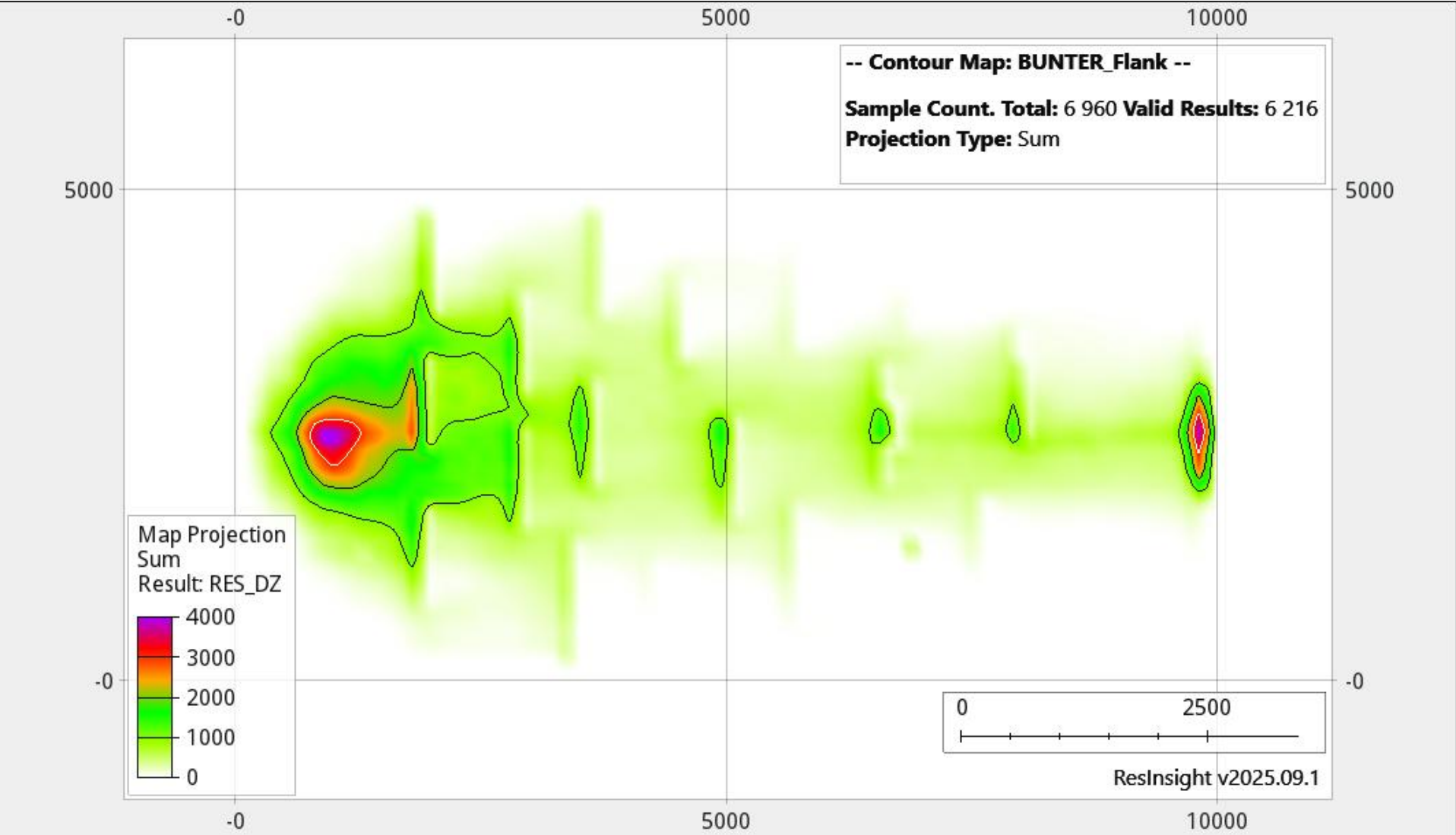
Cumulative residence mapping



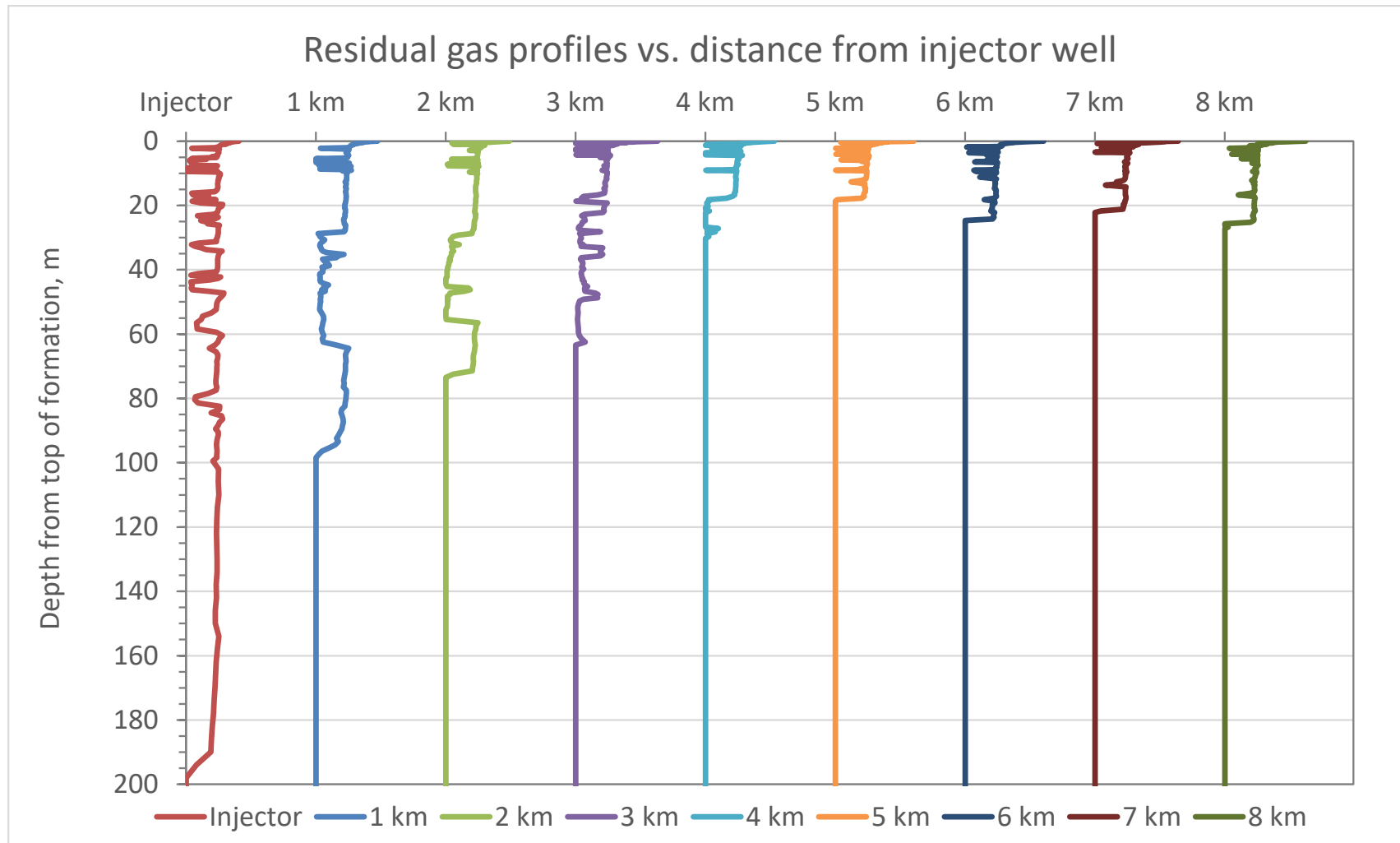
Total residence
1790 Mt.yrs

Cumulative residence mapping

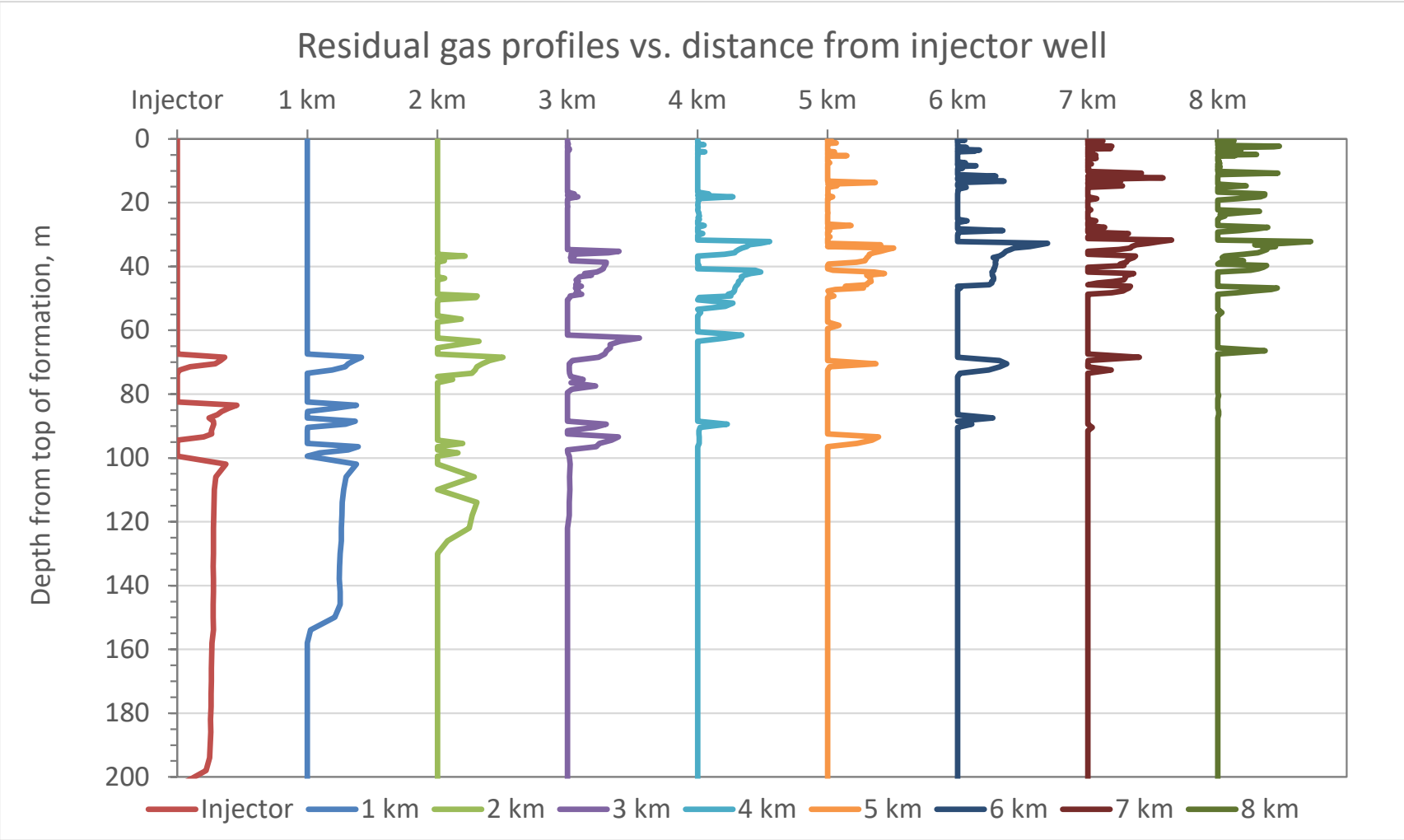
Total residence
2060 Mt.yrs



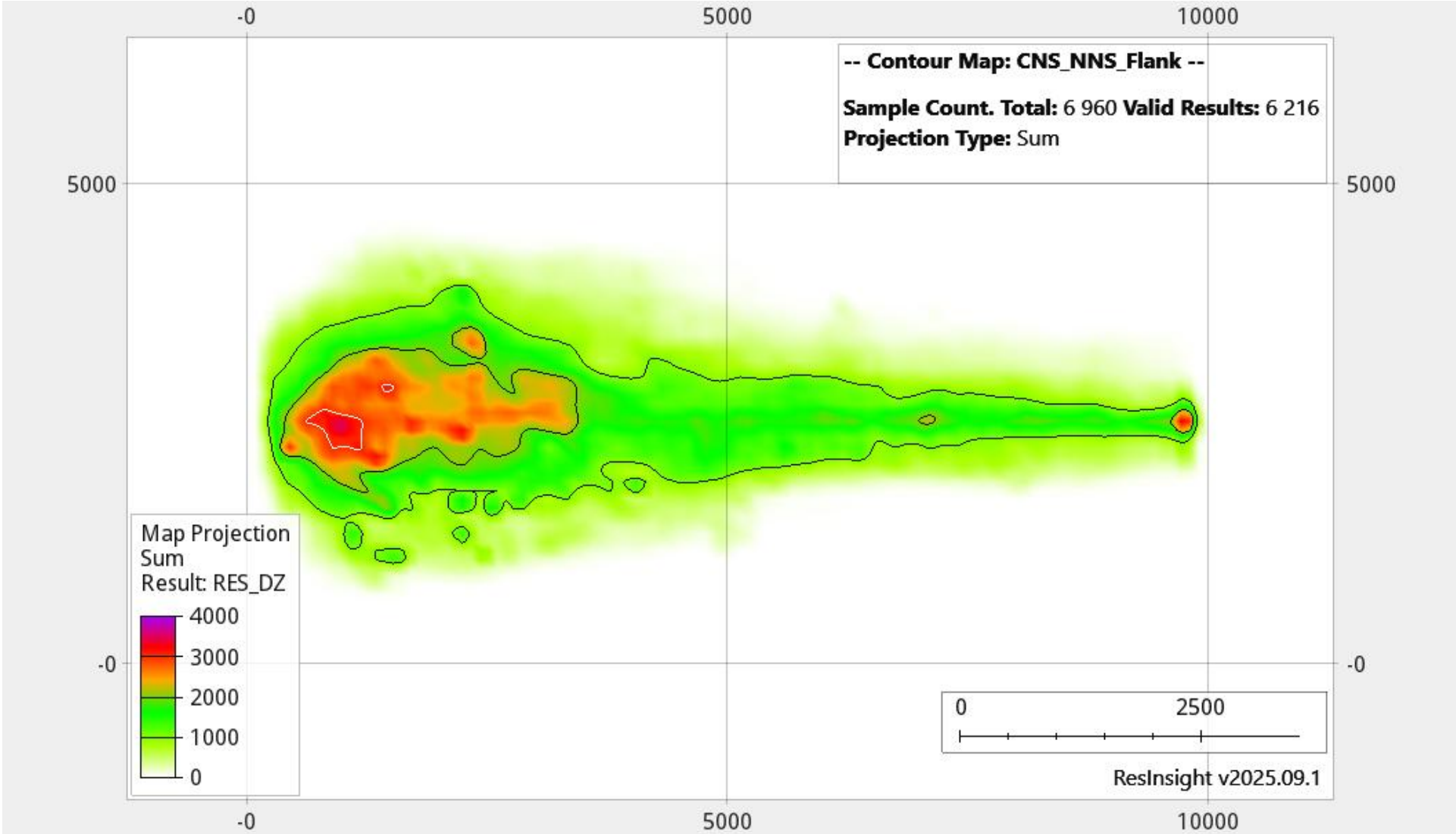
SNS Bunter: residual gas vs. distance



CNS Paleocene: residual gas vs. distance



CNS reference case



Total residence
3800 Mt.yrs

Increasing heterogeneity means ...

Increased capillary trapping

Enhanced capillary trapping due to **cumulative residence**



FORCE Stavanger

SCALE

The big challenge

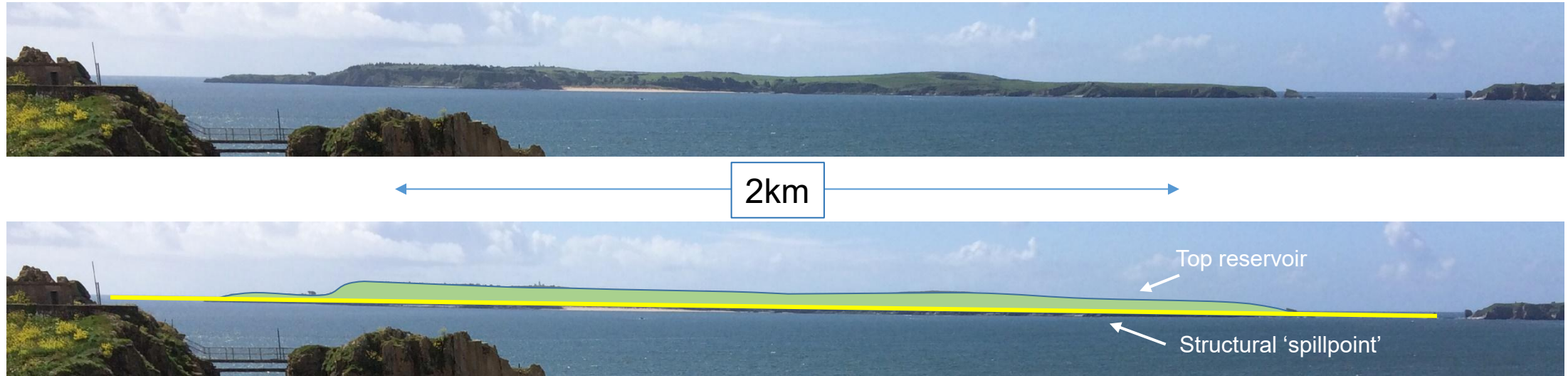


What does a million tonnes of CO₂ look like?





How many tonnes of CO₂ could you fit in here?



If an oil field under development:

10-15 million bbls

Assume CO₂ density around
600 kg/m³



0 response submitted

Ballpark volumes, storage in Caldey island

Scan the QR or use
link to join



<https://forms.office.com/e/ZwVpRyEmzg>

 Copy link

A - 0.1 MT

B - 1 MT

C - 10 MT

D - 100 MT

E - 1 GT



Treemap

Bar



1 of 1



responses submitted

Ballpark volumes, storage in Caldey island



Treemap

Bar

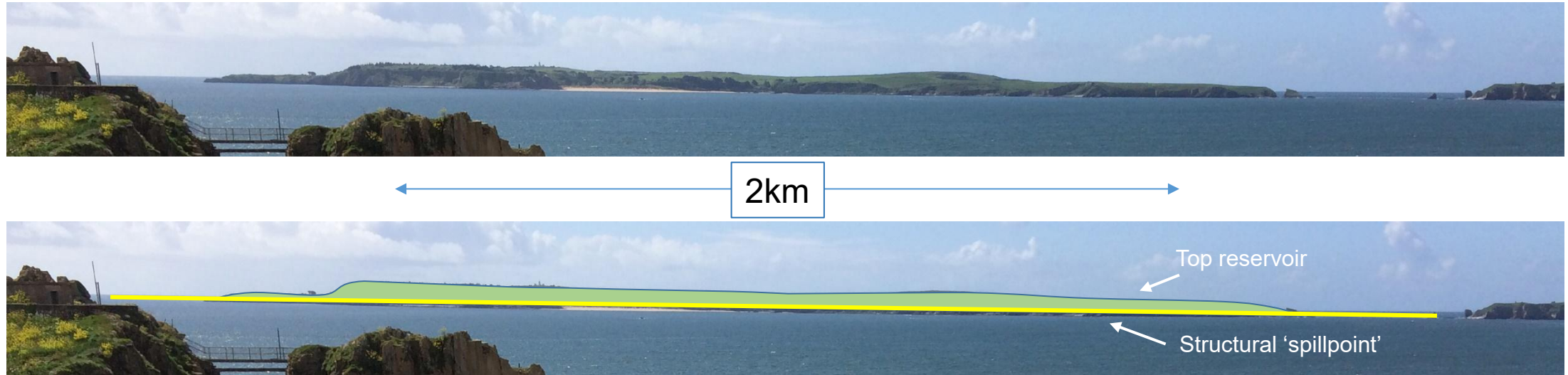


1 of 1

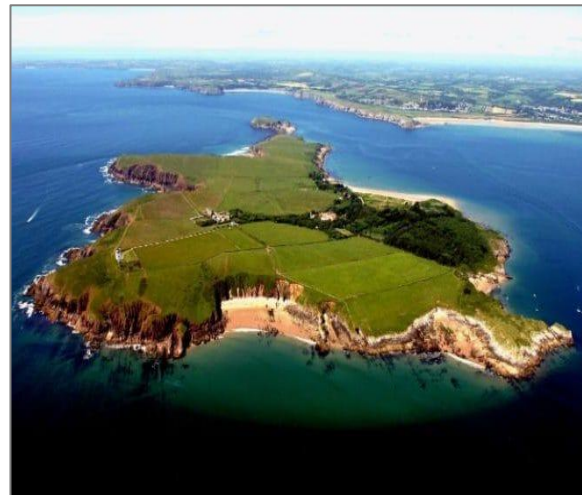




What does a million tonnes of CO₂ look like?



Assume CO₂ density around 600 kg/m³



If an oil field under development:

10-15 million bbls

If a depleted gas field, CO₂ store

A few 10's of MT

If an aquifer

0.1 MT

Scale

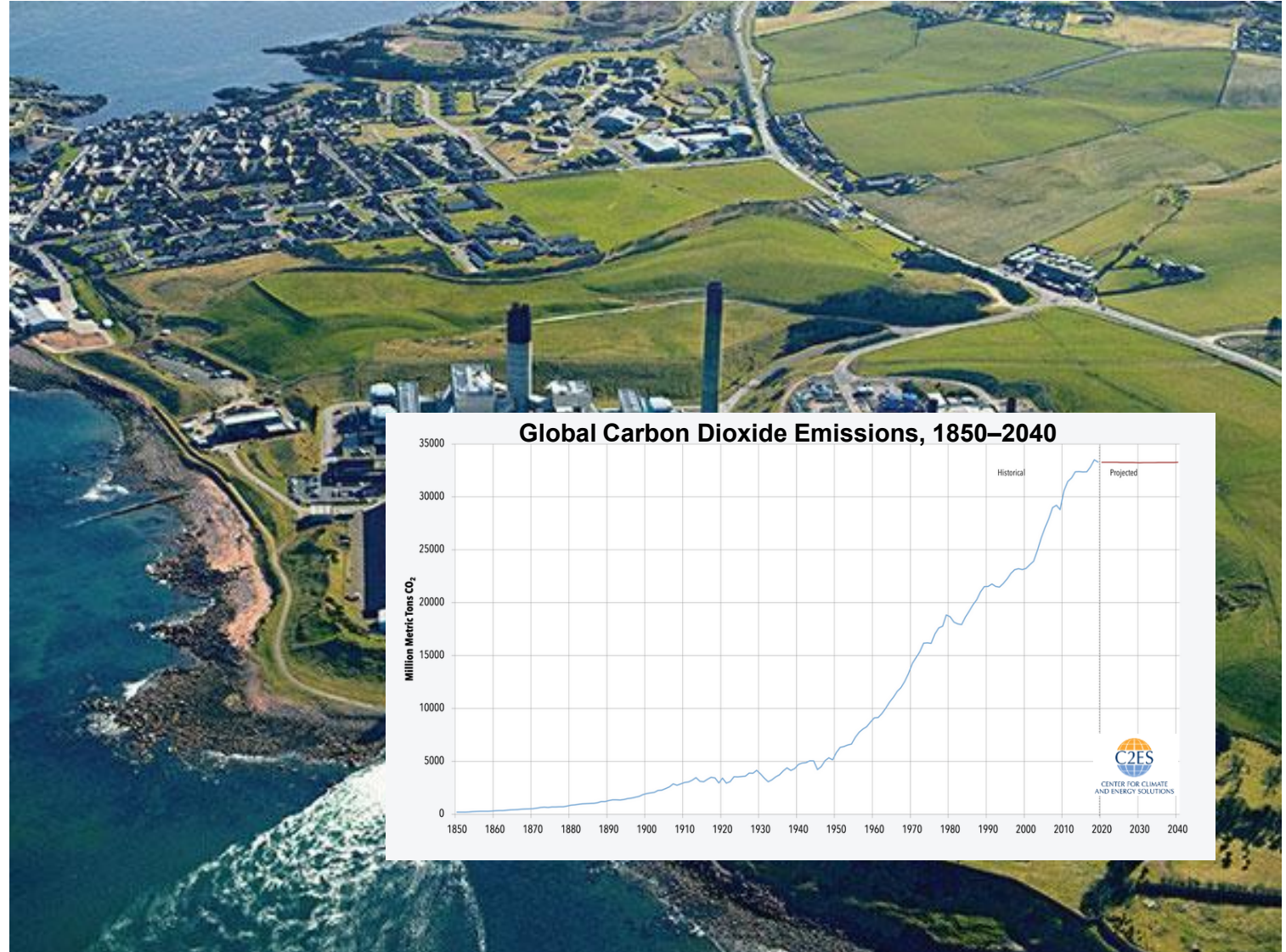
Peterhead Project

- 360 million tonne over 35 years
- 2 injection sites injecting 6 Mt/yr from 9 wells

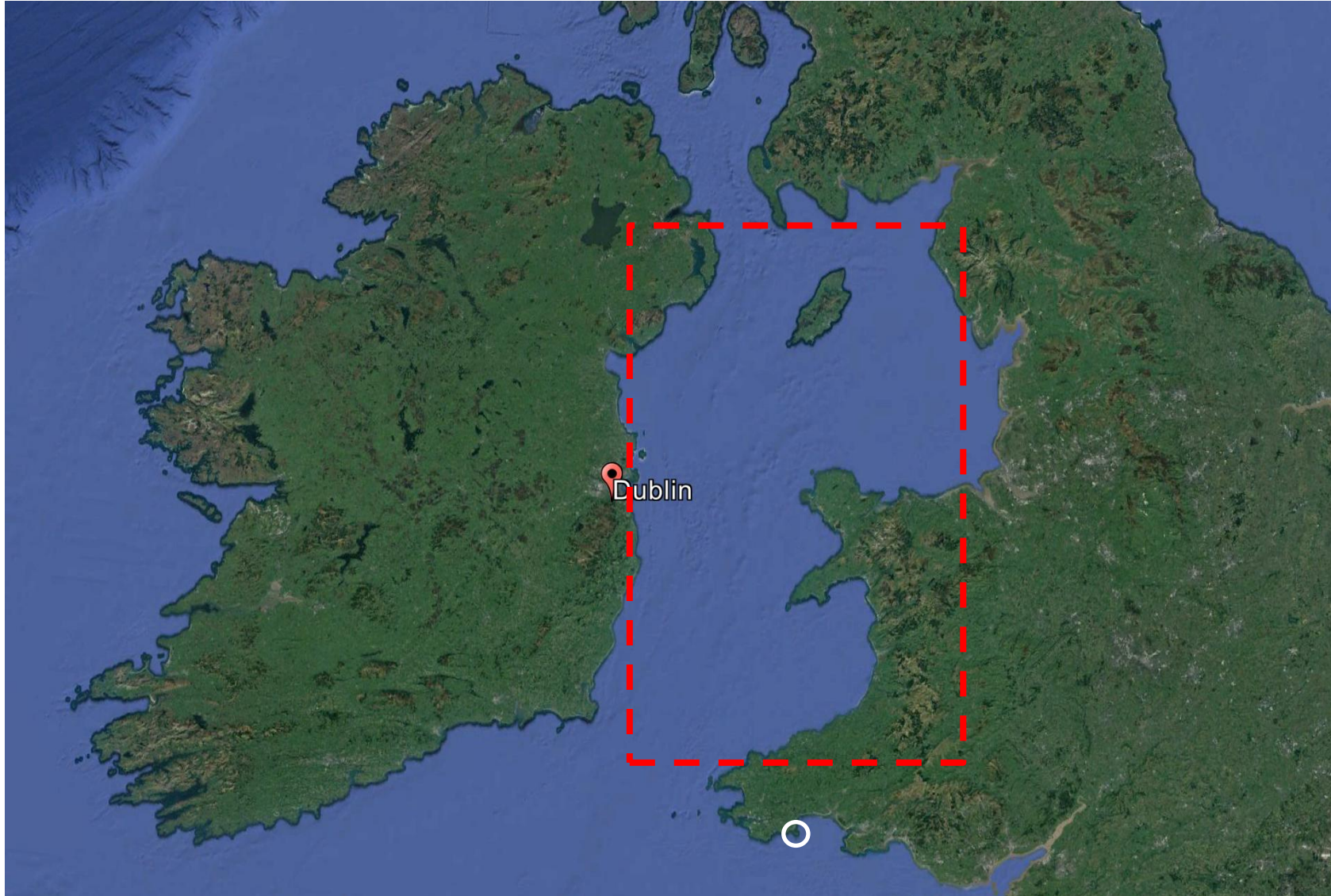
For comparison, we currently put about 35 Gigatonnes of CO₂ in the atmosphere each year

So we need ...

Nearly 3,500 Peterhead projects
Over 27,000 wells



Scale



About 300x150km

100m thick reservoir

100% net

20% porosity

Efficiency 5%

About 27 GT

Models for Storage vs. Production



Study volume

XXL



Fluids and forces

Supercritical



Heterogeneity - matrix

Friend



Heterogeneity - structure

Cumulative residence



Scale

Multi-scale workflows

