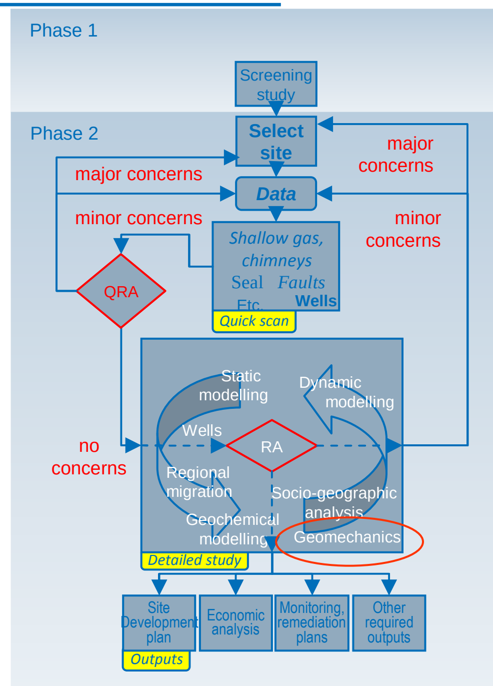
Characterisation of European CO_2 storage

Geomechanical characterisation of CO_2 storage sites: Assessment of stability at an offshore multi-store site

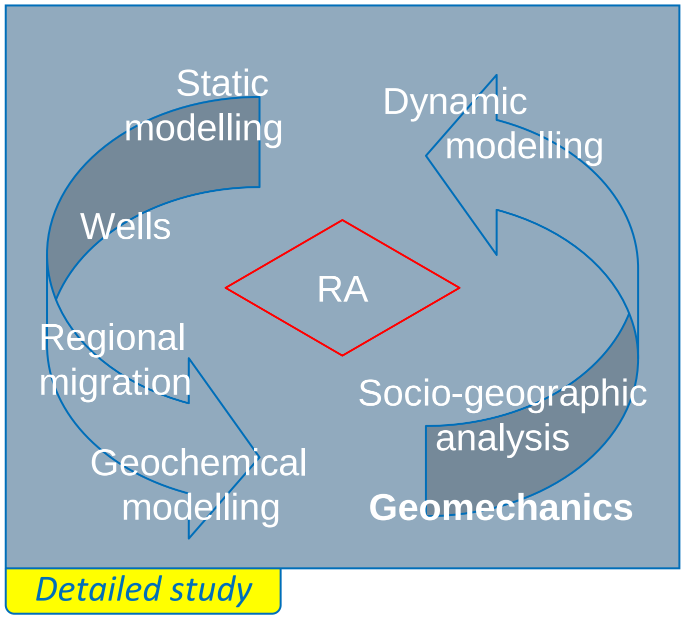
Ji-Quan Shi, Amer Syed, Rajesh Govindan, Anna Korre, Sevket Durucan

Imperial College London

Site characterisation study



- **Site characterisation workflow**
  - **Detailed study**
    - Static model building, **geomechanical analysis**, dynamic (injection and flow) modelling, etc.



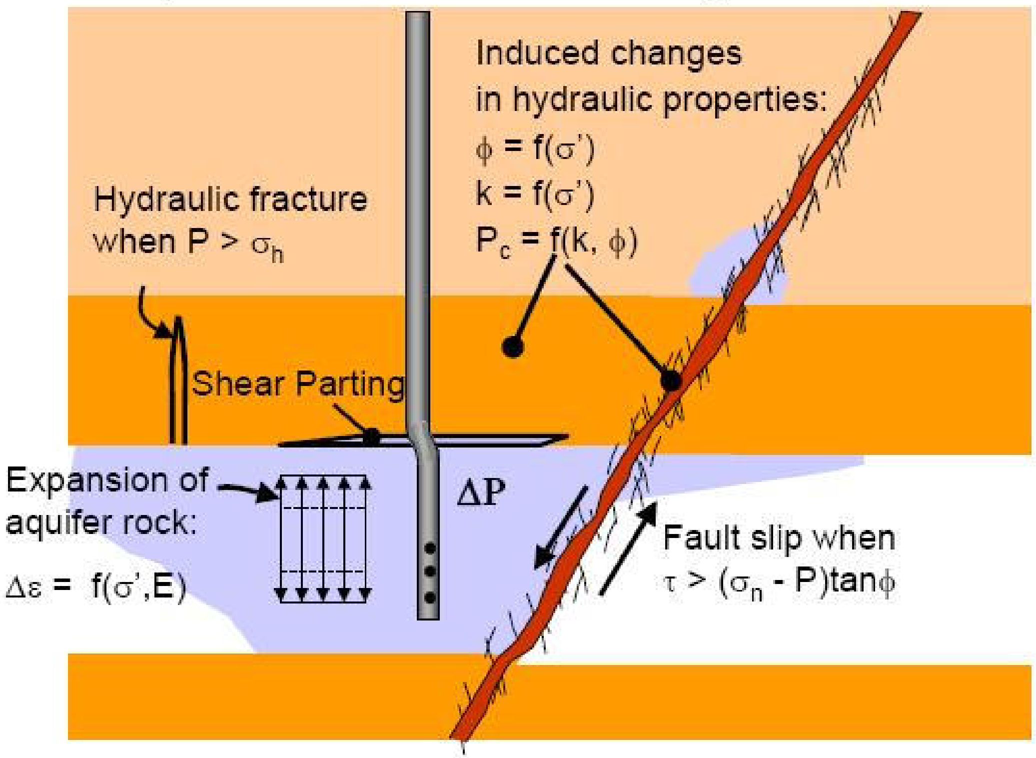
Maximum Sustainable Pore Pressure Increase in CO_2 Storage

- For safe storage of CO_2, the injection pressure should not exceed the **fracture pressure** of the rock formations.
- Pore pressure changes leads to changes in both the **Effective** and **Total stresses**.
- CO_2 injection into subsurface formations tends to raise the storage formation pressure, which would in turn result in a **reduction** in the **Effective stresses**.
- An unchecked increase in the reservoir pressure may cause **re-activation** (slip) of pre-existing **faults**, or **tensile fracturing**.

This leads to the concept of maximum sustainable pore pressure increase in CO_2 storage.

Geomechanical Processes in CO_2 Storage

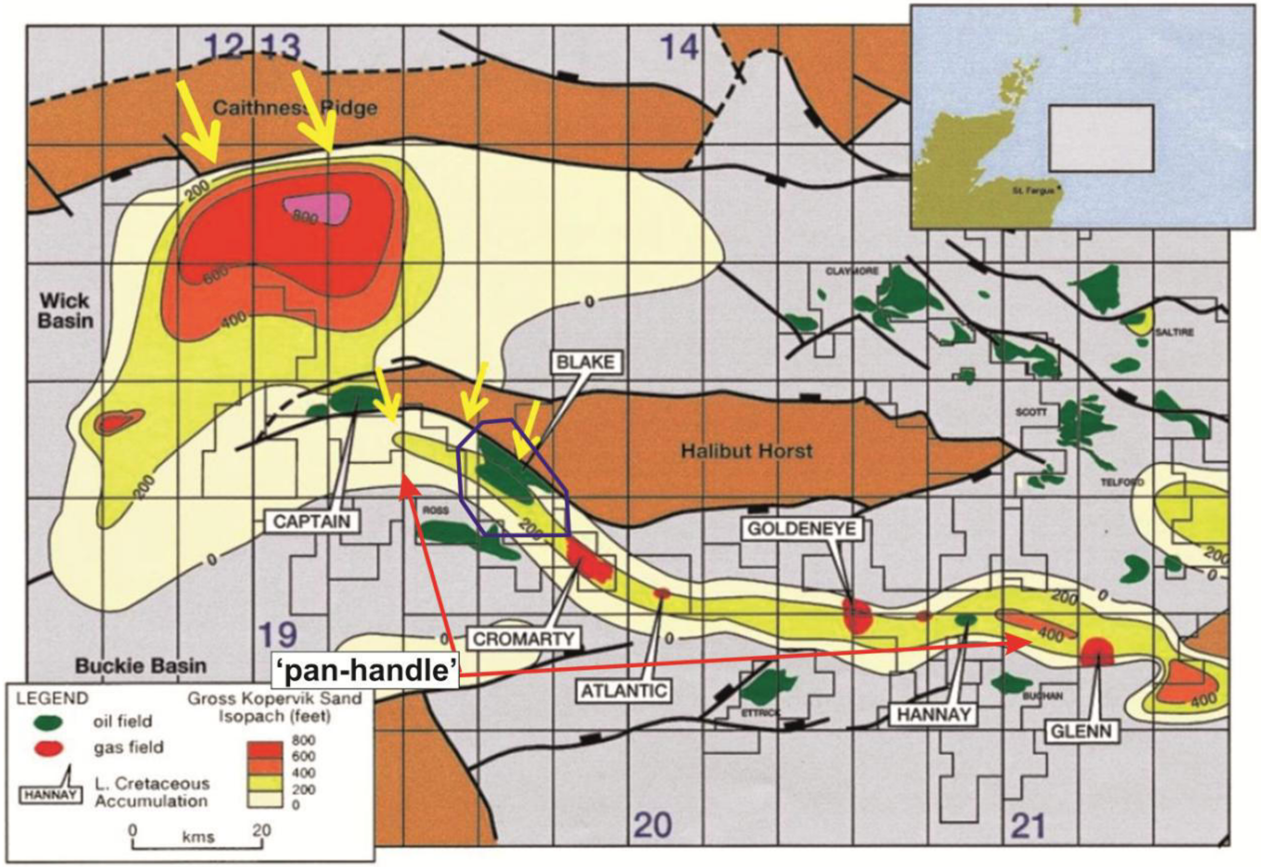
- **Storage reservoir pressure increase**
- **Expansion of reservoir rocks**
- **Induced changes in hydraulic properties (ϕ, k, Pc)**
- **Fault reactivation (slip)**
- **Hydraulic (tensile) fracturing**
- **Surface uplift**



(Source: Rutqvist, 2009)

Multi-store CO_2 storage site in the Outer Moray Firth, offshore Scotland

- **Consisting of a depleted hydrocarbon field and the surrounding host saline aquifer, the Captain Sandstone**

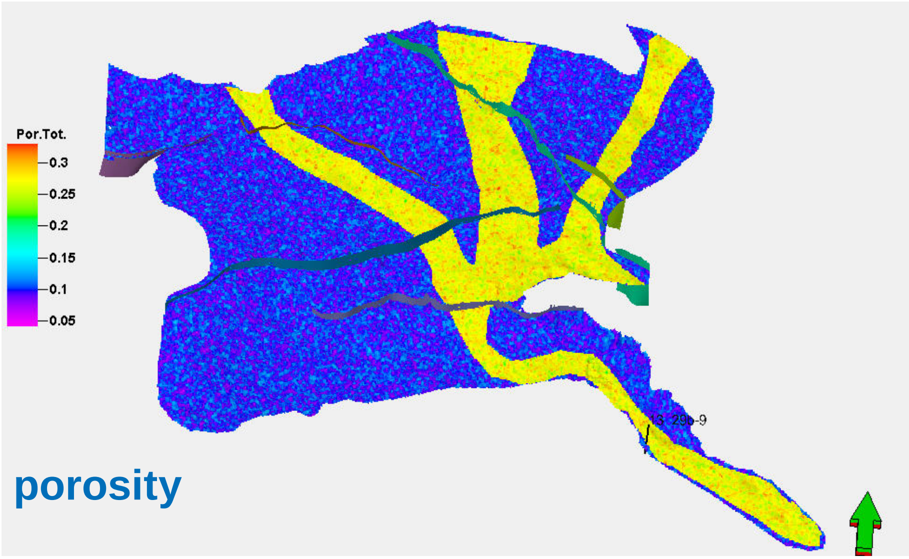


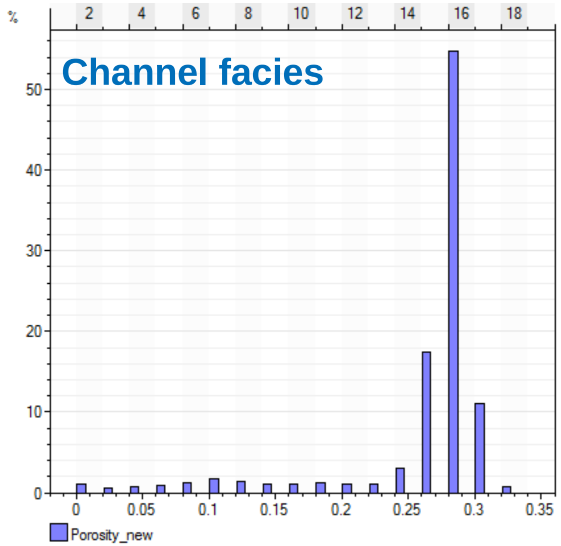
Objectives and Workflow

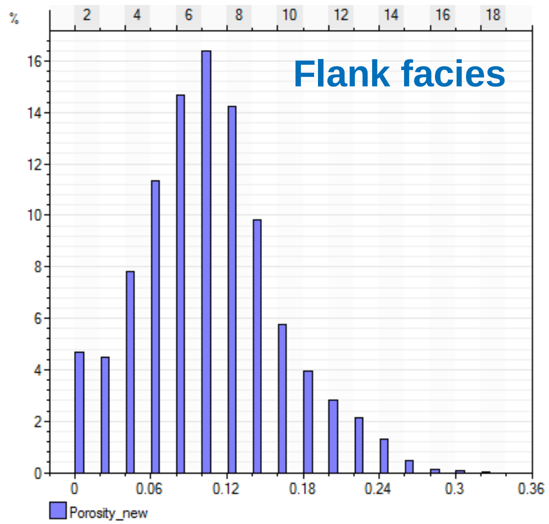
- Coupled flow and geomechanical simulations of CO_2 injection into the Captain Sandstone aimed at:
  - Evaluating the impact of CO_2 injection on changes in the stress field;
  - Evaluating mechanical stability, including fault reactivation.
- The flow and geomechanical modelling work was based on the attributed GoCAD static model by BGS and IFPEN within the SiteChar project.
- The workflow involved using ECLIPSE for flow simulation and coupled geomechanical modelling in VISAGE^{TM}.

The Upscaled Petrel Static Model for Flow and Geomechanical Modelling

Petrel Model: Porosity



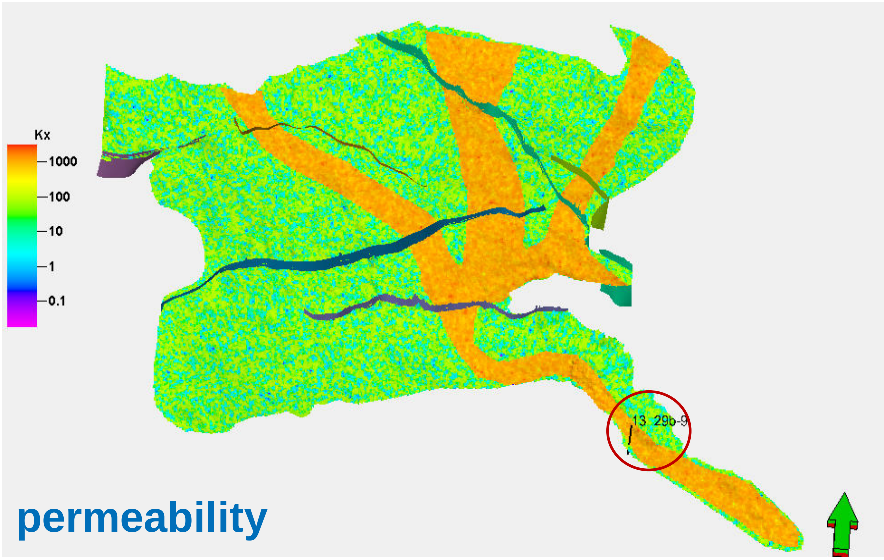




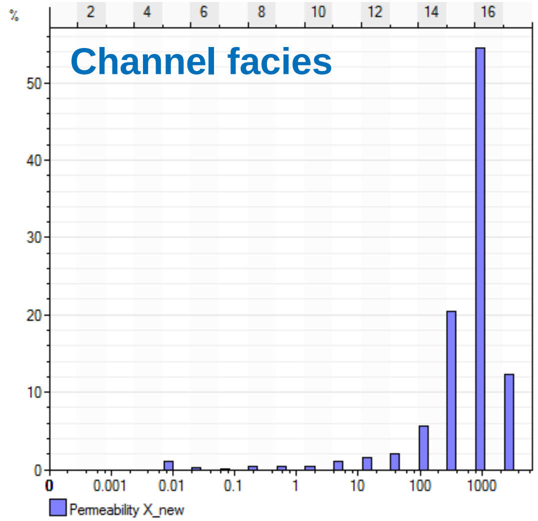
Layer	Porosity (fraction)	
	Channel	Flank
Mean	0.27	0.11
Minimum	0.01	0.01
Maximum	0.33	0.32

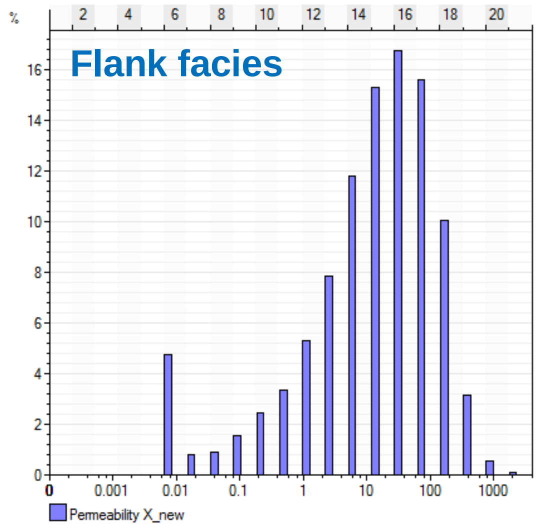
The Upscaled Petrel Static Model for Flow and Geomechanical Modelling

Petrel Model: Permeability



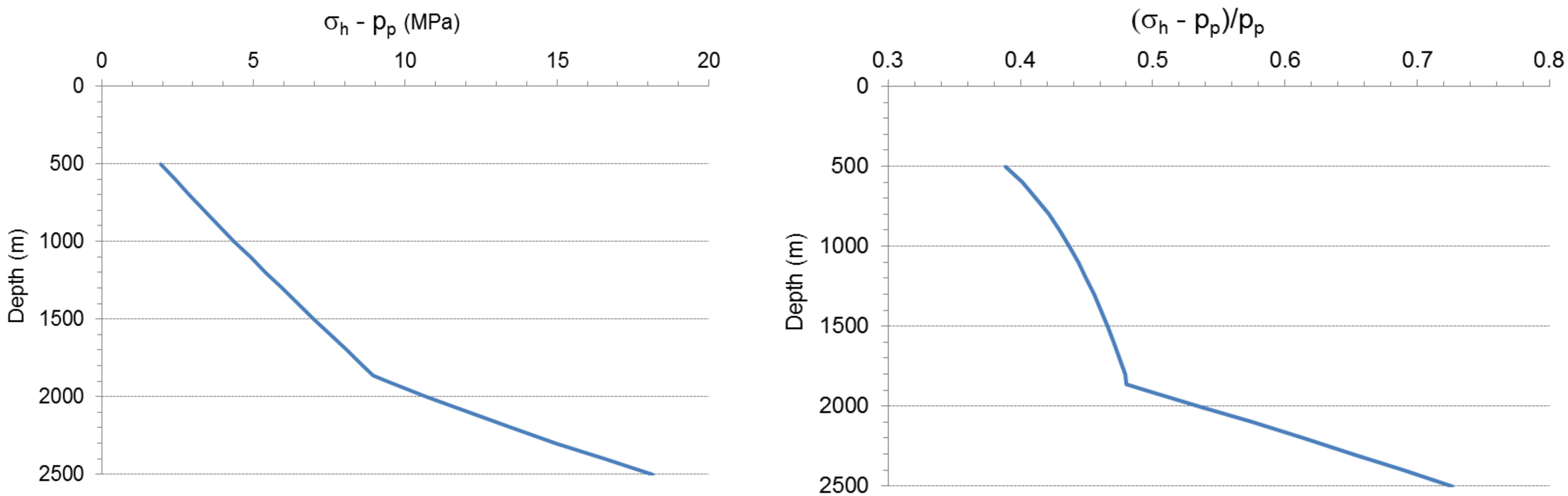
Layer	Permeability (mD)	
	Channel	Flank
Mean	1250	69.0
Minimum	0.01	0.01
Maximum	6000	3700





Pre-Injection Stress State and the Threshold Overpressure Ratio for Fracturing the Caprock

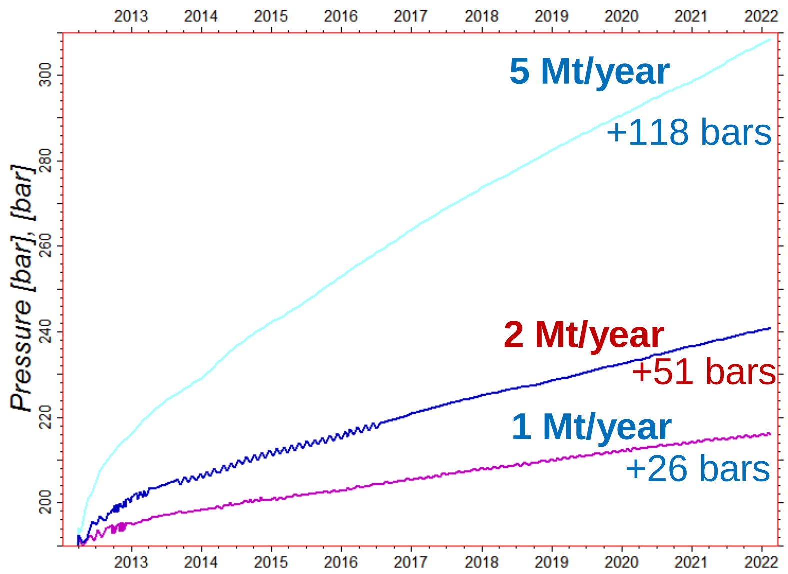
- **The in-situ stress and pore pressure profile at Goldeneye area has previously been determined using pore pressure information, log data, Leak-Off test (LOT) data, etc.**
- **The Goldeneye area is characterised by a normal stress regime (i.e. the vertical stress σ_v is the major principal stress), with the maximum horizontal stress (σ_H) orientated NNW-SSE.**
- **The overpressure threshold at a depth of 2,000 m is approximately 10 MPa, and the threshold overpressure ratio corresponding to the depth range 500 m to 2,000 m varies from ~0.4 to ~0.5.**

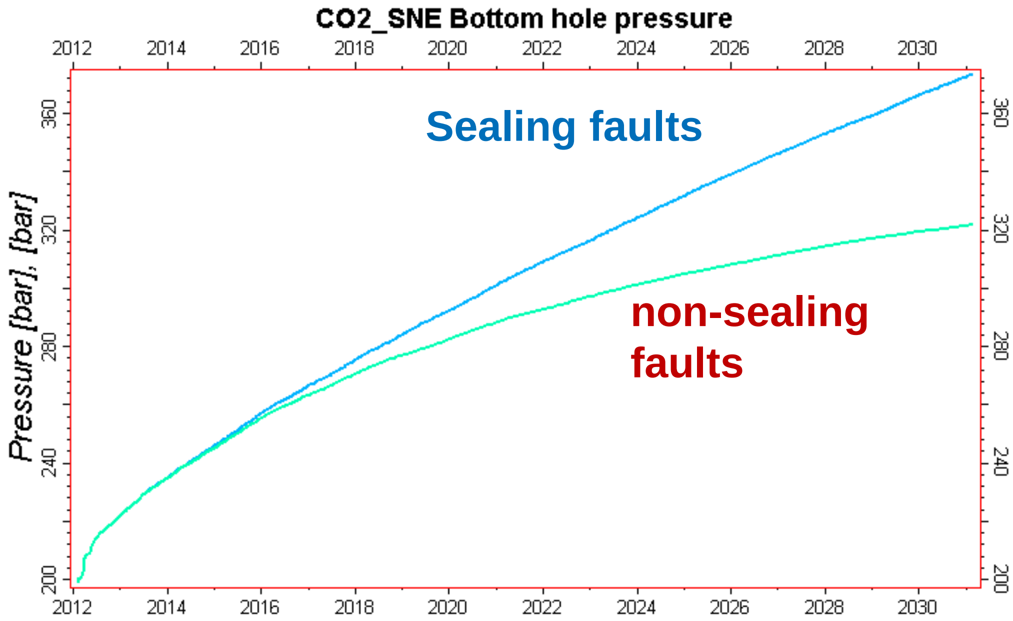


(Modified from ScottishPower CCS Consortium, 2011)

CO_2 Injection Simulation Results – Increase in Wellblock Pressure for Different Injection Rates

Injection into Captain saline aquifer at a rate of 1, 2 and 5 Mt CO_2/year for 20 years

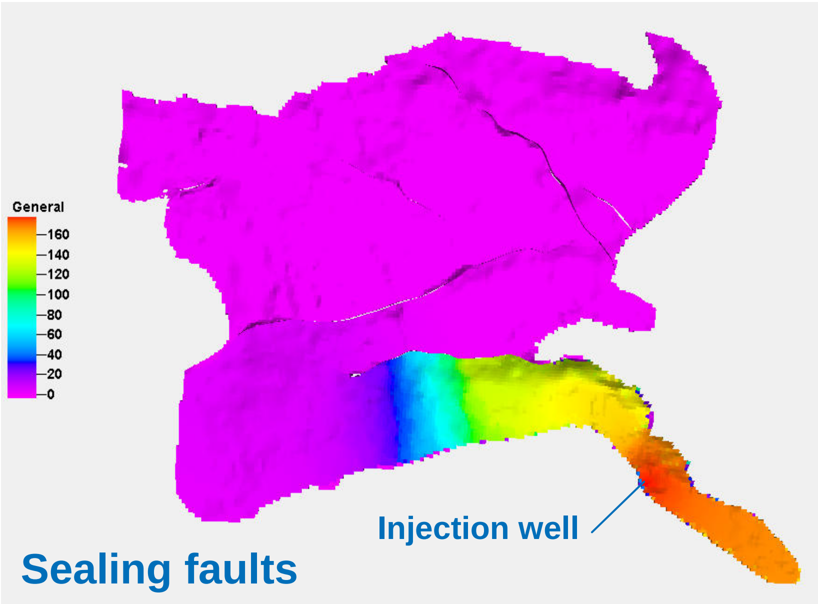


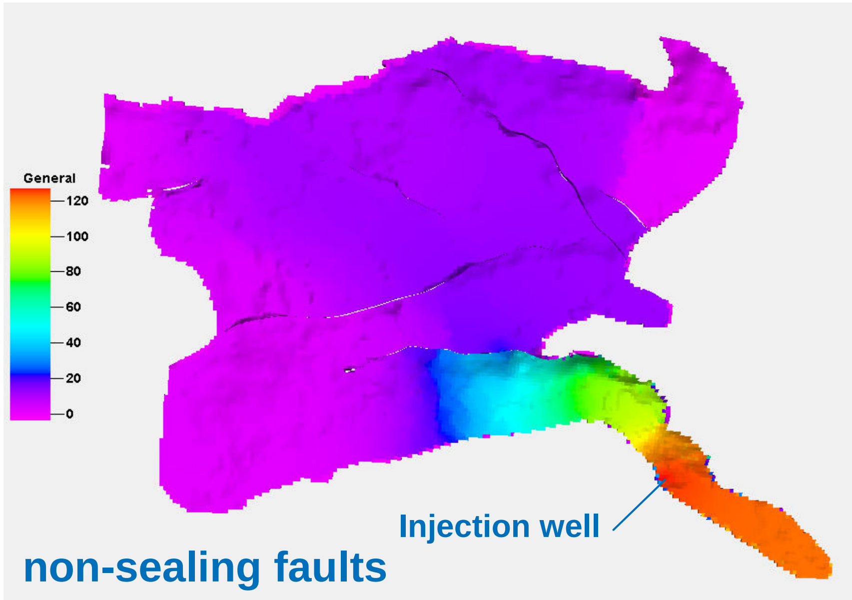


Scenario	10 year (bar)	20 year (bar)
Sealing	118	185
Non-sealing	108	135

CO_2 Injection Simulation Results – Overpressure Distribution

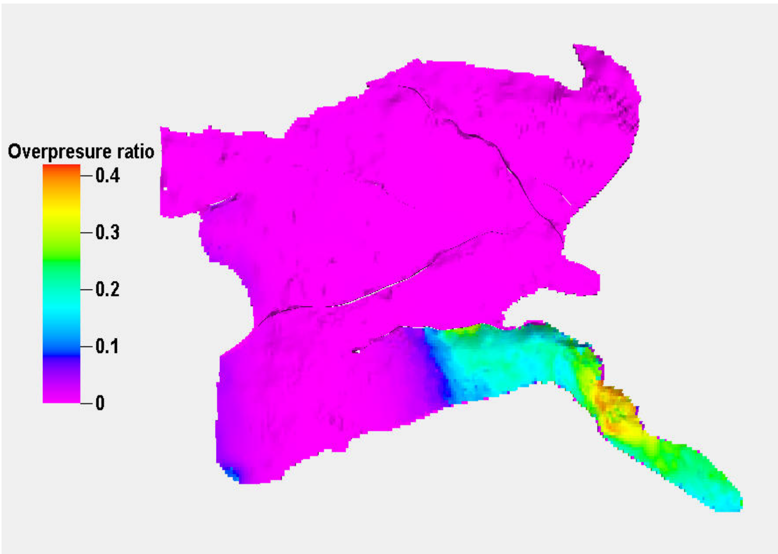
Injection into Captain saline aquifer at a rate of 5 Mt CO_2/year for 20 years



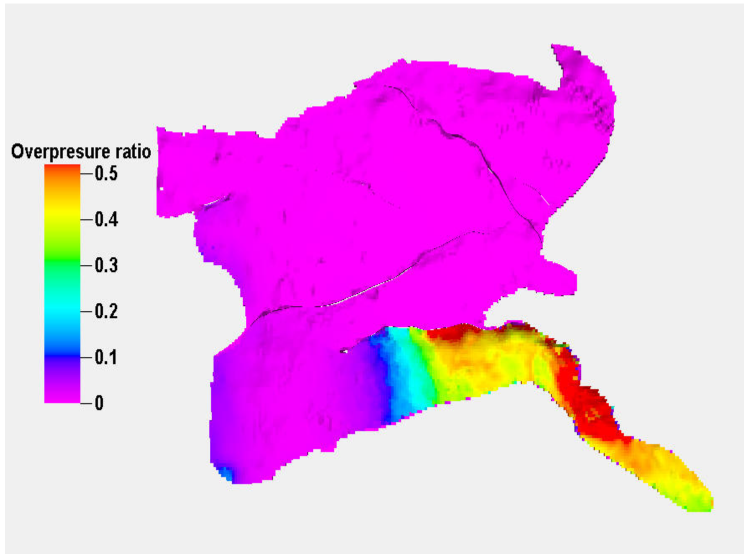


Overpressure Ratio for Geomechanical Stability

- The estimated overpressure threshold (for fracturing the caprock) for the depth range 500 m to 2,000 m lies between ~0.4 and ~0.5.
- The overpressure ratio generated by CO_2 injection over a 5 years period at a rate of 5 Mt/year is predicted to remain below the threshold (0.4).



After 5 years (25 Mt CO_2 stored)

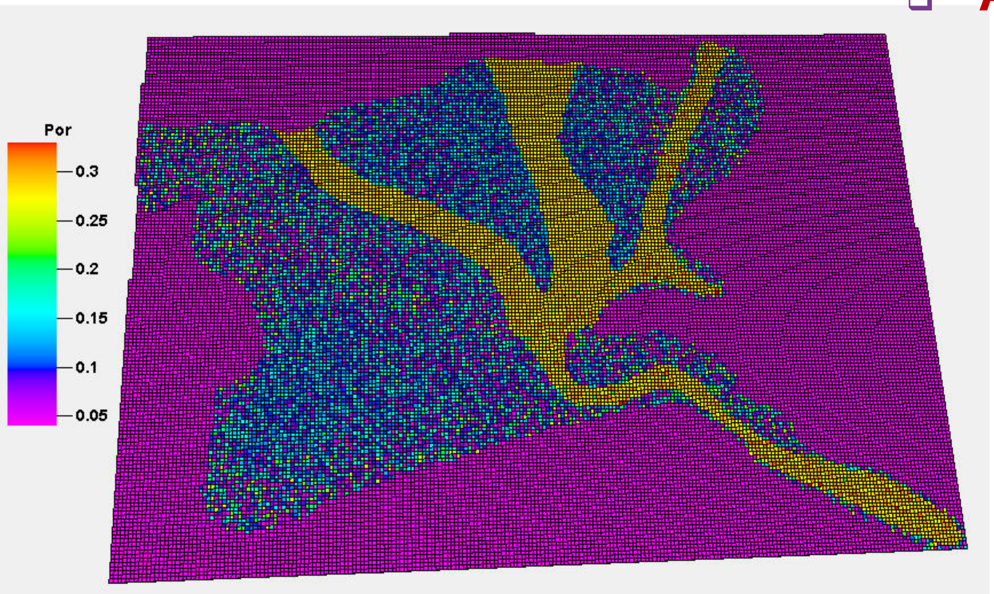


After 10 years (50 Mt CO_2 stored)

Coupled Flow-Geomechanics Modelling

The Extended Reservoir/Overburden Model

- The Top and Base Captain Sandstone surfaces were extended to a regular geometry to ensure the areas outside the original reservoir domain are properly gridded



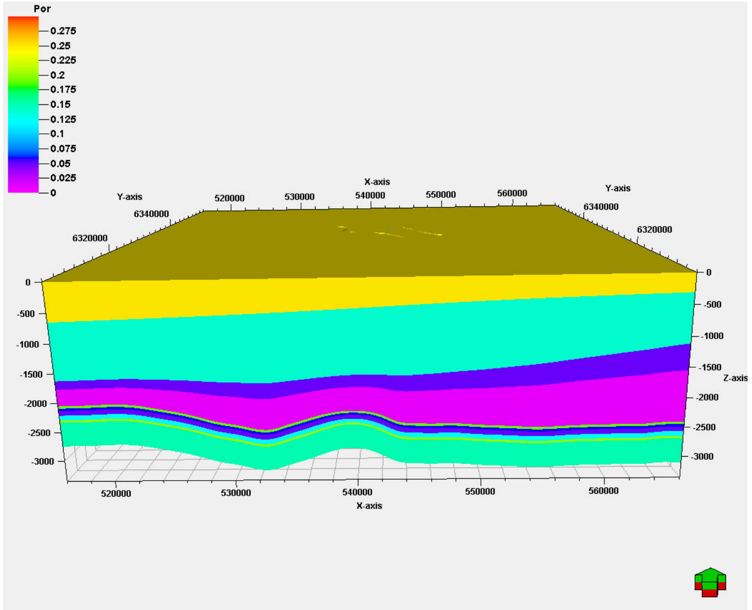
- **A total of nine layers:**
  - bottom four (layers 6-9) representing the Captain Sandstone
  - layer 5 is the immediate cap rock (Carrack and Rodby formations)
  - layers 3 and 4 make up the various formations bounded by the Base and Top Chalk surfaces.
  - The formations overlying the Chalk Group, up to the sea bed, are represented by Layers 1 and 2.

Geomechanical Model

Rock Elastic Properties

- Three generalised structures defined
  - Layers 3 - 4 : chalk
  - Layers 1, 2, 5 : mudstone
  - Layers 6 - 9 : sandstone

- The base case elastic properties are taken from the literature

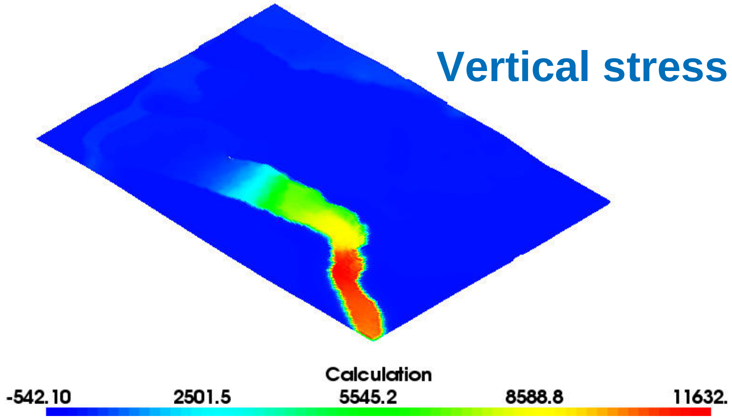


	Chalk Region	Mudstone Region	Sandstone Region
Young Modulus, E (GPa)	11	8.5	15
Poisson ratio, υ	0.32	0.27	0.32

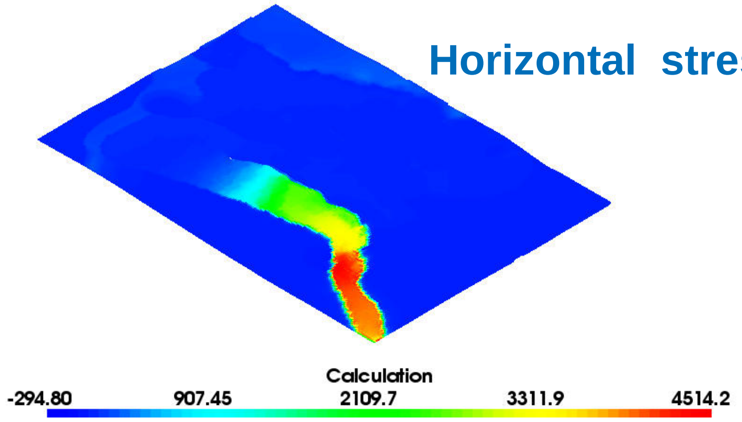
Geomechanical Modelling Results

Reduction in Reservoir Effective Stresses

Vertical stress (kPa)

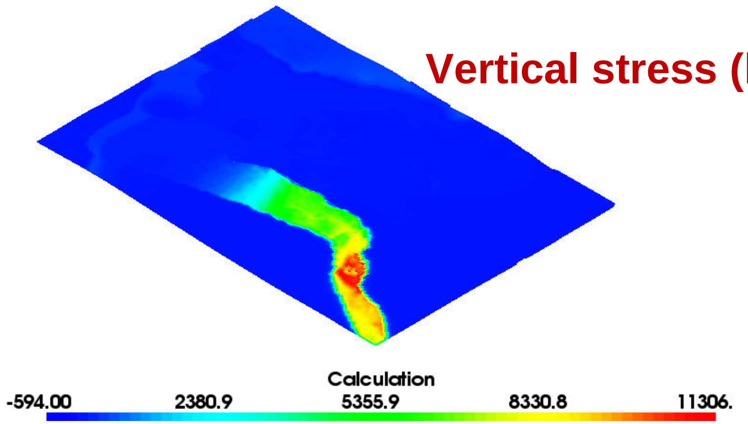


Horizontal stress (kPa)

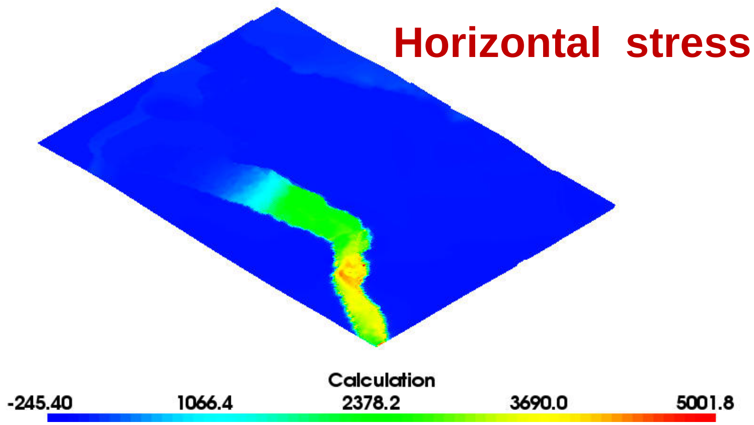


Reduction in Caprock Effective Stresses

Vertical stress (kPa)



Horizontal stress (kPa)



5 Mt CO_2/year for 10 years

Assessment of Shear Failure

The widely used Mohr-Coloumb failure criterion was used to check for shear failure:

$$\sigma_1' = \frac{1 + sin\varphi}{1 - sin\varphi}\sigma_3' + \frac{2S_0 cos\varphi}{1 - sin\varphi}$$

Where

σ'_1 and σ'_3 are respectively the effective major and minor principal stresses

S_0 is cohesion and

φ is the angle of internal friction.

$$F = \sigma_1' - \left(\frac{1 + sin\varphi}{1 - sin\varphi}\sigma_3' + \frac{2S_0 cos\varphi}{1 - sin\varphi}\right)$$

$F < 0$ *indicates shear failure*

$F > 0$ *indicates intact rock*

	Captain Sandstone	Caprock
Internal friction angle (º)	4.4	13
Cohesion, MPa	3	6

Stress State Scenarios

- As the effective vertical stress is expected to decrease at a faster pace than the horizontal stresses as the reservoir is being pressurized, two scenarios were considered for shear failure assessment:

    1. **the vertical stress remains the major stress (normal stress regime)**
    2. **the vertical stress is no longer the major stress, i.e. $\sigma_H > \sigma_v > \sigma_h$ (strike-slip stress regime).**

- The results of shear failure assessment have shown that no failure would occur in the both Captain Sandstone and the caprock for the two stress scenarios considered.

Conclusions

- Analysis of the reported minimum horizontal stress and pore pressure profile showed that the threshold overpressure ratio for fracturing is between 0.4 and 0.5.
- Reservoir simulation of CO_2 injection into the aquifer down-dip of the Blake Field, at a rate of 5 Mt/year revealed that the overpressure after 5 years of injection would not exceed the fracture pressure threshold.
- However, the fracture pressure threshold would be exceeded if injection were to continue for a further 5 years at this rate.
- Evaluation of the coupled flow and geomechanical modelling results suggested that no shear failure or fault slip in either the Captain Sandstone or the cap rock would occur after injection of 25 million tonnes of CO_2 over a 5 year period.
- Given the uncertainties present in the attribution of both the flow and geomechanical models, including the pre-injection stress state, the geomechanical modelling results should be viewed with caution.