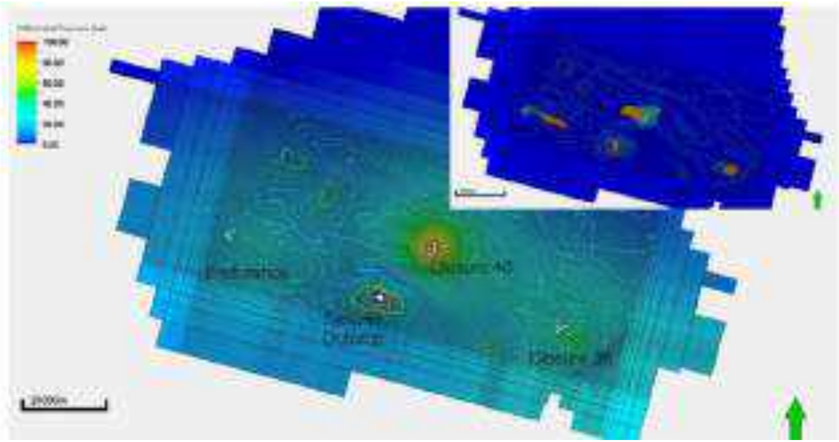
BGS British Geological Survey

IDRIC

SCCS

The Bunter Sandstone Formation

CO_2 storage in an extensive hydraulically-connected saline aquifer



Agenda

- 14:00 *Welcome & Introduction* - Jonathan Pearce, BGS (10 min)
- 14:10 *Capturing the carbon storage potential of the Bunter Sandstone Formation* - Lucy Heaton, North Sea Transition Authority
- 14:20 Adrian Topham & Amy Bloomfield-Clarke, The Crown Estate
- 14:30 *Regional compartmentalisation of the Bunter Sandstone* - Lucy Abel, BGS
- 14:40 *Impact of large-scale CO_2 injection in the Bunter Sandstone* - John Williams, BGS
- 14:50 *The Impact of Capillary Heterogeneity on CO_2 Plume Migration at the Endurance CCS Target Site in the UK – a Core to Field Scale Study* - Nele Wenck, Imperial College London
- 15:00 Q&A
- 15:25 Wrap-up
- 15:30 End

SCCS

North Sea Transition Authority

Capturing the carbon storage potential of the Bunter Sandstone Fm

Driving the UK towards NetZero

Lucy Heaton (Senior Geoscientist, New Ventures Directorate)

15/06/2023

1st carbon storage licence round: offers of award

North Sea Transition Authority

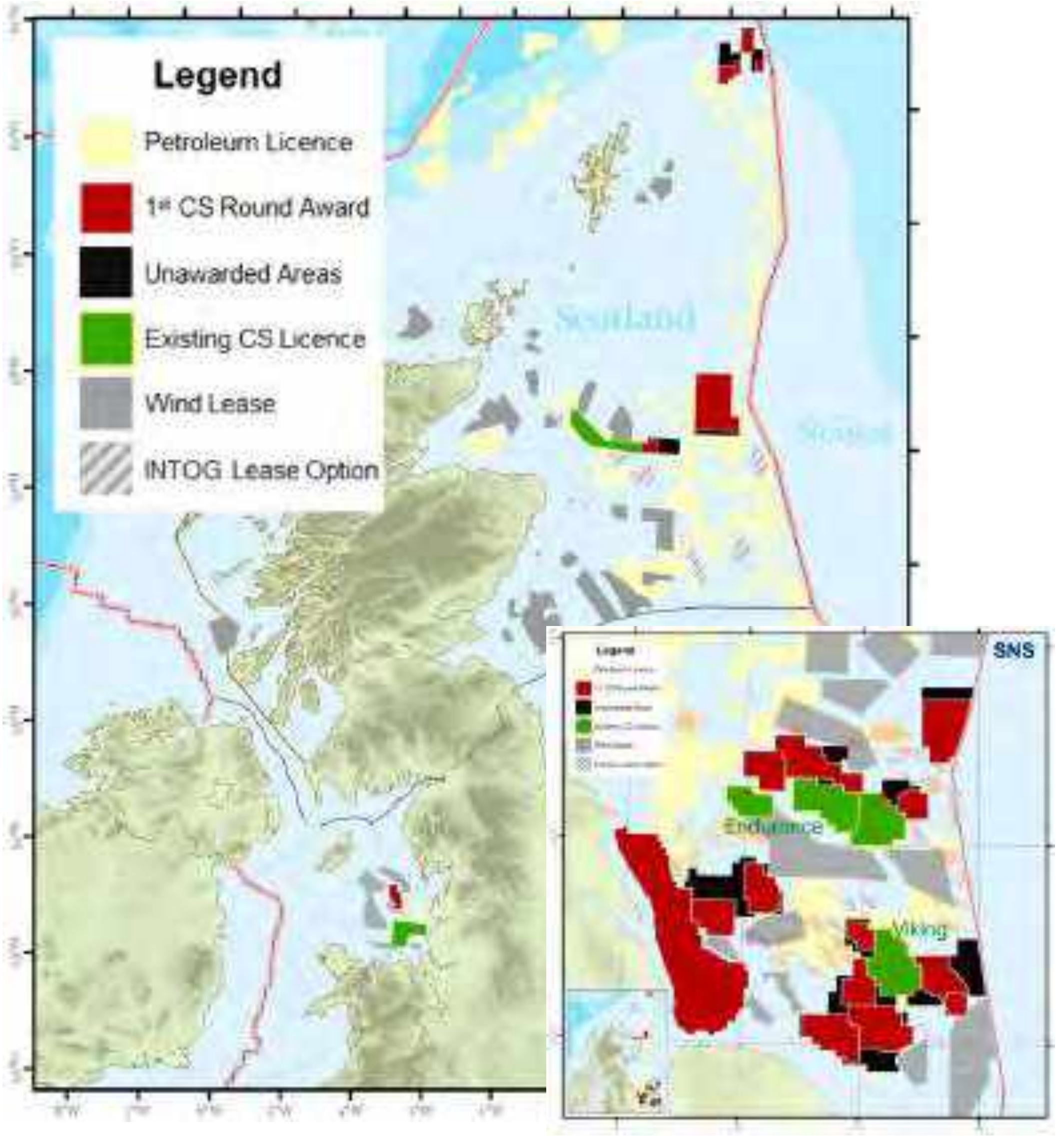
Offers of award have been made with responses expected imminently

- 20 licences offered for award covering ~12,000 km^2
- Awards in all areas made available for application
- Diversified portfolio covering Aquifers & Depleted Fields stores
- Some projects potentially injecting before 2030

Key Success Metrics

If all offers accepted….

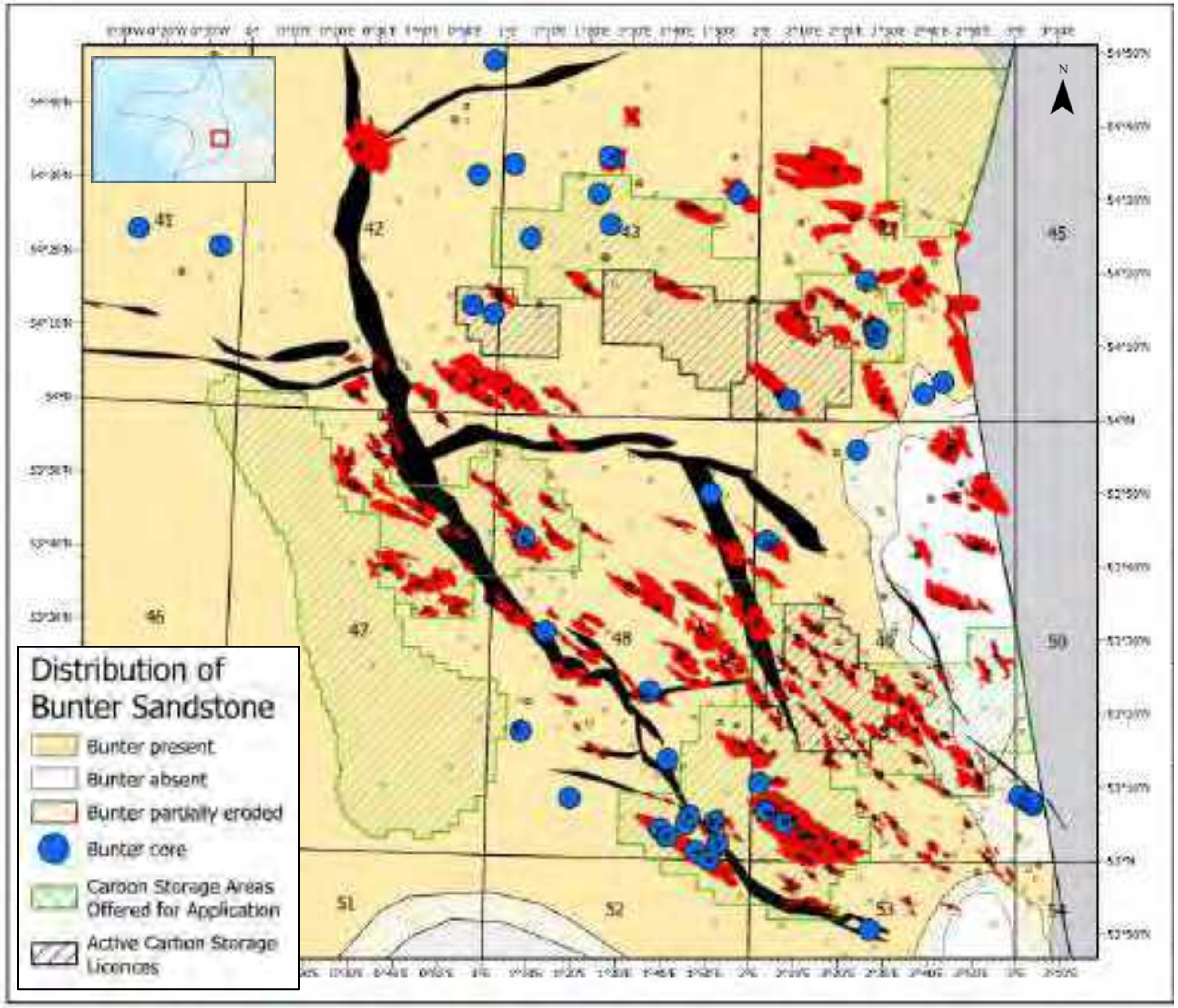
- 5 Firm Wells/Tests (9 Contingent)
- 4 Firm Seismic Shoots (5 Contingent)
- Additional reprocessing and studies commitments



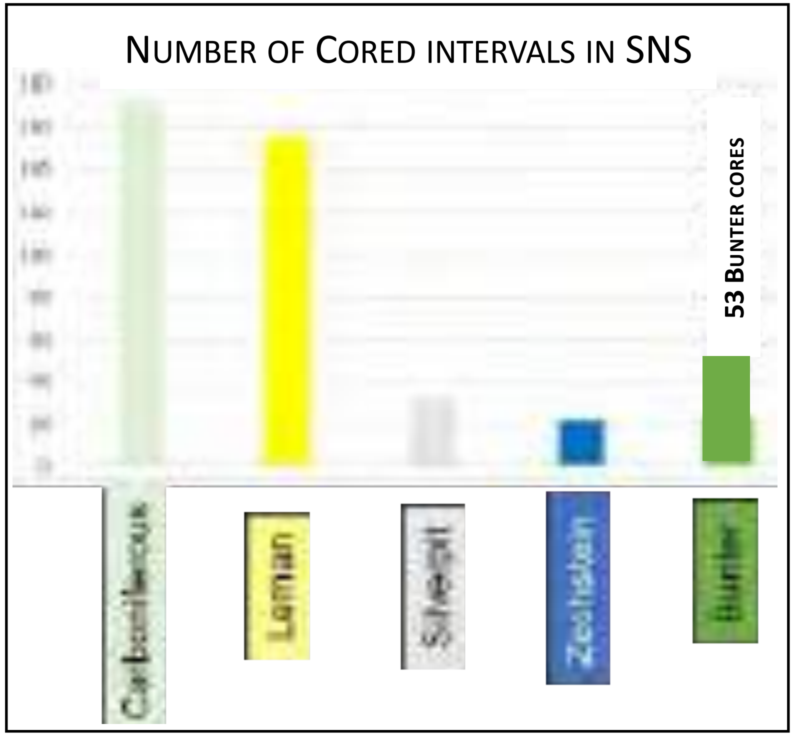
A high level of appraisal is required in some parts of the portfolio awarded in the 1st round

Better subsurface characterisation is key to successful storage

North Sea Transition Authority



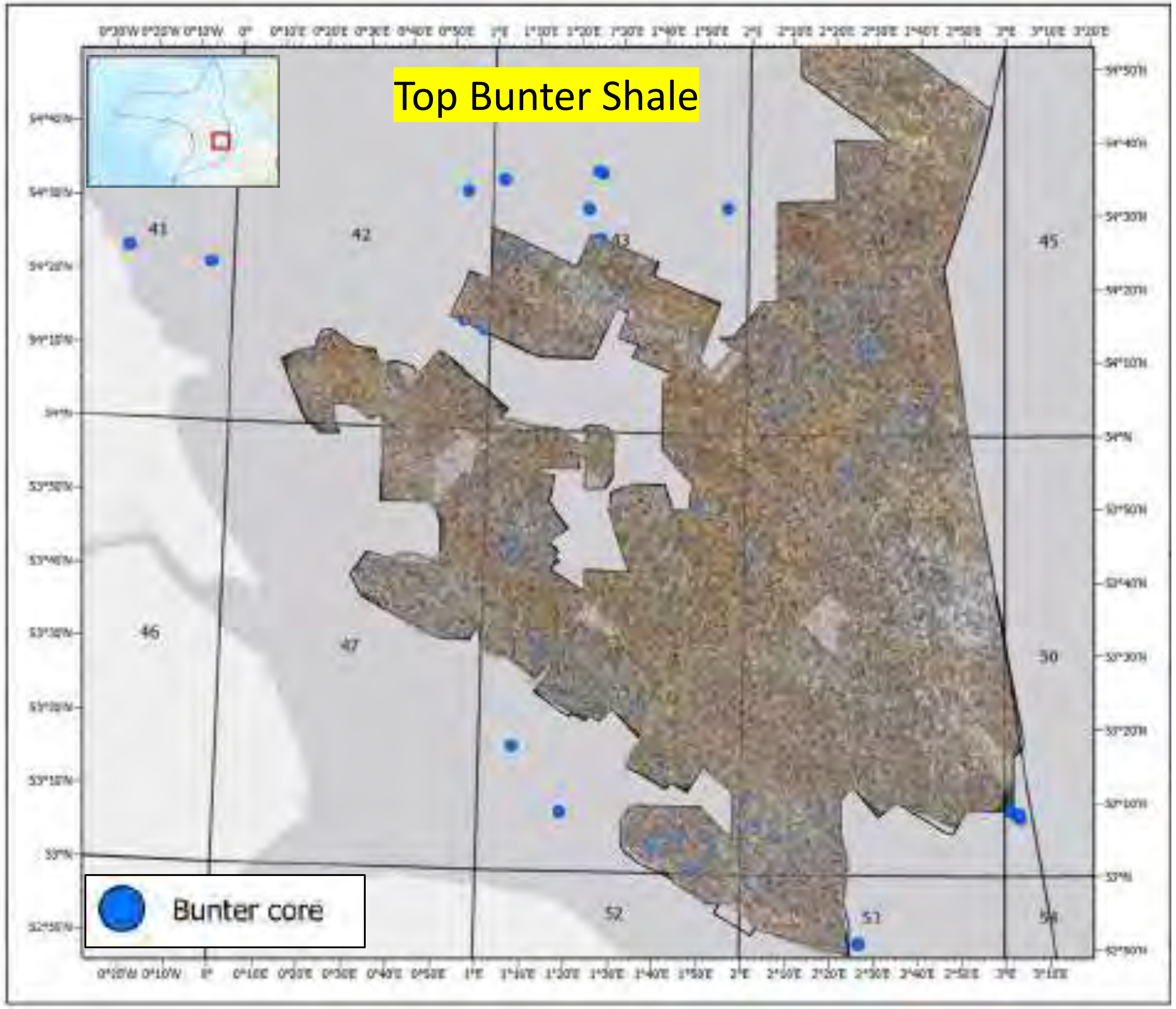
- > 2000 penetrations of the Bunter Sandstone
- ~ 53 whole or partial cores
- sparse density-neutron
- very few pressure/fluid samples

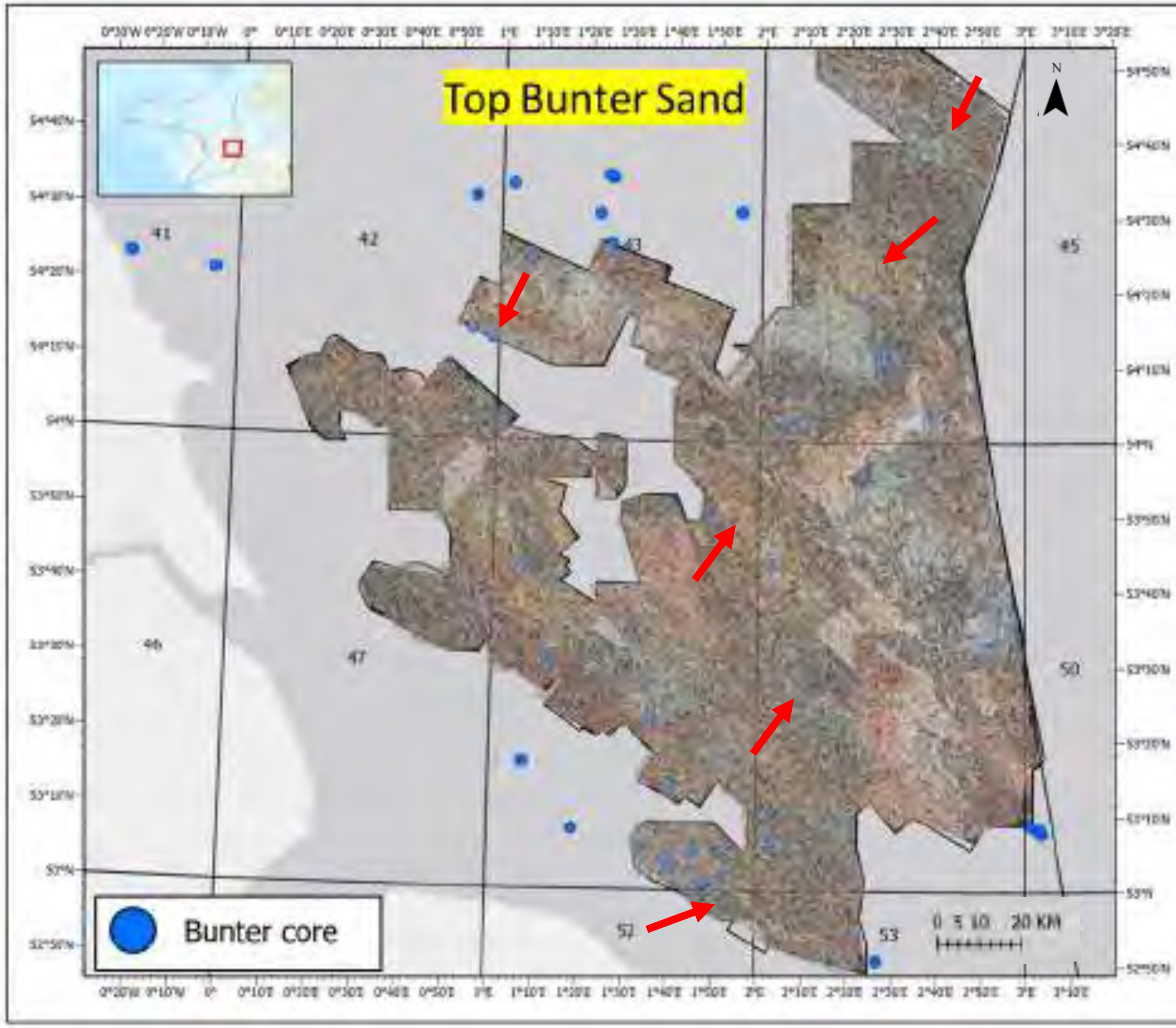


Despite being widely drilled, the Bunter is relatively under-appraised

Integrating wells and seismic to fill in the gaps

North Sea Transition Authority



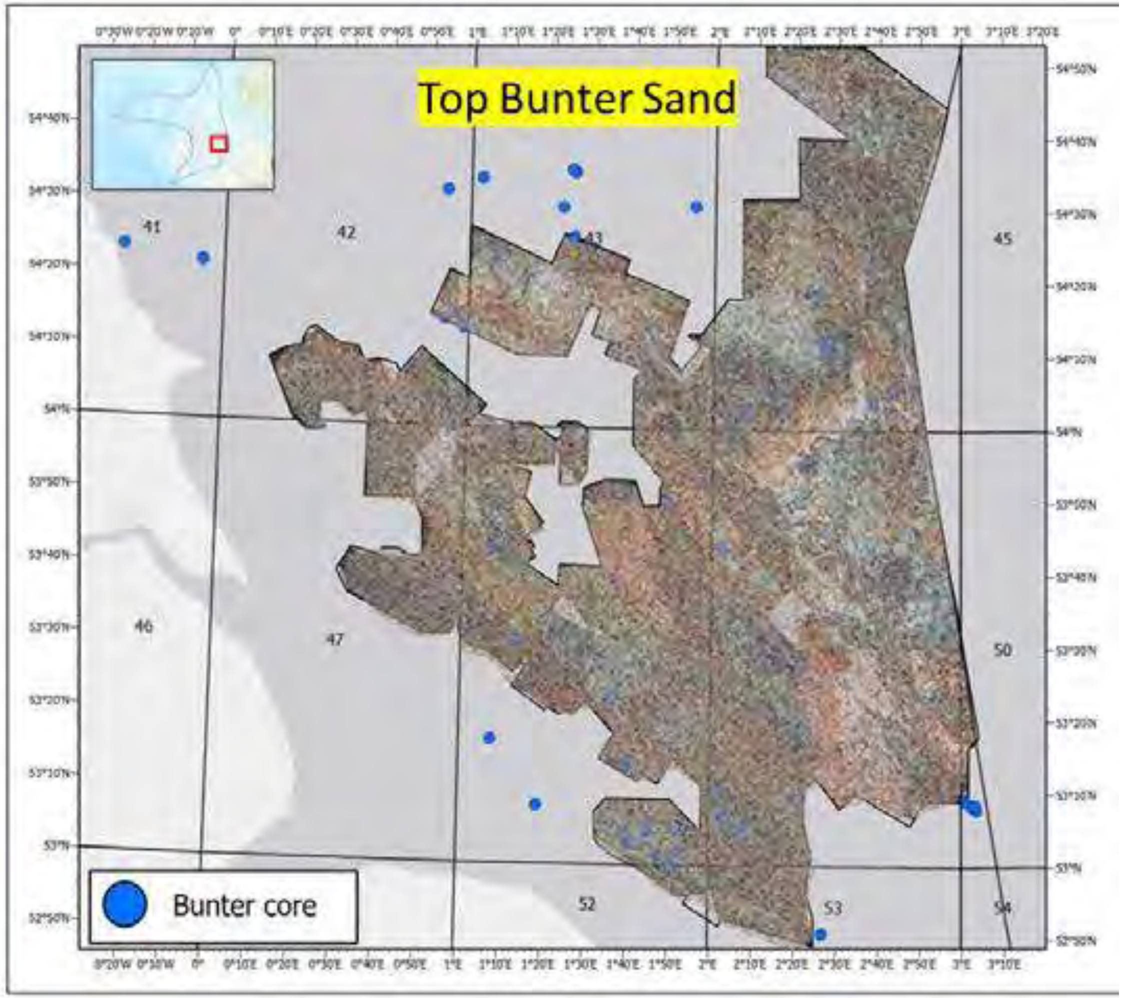


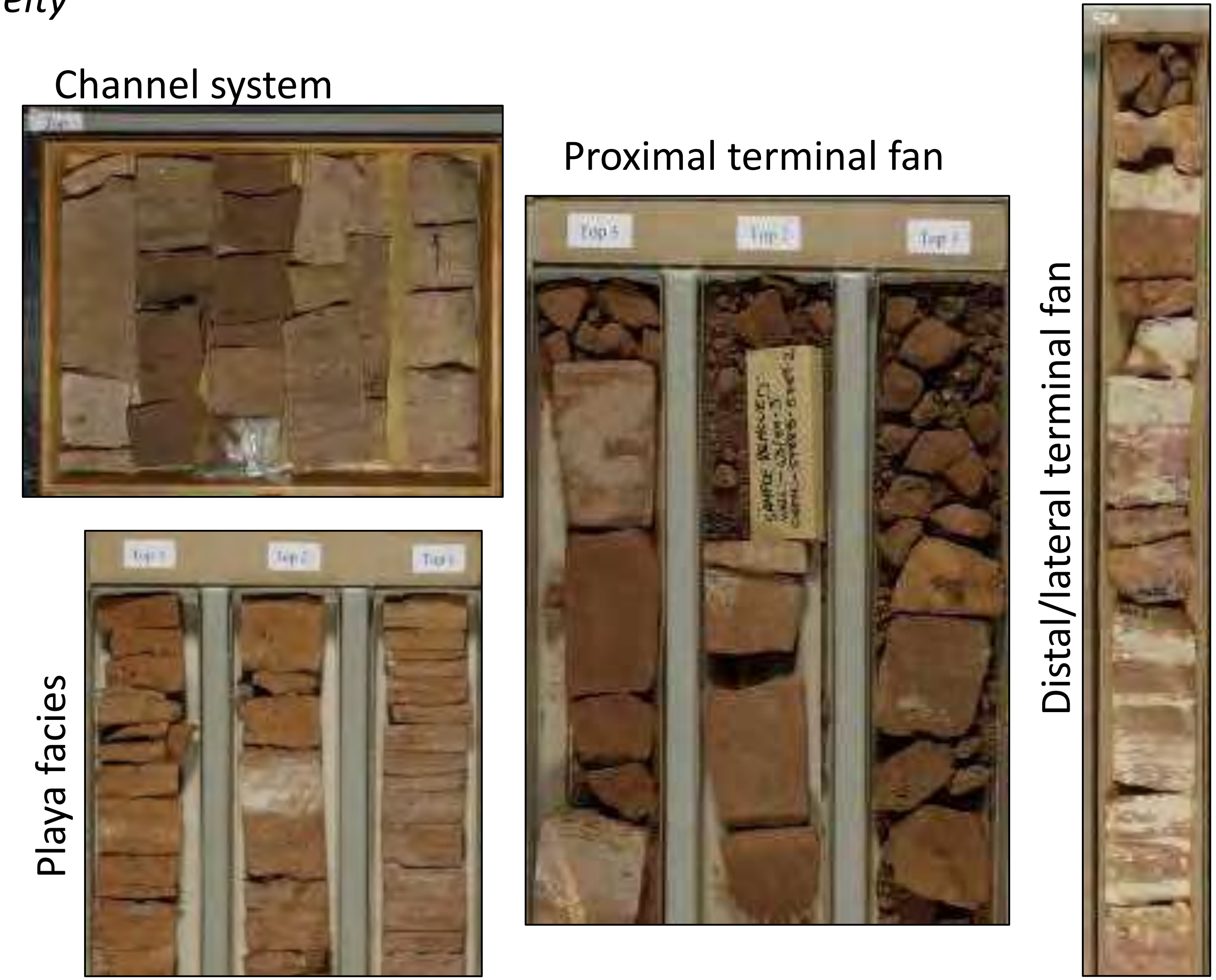
Progressive development of Bunter system

Capturing Bunter heterogeneity through integration

North Sea Transition Authority

"The Bunter is a tank of sand"……..but it is also a fluvial depositional setting with that comes with lateral and vertical heterogeneity

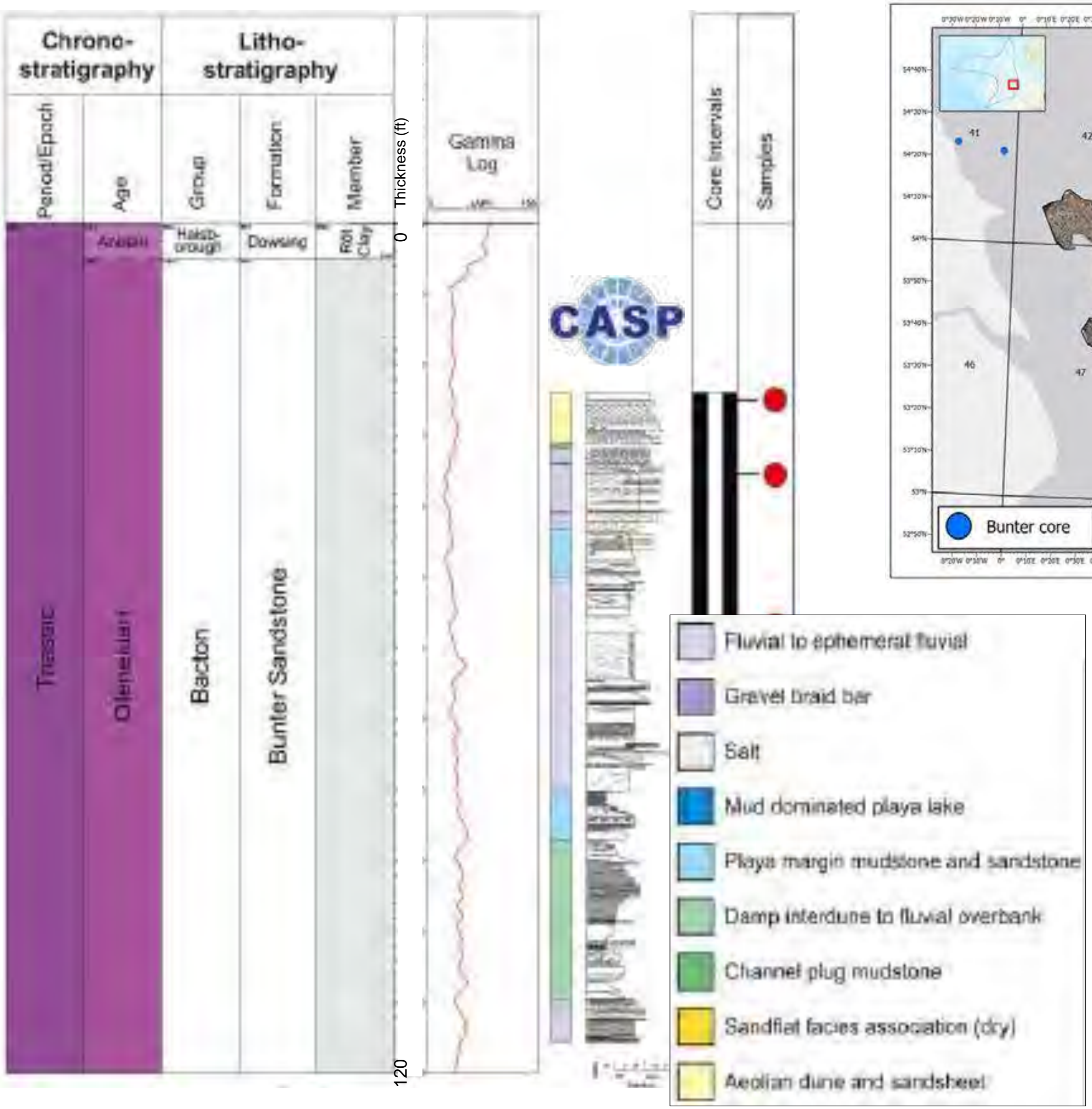


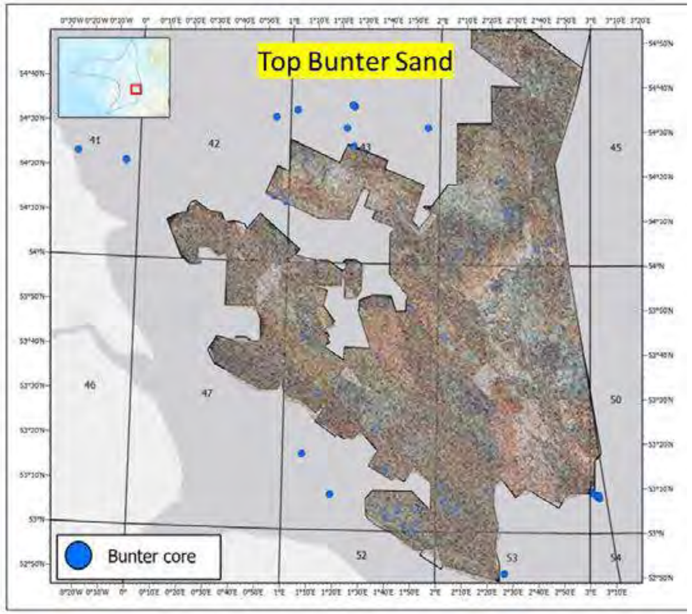


Optimum use of subsurface data is one of the key stewardship expectations of the NSTA

Capturing Bunter heterogeneity through integration

North Sea Transition Authority





Channel system

Proximal terminal fan

Playa facies

Distal/lateral terminal fan

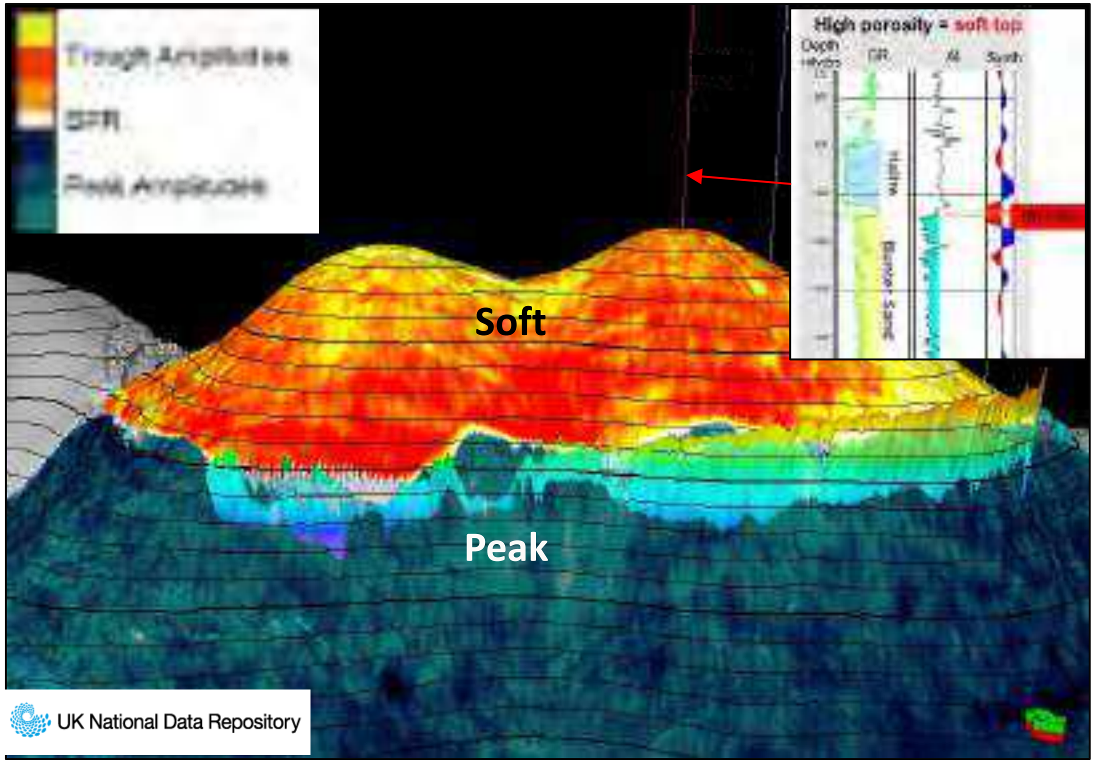
Optimum use of subsurface data is one of the key stewardship expectations of the NSTA

Capturing Bunter storage potential in the SNS

North Sea Transition Authority

Heterogeneity in the Bunter could impact:

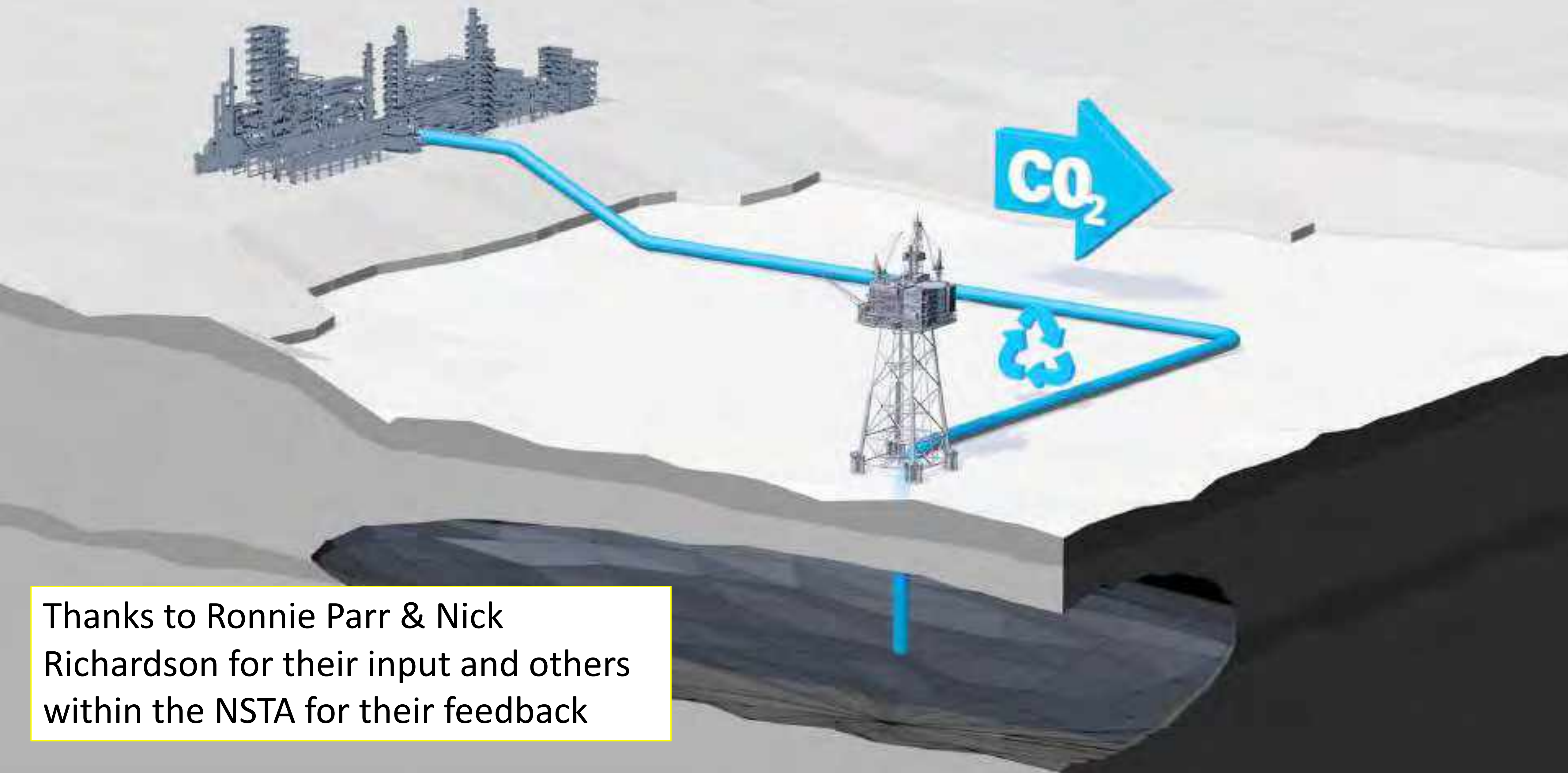
- Injectivity
- Connectivity / communication
- Volumetric capacity
- Time



Early appraisal is key

Optimum use of subsurface data is one of the key stewardship expectations of the NSTA

North Sea Transition Authority



Thanks to Ronnie Parr & Nick Richardson for their input and others within the NSTA for their feedback

Informing a Co-ordinated Approach to Future Seabed Use

Dr Amy Bloomfield-Clarke

Bunter Sandstone Webinar June 2023

THE CROWN ESTATE

Agenda

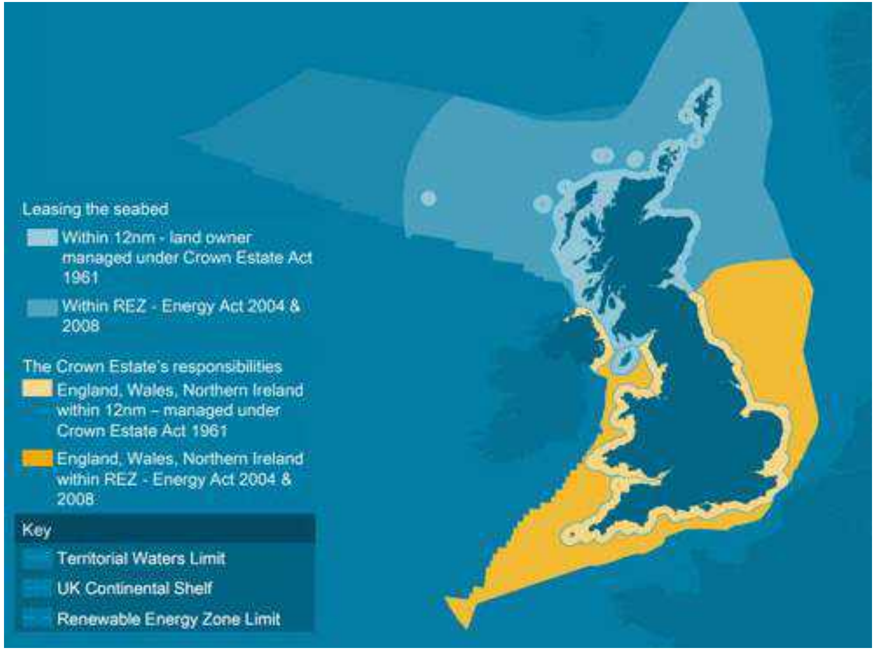
1. The Crown Estate Purpose and Role
2. Strategic Management in the Marine and Subsurface Environment
3. Maximising the Potential of the Seabed
4. Leasing Rights for Carbon Storage

The Crown Estate

- Owners and managers of the seabed in England, Wales and Northern Ireland

- Asset management and leasing

- Play an important role in the growth and sustainable development of the seabed, including within:
  - Offshore Wind
  - CCUS
  - Marine Aggregates
  - Cables and Pipelines
  - Nature restoration



The Crown Estate Purpose and Role

PURPOSE

- …to create lasting and shared prosperity for the nation
- Create and accelerate new opportunities to assist with the energy transition

ROLE

- Work in partnership with our customers and stakeholders to support the long-term sustainable development of the seabed
- Wish to enable carbon storage appraisal while ensuring existing rights of other seabed users are protected

Strategic Management in the Marine and Subsurface Environment

- Demand for marine space increasing with newly emerging industries including offshore wind and CCUS
- Intend to digitally map the seabed resource needed to meet future demand
- Aim to enable the delivery of multiple priorities and co-ordination of future activities to 2050
- Building an integrated, spatial analysis platform
- Drive the design of The Crown Estate's longer-term seabed leasing process

Courtesy, MMO

Maximising the Potential of the Seabed

- Offshore Wind and CCUS Colocation Forum: strategic co-ordination of colocation research and activity

- Recognises that both sectors have a significant role to play, including ambitions to:
    - Deliver four CCUS clusters, capturing 20-30 $MtCO_2$ across the economy per year by 2030
    - Deliver 50GW of offshore wind, including 5GW of innovative flowing offshore wind by 2030

- Four major workstreams:
    - Spatial characterisation
    - Measurement, monitoring and verification (MMV)
    - Demonstration of colocation scenarios
    - Best practice in simultaneous operations

Leasing Rights for Carbon Storage

- Currently working on creating a transparent leasing process for carbon storage
- We are actively working with NSTA and DESNZ to ensure alignment and accelerate the enabling of the sector
- The results of a joint market engagement survey to CCUS developers survey are feeding into our leasing design

Summary

- The Crown Estate’s role has multiple priorities:
  - To enable carbon storage appraisal within an increasingly busy marine environment
  - To enable the delivery of multiple priorities and co-ordination of future activities to 2050
  - To protecting the rights of other seabed users
  - To ensure long-term sustainable development of the seabed

- Digitally mapping the seabed resource will help us to meet future demand

- We aim to maximise the potential of the seabed including via the Offshore Wind and CCUS Colocation Forum to understand the opportunities and challenges to colocation of projects

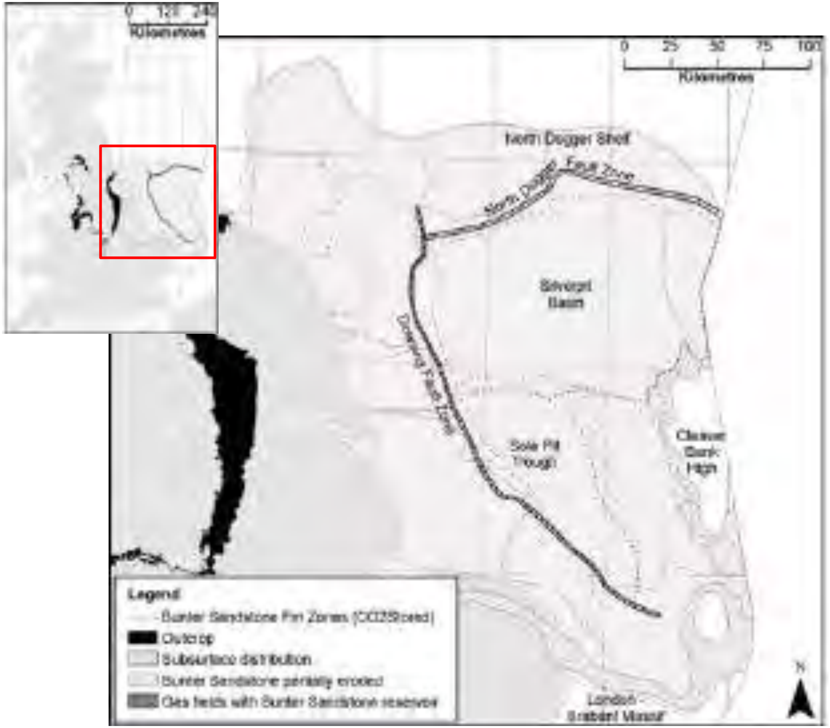
- To provide suitable leasing products and services for future CCUS projects

LUCY ABEL

Regional compartmentalisation of the Bunter Sandstone

British Geological Survey

Regional and Structural Geology



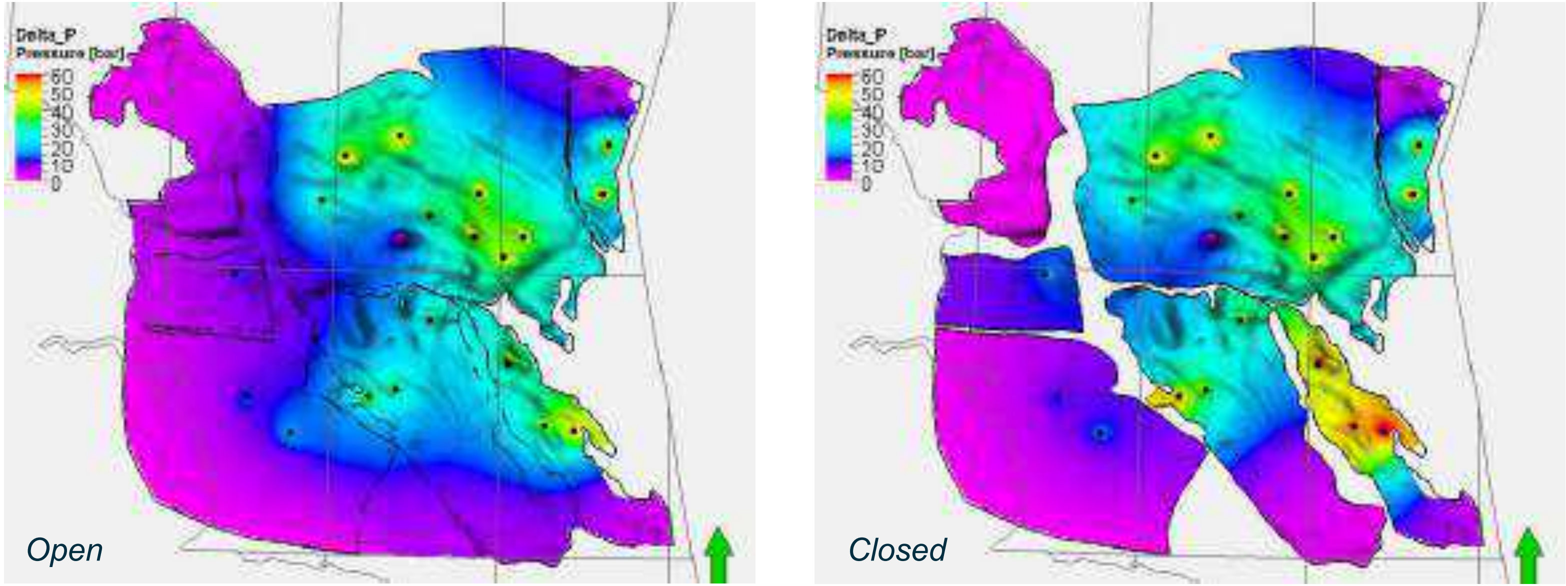
Structural map of the Southern North Sea

- The Southern North Sea is made up of several sub basins and regional highs largely controlled by the underlying Permian salt. This deforms the overlying Bunter Sandstone separating it into separate zones.

- The regional zones of the Bunter Sandstone Formation have been taken from the CO2Stored Database

Regional pressure modelling due to CO_2 Injection

- Regional modelling completed based on Bunter Sandstone Formation Zones as defined by the CO2Stored database



Pressure increase above hydrostatic conditions after 30 years of injection at a rate of 2 Mt/yr CO2 for cases with faults closed (top) and open (right). Cells representing fault boundaries are removed from the model when closed and have the properties of Zone 4 when open. Injection wells are marked with black circles.

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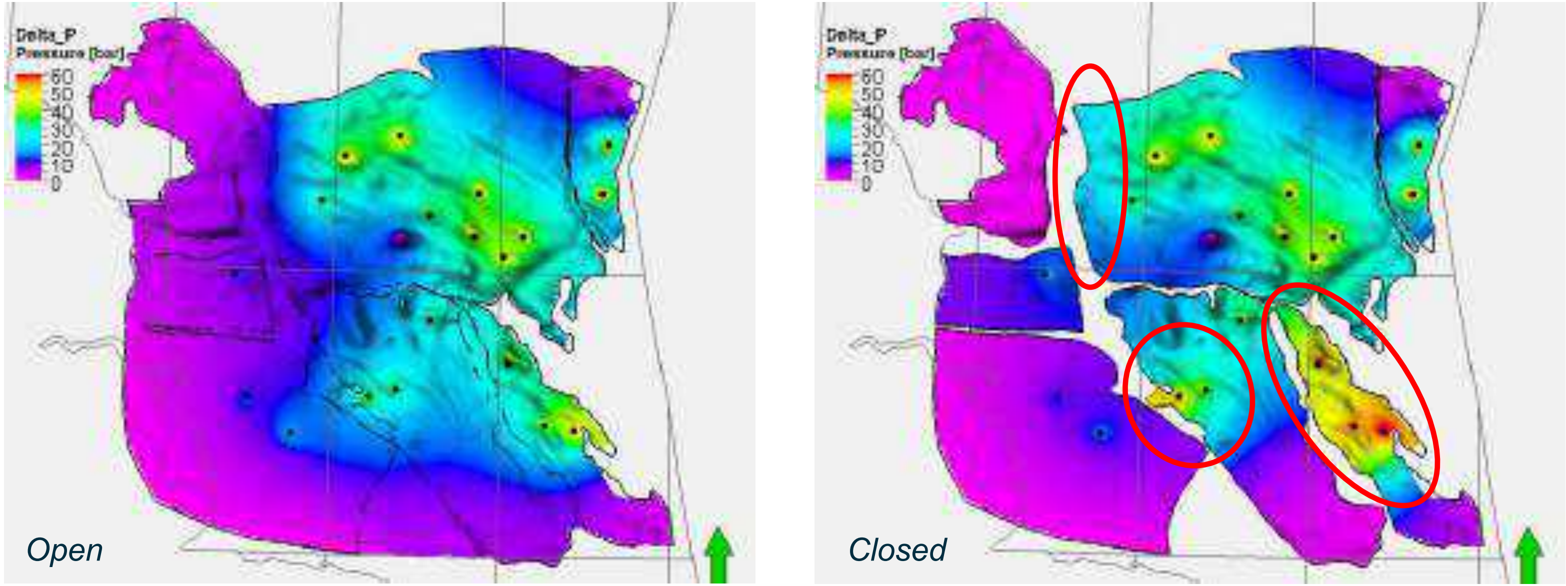

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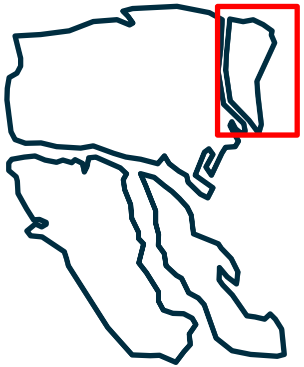
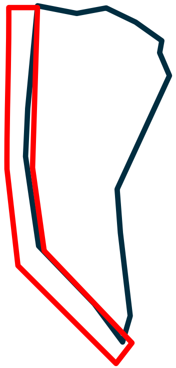
Mapping the variation in structural separation styles in the Bunter Sandstone

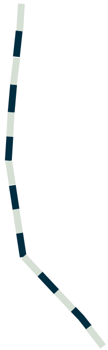
- Interpretation of the main stratigraphical horizons in the SNS focusing on the Bunter Sandstone Formation
- Review of the CO2Stored zone boundaries and revision where necessary
- Mapping and characterising the regional structural style



Bunter Zone Boundaries



Area 5



Division into 5 km segments

Classification

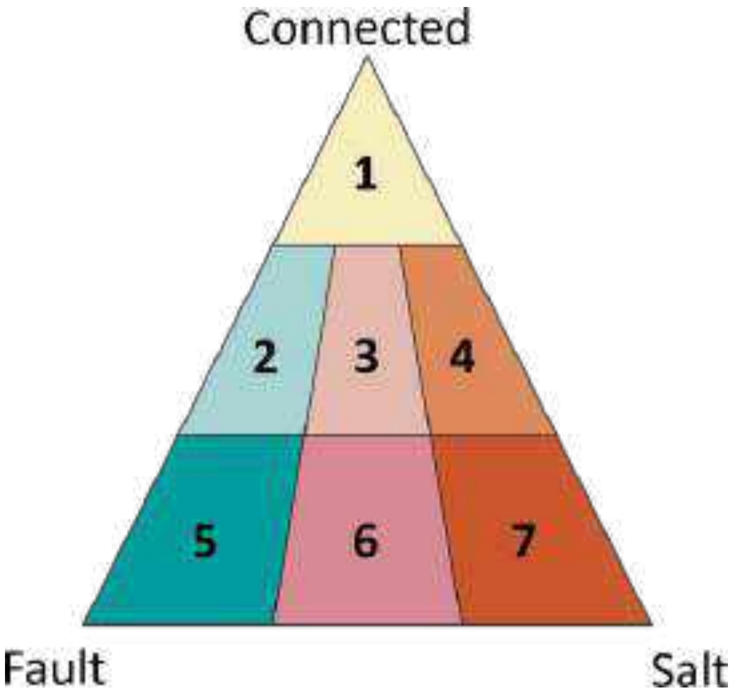
Boundary Classification Scheme

Based on 3 end members:

- Connected: no separation of the Bunter sandstone
- Faulted: complete separation - no juxtaposition
- Salt: complete separation by salt

4 intermediary categories then fall out of this classification:

- 2: faulted with juxtaposition
- 3: juxtaposition despite faulting & salt deformation
- 4: salt deformation with juxtaposition – not seen as faulting usually occurs with salt deformation
- 6: Complete separation by salt and faulting



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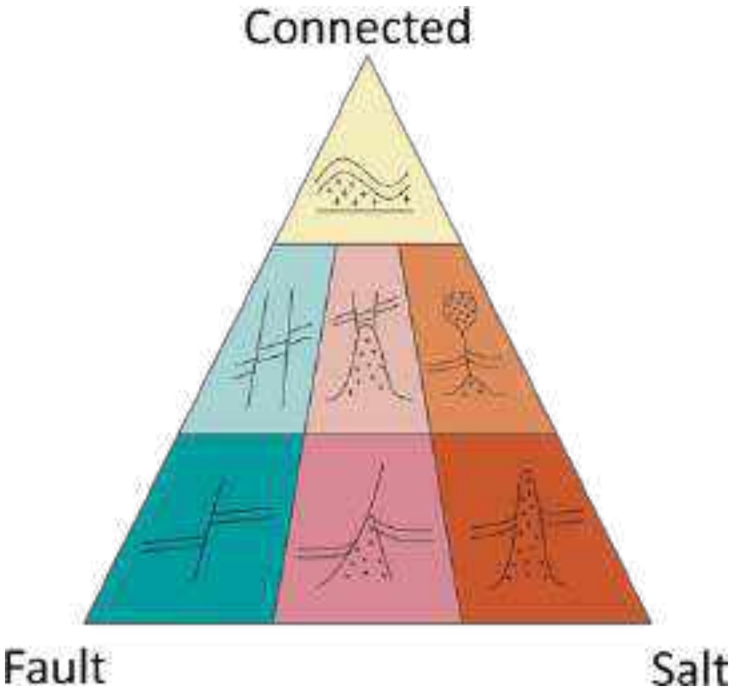
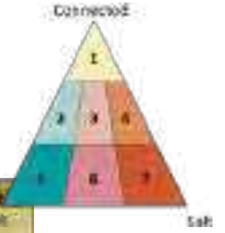
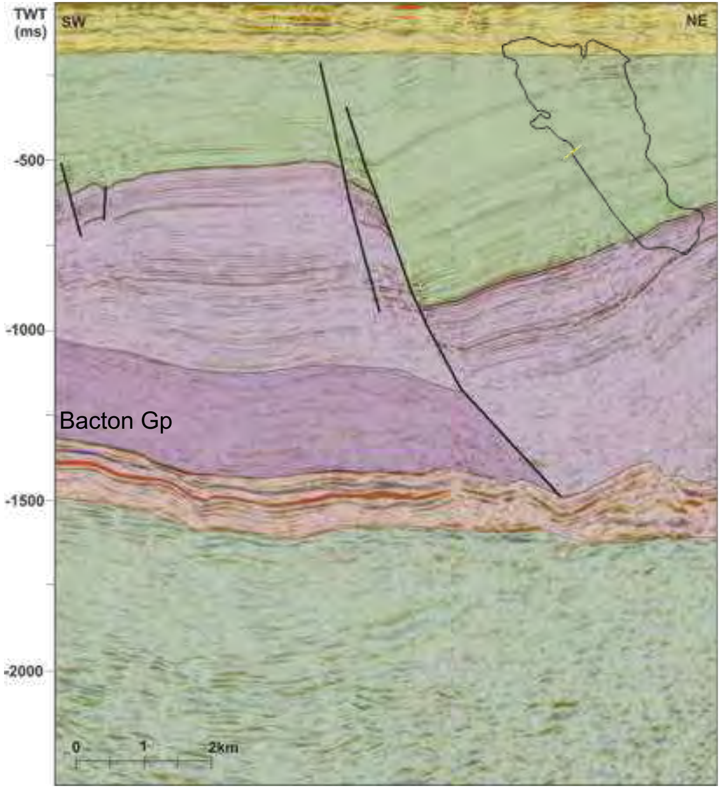
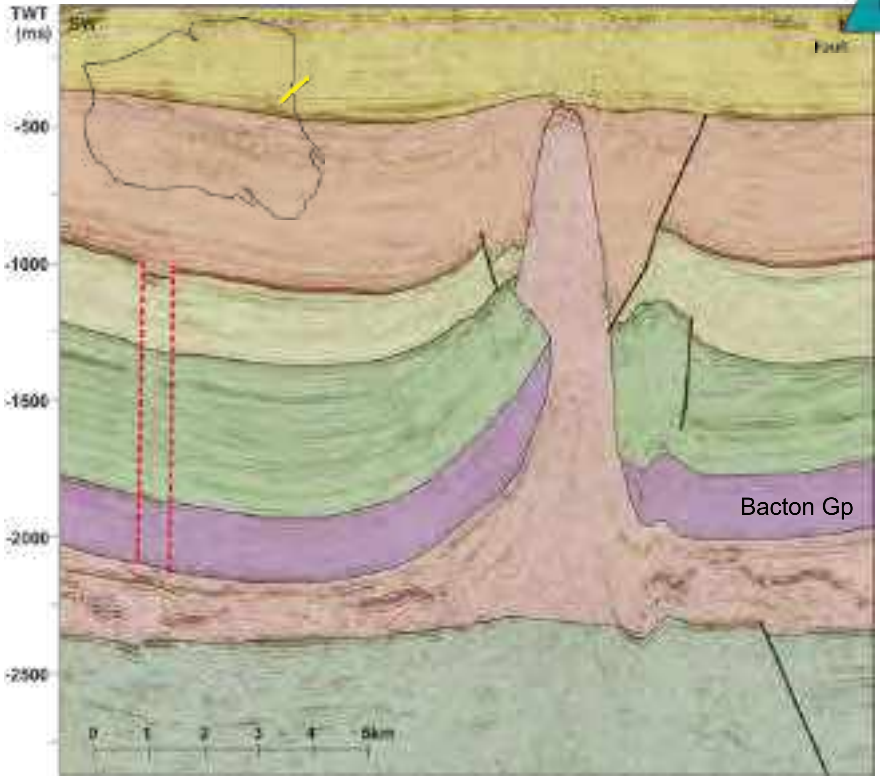


Boundary Classification Scheme



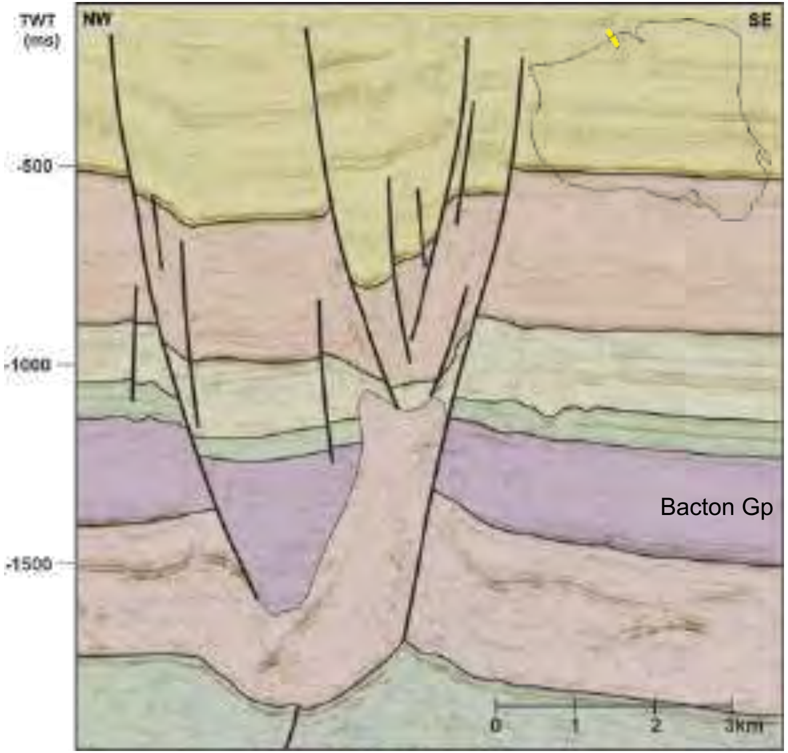


Class 5

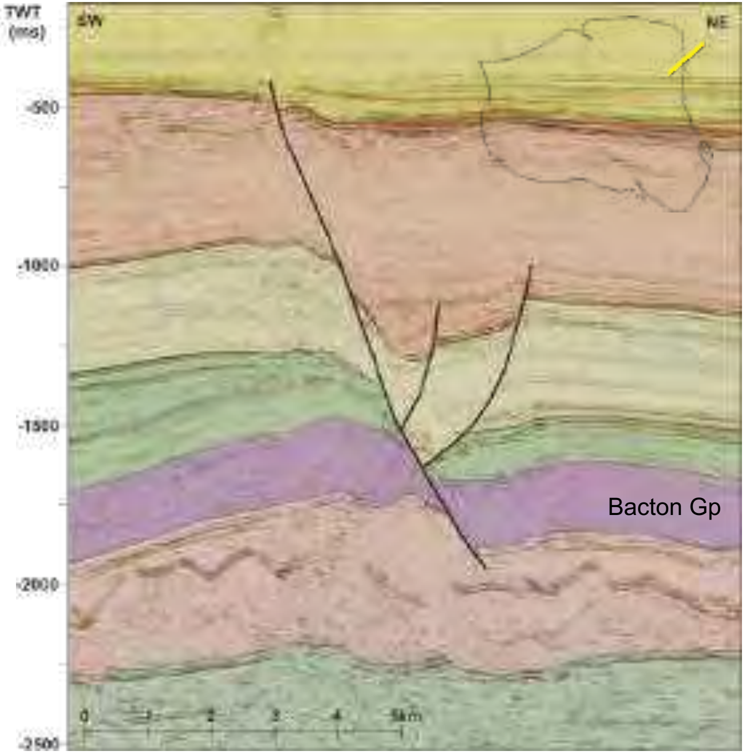


Class 7

Boundary Classification Scheme



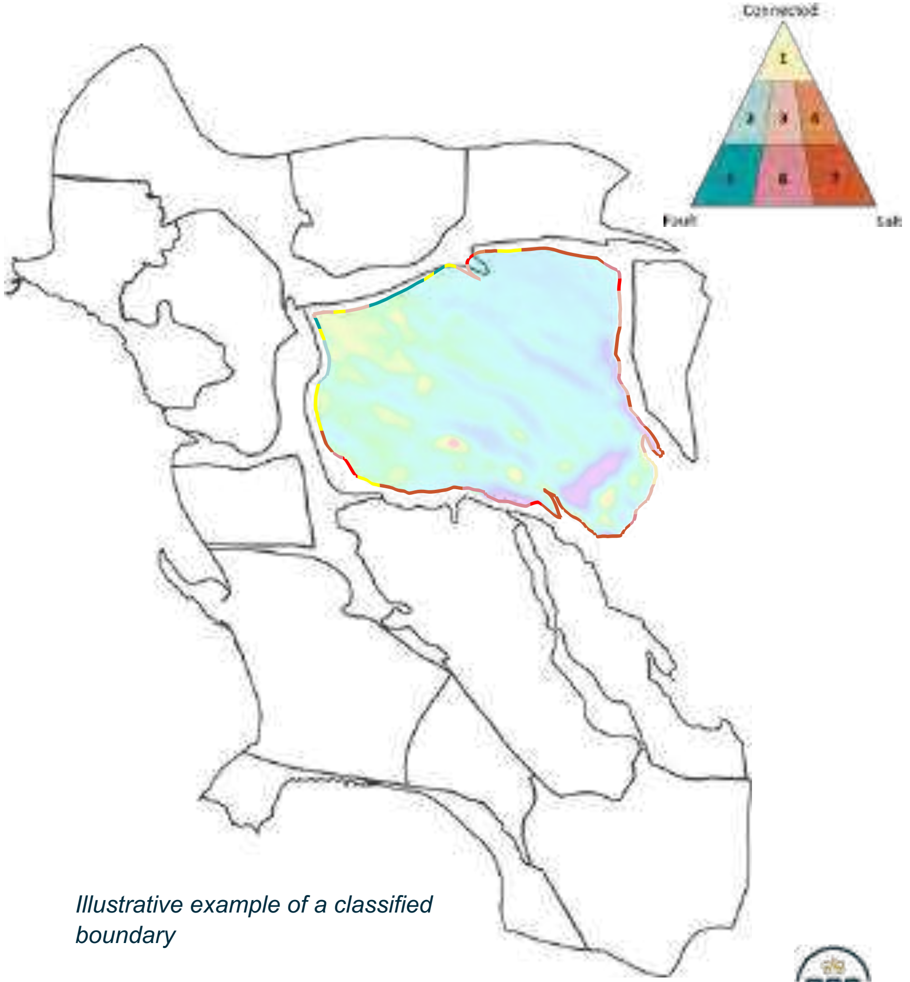
Class 6



Class 2

Mapping the boundaries

- The scheme will then be used to classify each boundary
- It will differentiate areas of complete geometric separation Class 5,6 & 7 from areas with communication
- Areas of uncertainty or complexity will be highlighted for potential future work
- The results will be used to constrain the boundary conditions further than the current binary conditions i.e. open or closed



Illustrative example of a classified boundary

British Geological Survey

THANK YOU

JOHN WILLIAMS & GARETH WILLIAMS

Impact of large-scale CO_2 injection

British Geological Survey

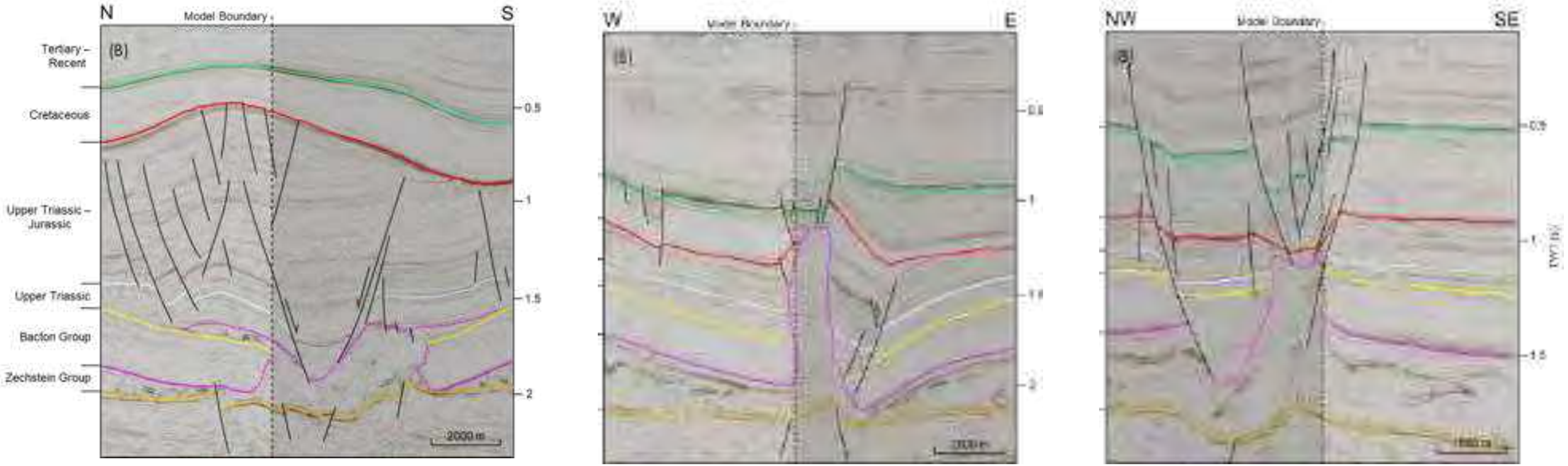
Introduction

- Numerous closures of interest contained within potentially hydraulically-connected aquifer volumes
- Previous studies show that pressure interaction will likely occur between sites
- Several licenced sites, including Endurance are located in the Silverpit Basin
- *How will the system behave if large-scale injection is initiated at multiple sites?*
- *A seabed outcrop will likely act to alleviate pressure increase by enabling brine to escape the system*

Approximate location of seabed outcrop

Boundary conditions

- No large-scale barriers to flow anticipated within the region
- Good lateral communication assumed within the region, but closed boundary conditions

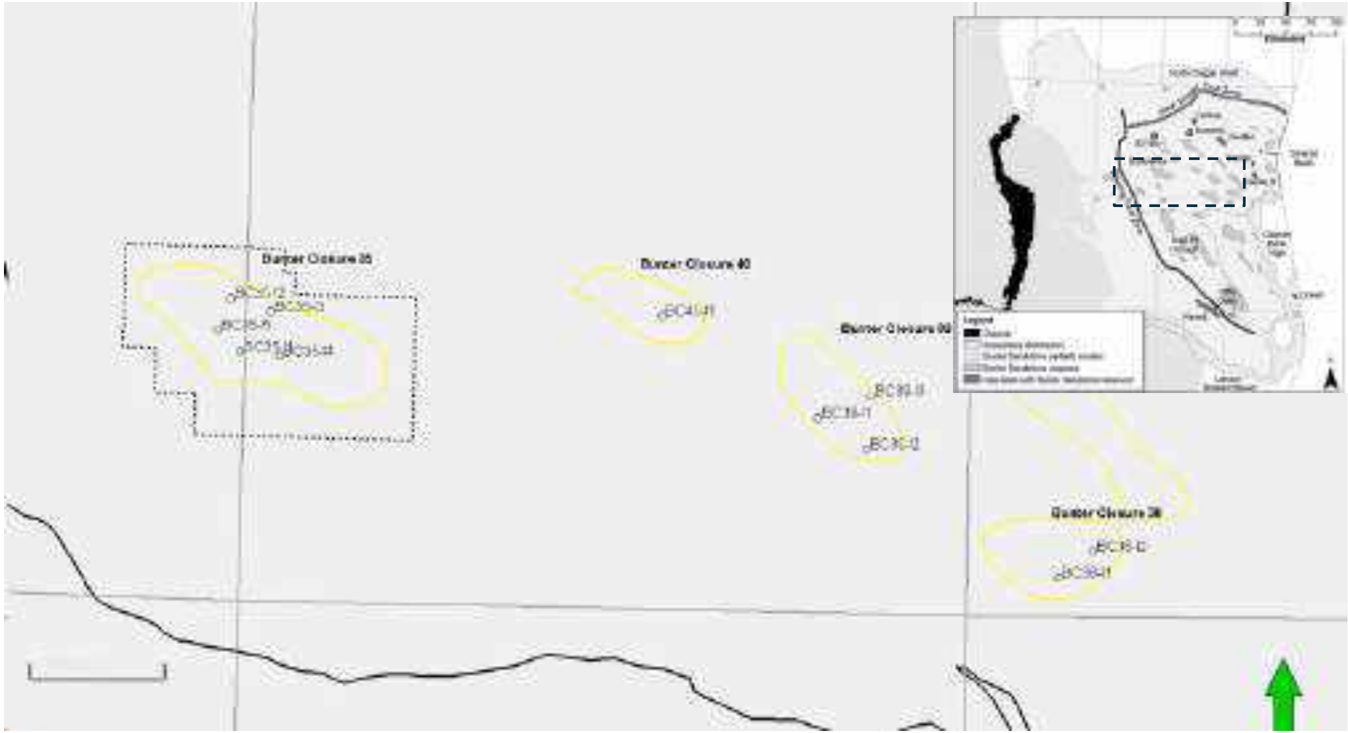


From Bridger et al. (2021) Presented at the 82nd EAGE Annual Conference & Exhibition.

Large-scale storage scenario

- Credible injection scenario based on the NEP path to 10 Mtpa (Phase 2)
- Total injected target mass of 232 Mt (c. 1.24E+11 SM^3)
- Initiating injection at Endurance in 2026 (4 Mtpa), and addition of Bunter Closures BC40 (1 Mtpa), BC39 (3 Mtpa) and BC36 (2 Mtpa) from 2029
- Target injection rate of 1 Mtpa per well, with wells placed under group control for each individual closure
- Bottom-hole pressure limit set at 75% of lithostatic pressure gradient (c. 220 bar)
- End of injection 01 Jan 2051

Injection scenario map



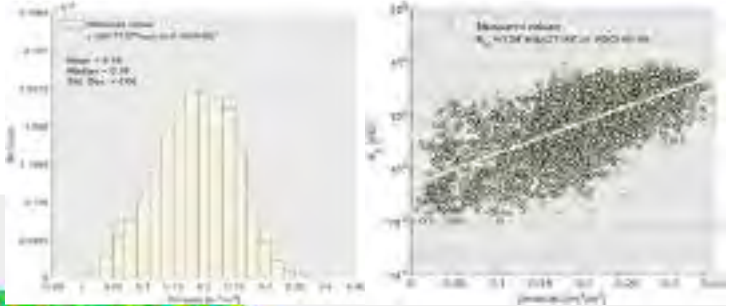
Base-case geological model

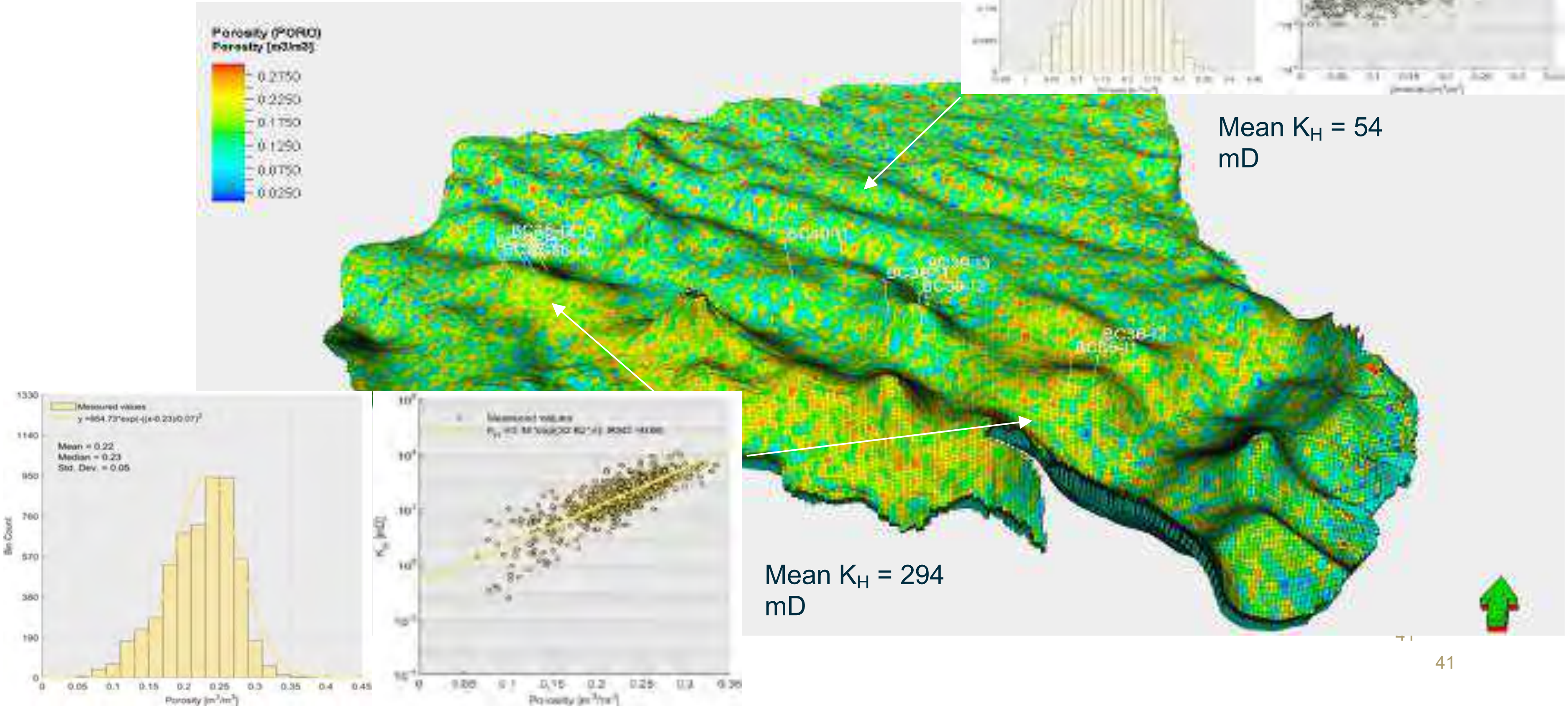
- Regional model based on seismic and well data (400 x 400 m mesh)

Model layer	Formation	Porosity (m^3/m^3)	KH (mD)	K_V/K_H	Corey relative permeability model
Caprock	Solling Claystone	0.1[3]	0.005[3]	0.1	Calmar Shale[1] (NW=2.47; NG=1.3; KRG_{MAX}=0.186)
Reservoir	Bunter Sandstone	Variable; Gaussian random function simulation	Porosity-K_H linear transform	0.1	B.P. base-case[2] (NW=4; NG=2.5; KRG_{MAX}=0.7)
Under-burden	Bunter Shale	0.1[3]	0.005[3]	0.1	Calmar Shale[1]

[1]Bennion & Bachu (2007); [2]NS051-SS-REP-000-00015 (2021); [3]Based on measurements for Solling Claystone (Spain and Conrad, 1997) and Mercia Mudstone samples (Armitage et al., 2016)

Reservoir property distribution





Mean K_H = 54 mD

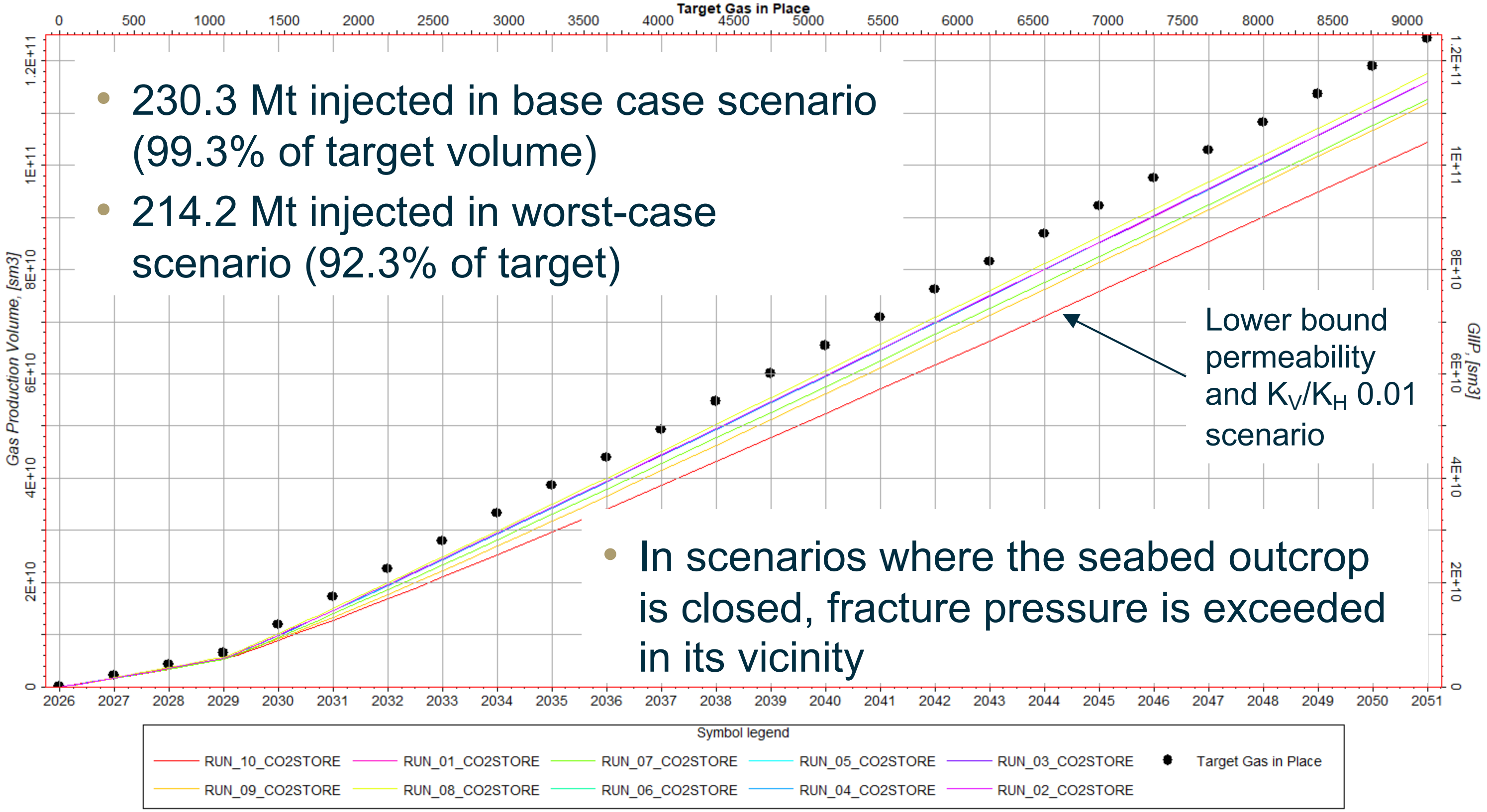
Mean K_H = 294 mD

Simulation scenarios

Simulation Run	Description
01	Base Case
02	Test effect of using MULTPV instead of analytical aquifer for seabed outcrop
03	Test effect of using numerical aquifer instead of analytical aquifer for seabed outcrop
04	Test effect of shutting the seabed outcrop
05	Test effect of impermeable top & base boundary conditions
06	Test effect of impermeable top & base boundary conditions & shutting the seabed outcrop
07	Test effect of reducing K_V/K_H to 0.01 (0.04 DST) - Base Case is 0.1
08	Test effect of increasing K_V/K_H to 0.36 (maximum from VIT and core plug data) - Base Case is 0.1
09	KH = 0.65 * KH Base Case (to match lower bound permeability from Esmond pressure recovery model); K_V/K_H 0.1
10	KH = 0.65 * KH Base Case (to match lower bound permeability from Esmond pressure recovery model); K_V/K_H 0.01

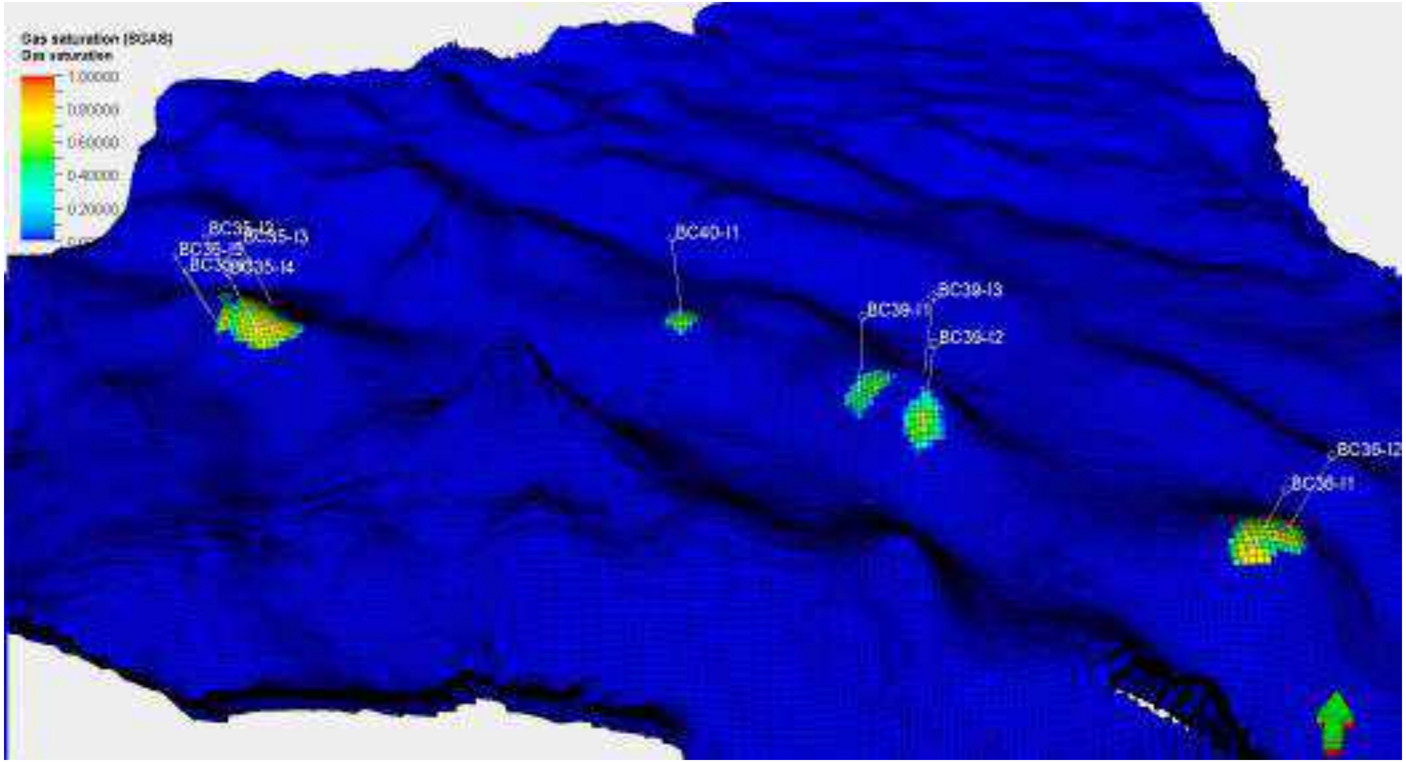
Cumulative injected volumes

- 230.3 Mt injected in base case scenario (99.3% of target volume)
- 214.2 Mt injected in worst-case scenario (92.3% of target)



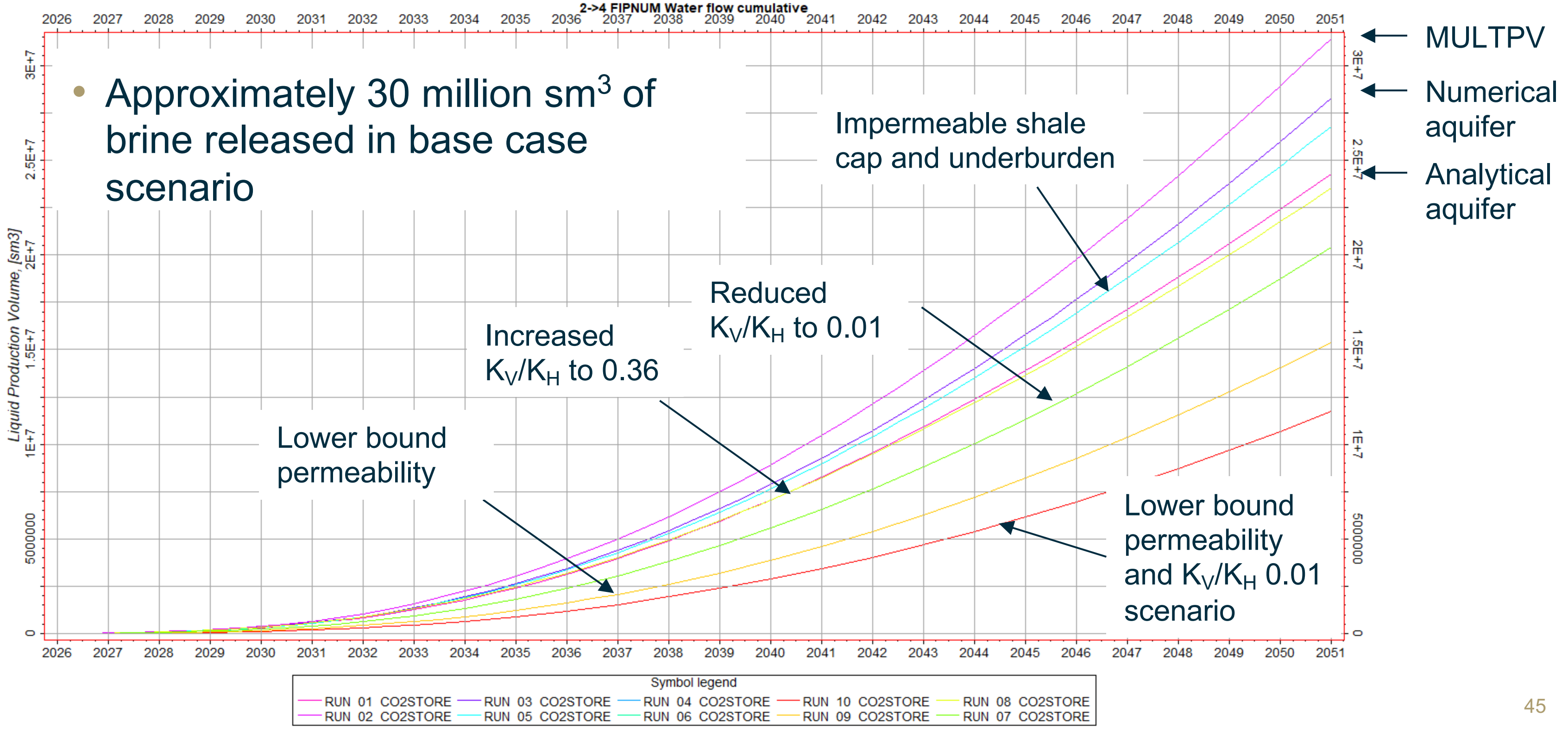
- In scenarios where the seabed outcrop is closed, fracture pressure is exceeded in its vicinity

Simulated CO_2 plume distribution



Brine discharge through outcrop

- Approximately 30 million sm^3 of brine released in base case scenario



Conclusions

- Under model assumptions the Bunter Sandstone is capable of storing a significant volume of CO_2 across multiple stores
- The seabed outcrop enables large-volumes of brine to exit the system, alleviating the resulting pressure increase
- If the seabed outcrop is closed, brine production will be required to meet the storage capacity requirements
- Brine production wells would be required to manage pressure at individual sites if higher injection rates required
- Increased pressure will be experienced across the connected aquifer volume and pressure will interact between sites (not an issue in the scenario considered here, but may impact on future developments)

THANK YOU

Any questions?

Imperial College London

The Impact of Capillary Heterogeneity on CO_2 Plume Migration at the Endurance CCS Target Site in the UK – a Core to Field Scale Study

Nele Wenck[1], Samuel Jackson[1,2], Ann Muggeridge[1], Senyou An[1], Julian Barnett[3], and Samuel Krevor[1]

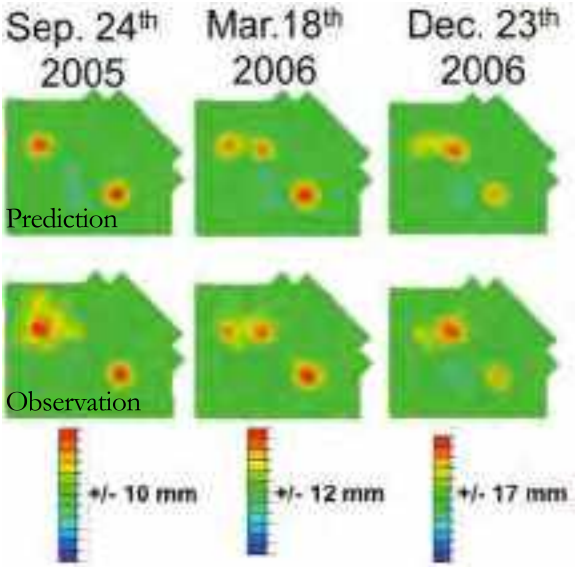
[1]Department of Earth Science and Engineering, Imperial College London, United Kingdom

[2]CSIRO Energy, Private Bag 10, Clayton South, Victoria 3169, Australia

[3]National Grid, 35 Homer Road, Solihull, West Midlands, B91 3QJ, UK

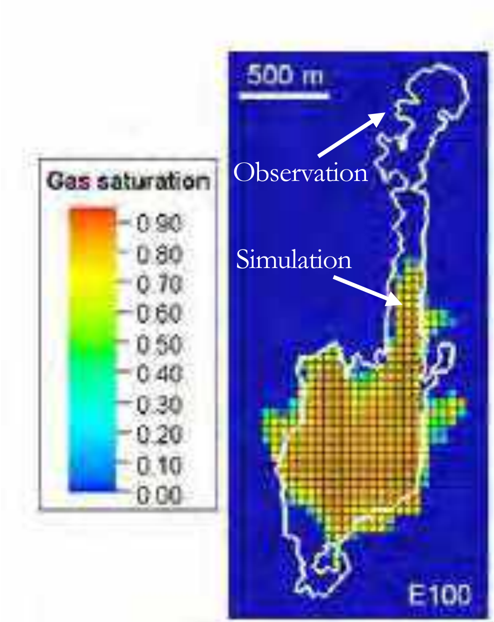
Reservoir Simulations Don't Match Field Observations

In Salah, Algeria



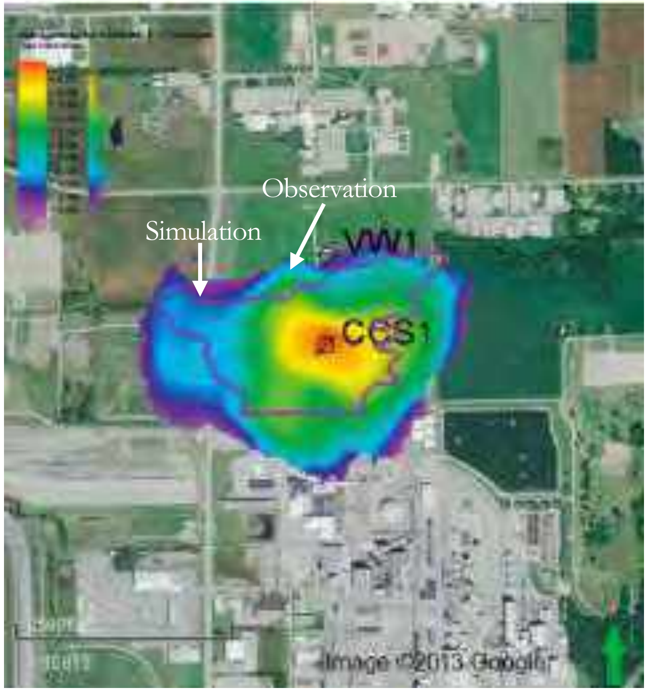
Deflandre (2013)

Sleipner, Norway



Williams et al (2018)

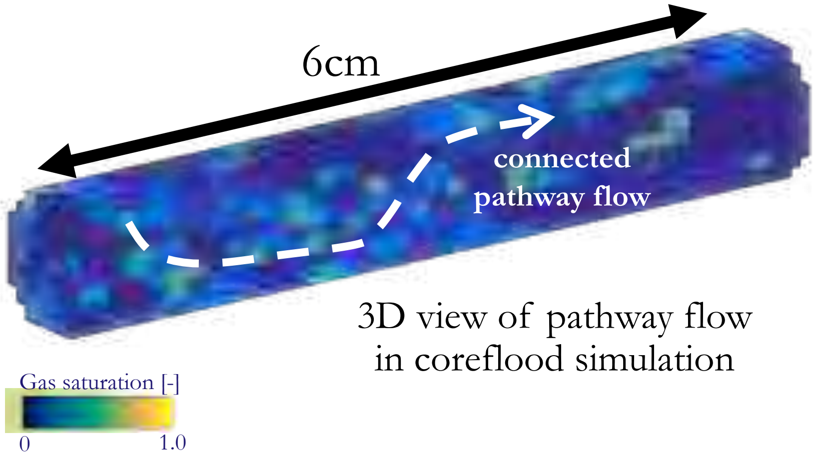
Decatur, USA



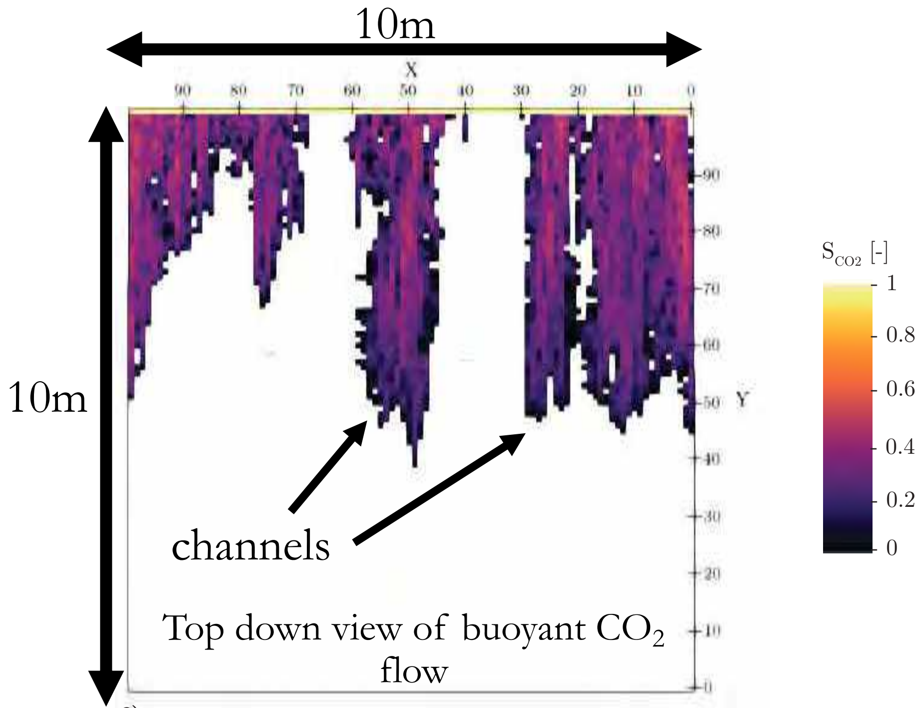
Bauer et al (2019)

Conventional Reservoir Models Omit the Upscaled Impact Of Capillary Heterogeneity

- Causes saturation discontinuities and forms flow patterns e.g. connected pathway flow, channels
- **Leads to relative permeability variations –need to be accounted for field scale simulations**



3D view of pathway flow in coreflood simulation

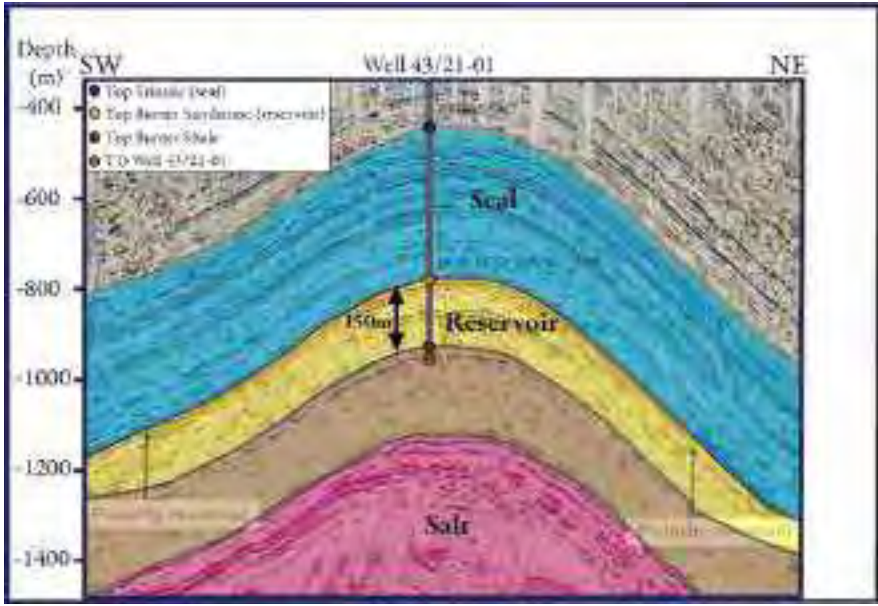


Top down view of buoyant CO_2 flow

Quantify the Impact of P_c Heterogeneity on CO_2 Flow at Proposed CCS Site

- Net Zero Teesside project: BP, Eni, Equinor, Shell and Total
- UK Storage Site With >1000 Mt CO_2 Storage Potential
- Four-way dip closure, saline aquifer (Bunter sandstone), 150-250m thick

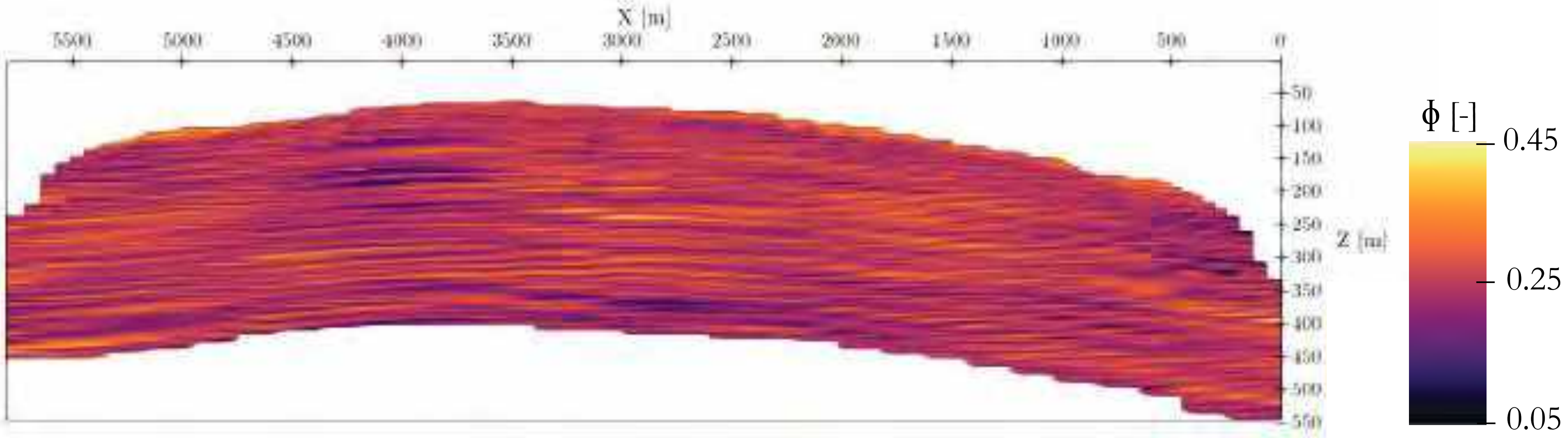
Adapted from: White Rose (2016)



Adapted from: White Rose (2016)

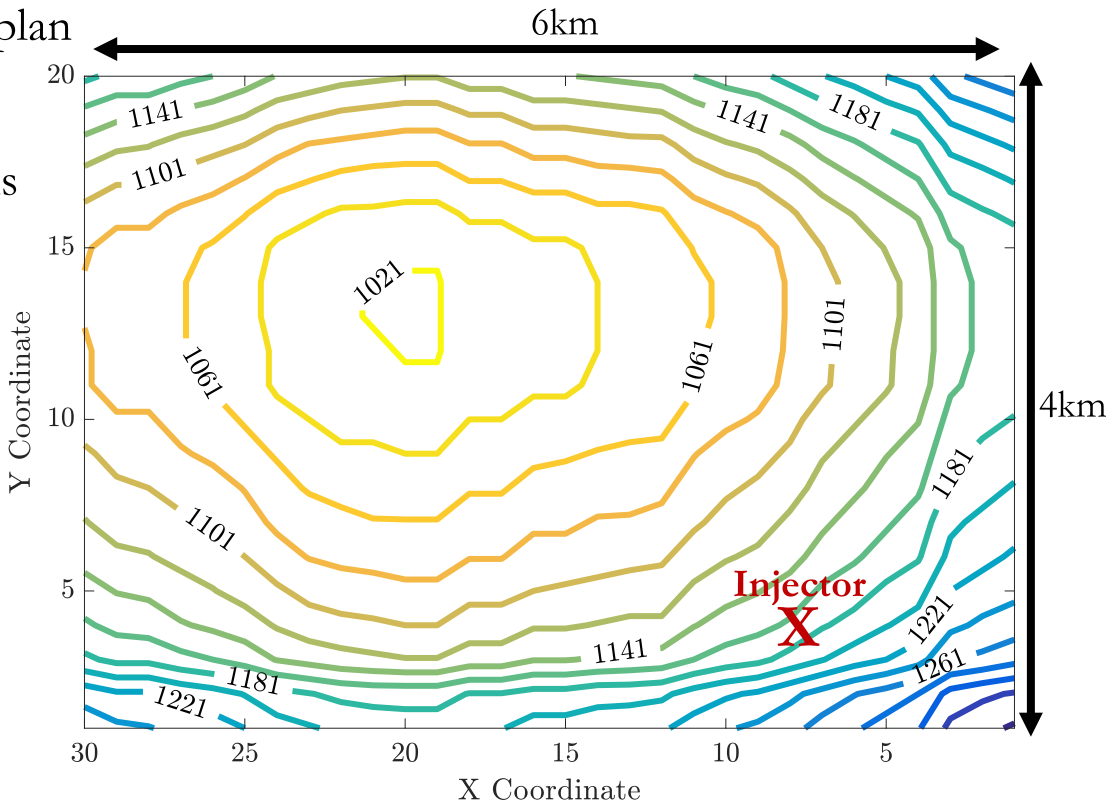
Workflow to Upscale the Impact of P_c Heterogeneity in 3D

- Well log measurements, core flood data and geological constraints to build a field-scale model
- Capillary-limit upscaling scheme using MIP (Wolff et al., 2013; Jackson & Krevor, 2020)
- Domain Size (x,y,z): 6000m, 4000m, 250m
- **Correlation Lengths (x,y,z): 1000m, 760m, 4m** (from geological studies)



Quantifying the Impact of Disregarding P_c Heterogeneity in Reservoir Models

- 'CI2' injector from field development plan
- Q = 3130 m^3/day for 25yr
- Constant pressure boundary conditions



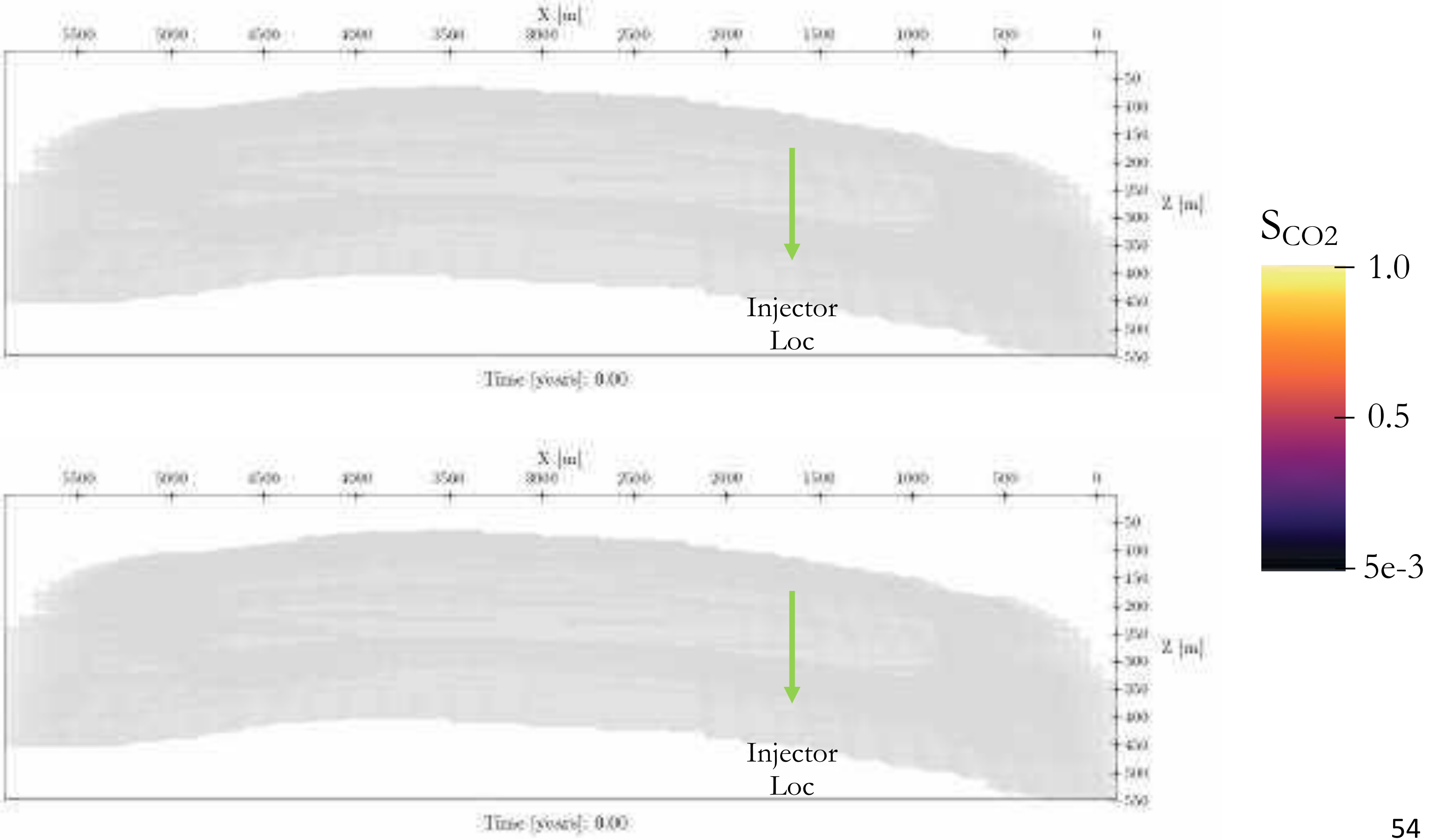
<u>Two Scenarios:</u>

1. **Accounting for P_c heterogeneity:**
   - Upscaled, heterogeneous ϕ and K
   - Upscaled, heterogeneous k_r
   - Upscaled, heterogeneous P_c
2. **Disregarding P_c heterogeneity:**
   - Upscaled, heterogeneous ϕ and K
   - Homogenous k_r
   - $P_c = 0$

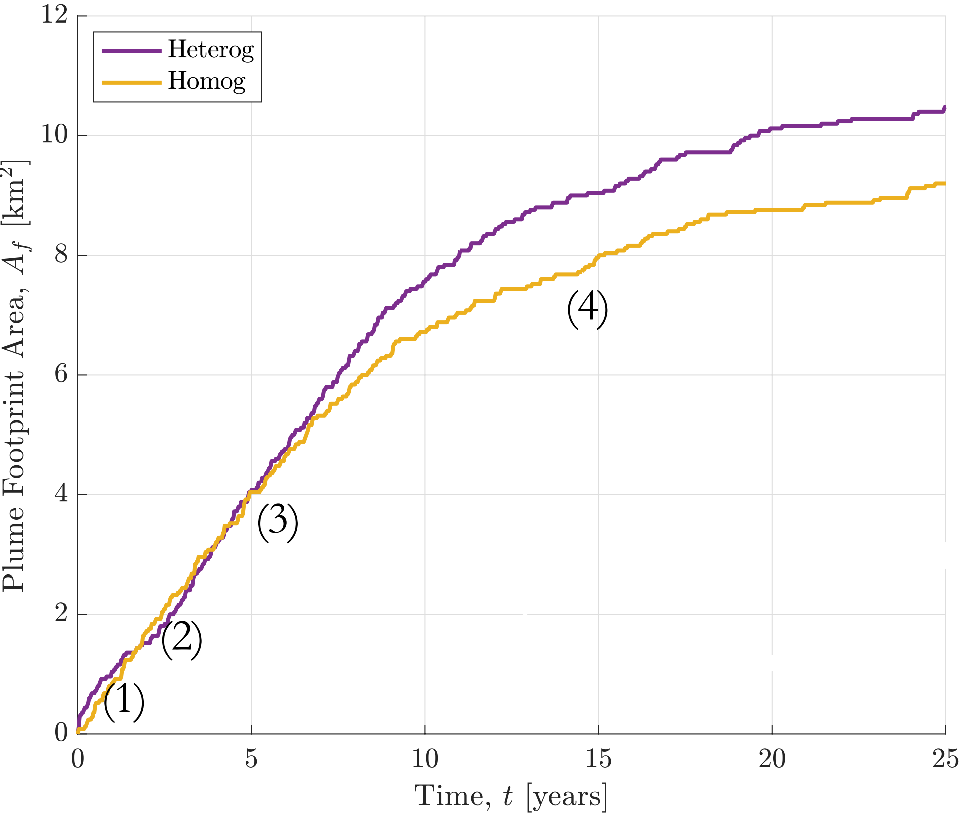
CO_2 Flow Patterns Vary Significantly in Two Models

Homogeneous

Heterogeneous

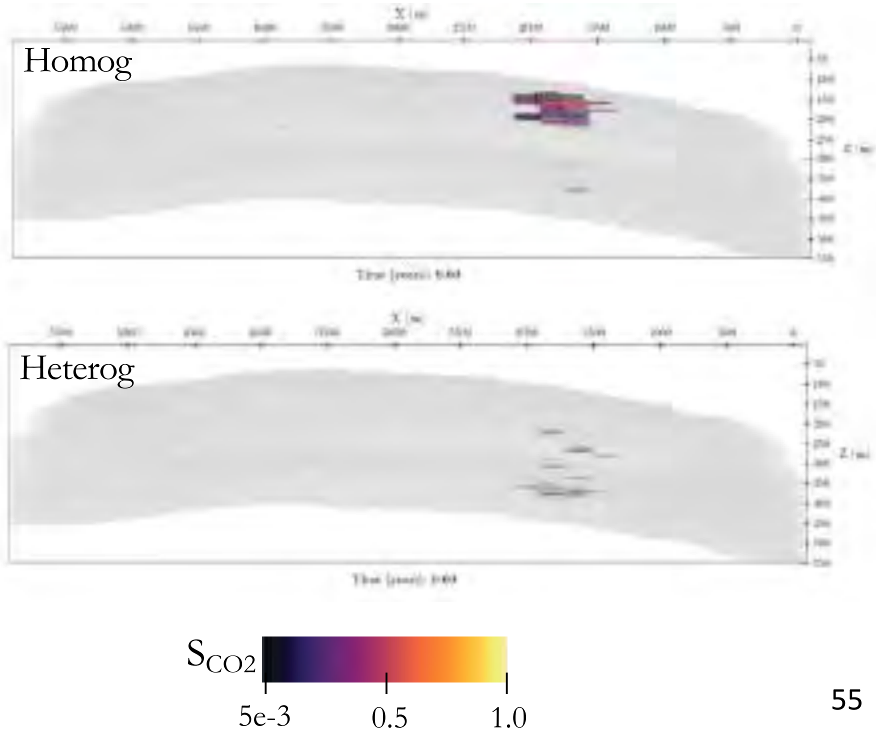


Capillary Heterogeneity Leads to Increased Sweep and Plume Spreading near Injection Point

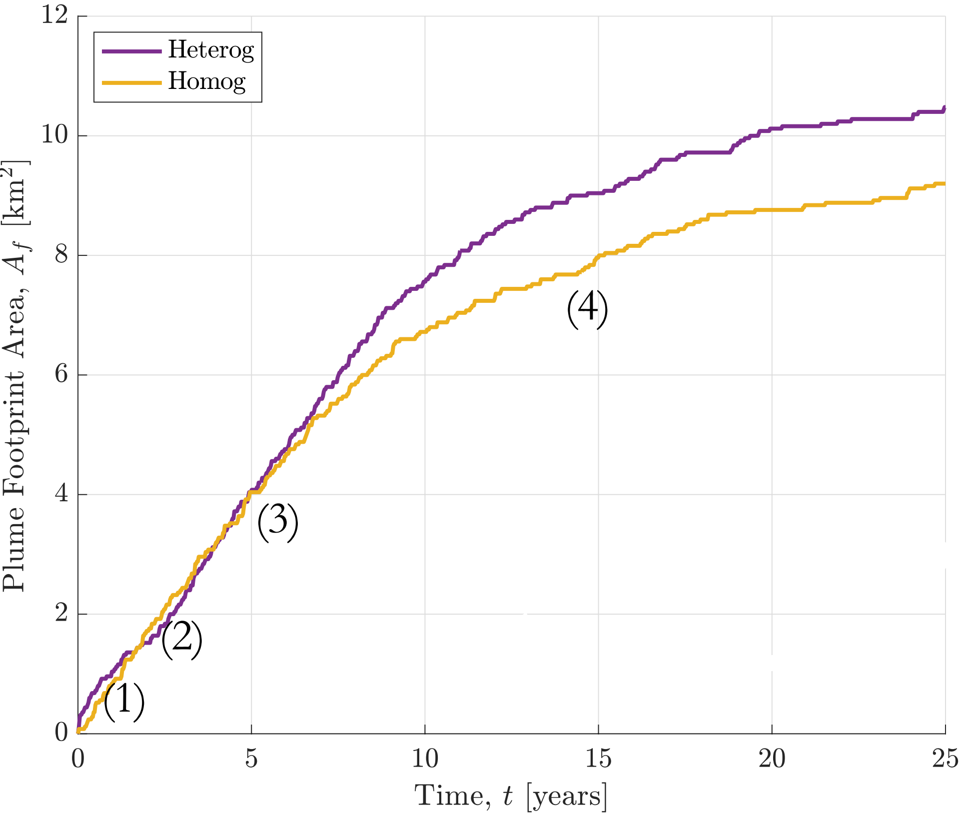


Footprint Area = The area of CO_2 plume when projected onto horizontal plane

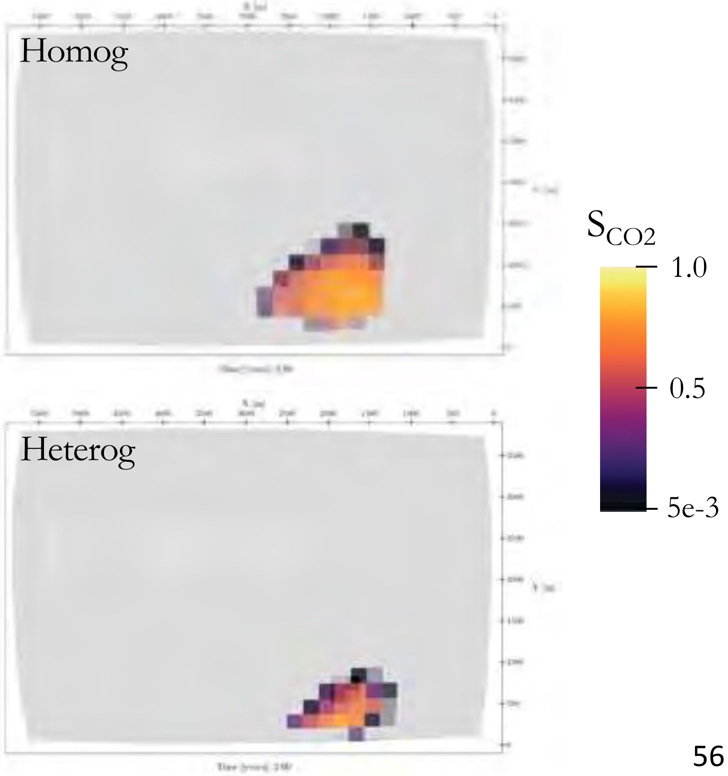
1. Near the wellbore, vertical heterogeneity acts as barriers to CO_2 and CO_2 spreads laterally



Capillary Heterogeneity Leads to Increased Sweep and Plume Spreading near Injection Point

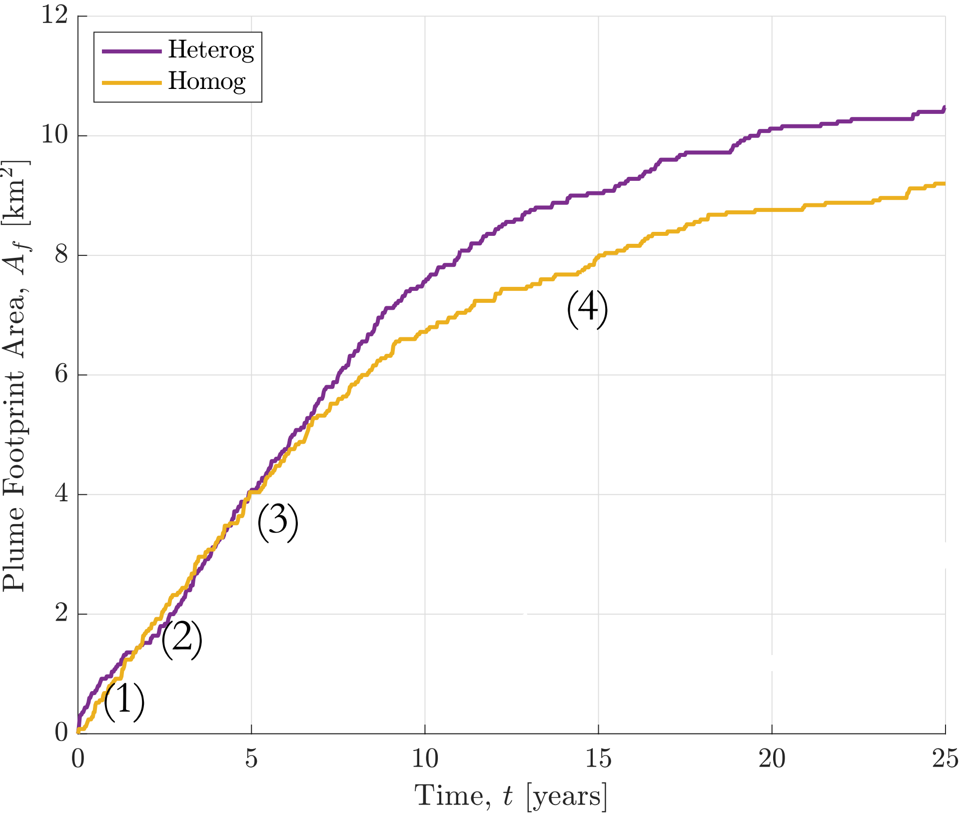


2. CO_2 rises more slowly due to heterogeneity and spreads laterally after hitting caprock

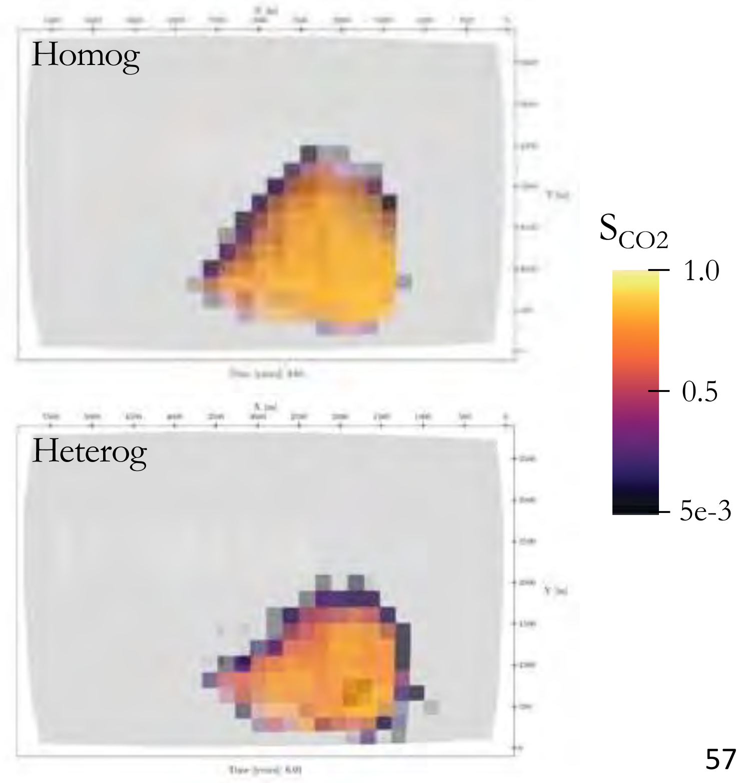


Footprint Area = The area of CO_2 plume when projected onto horizontal plane

Capillary Heterogeneity Leads to Increased Rates of Lateral Migration through Thin Channelling

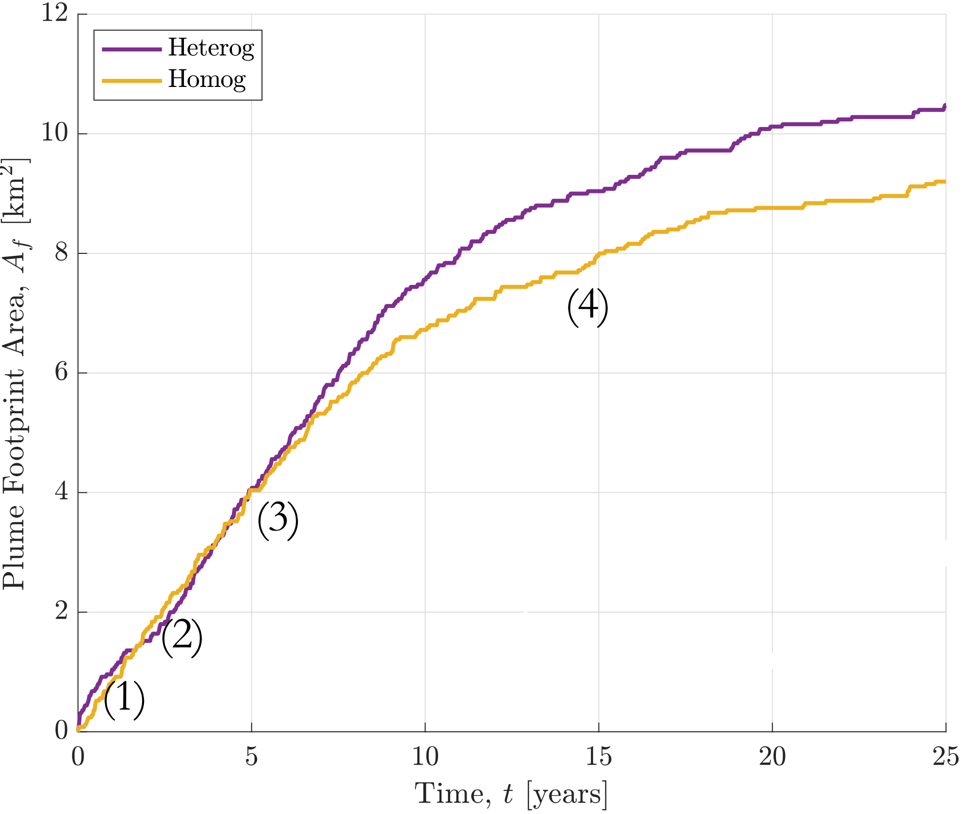


3. Footprint areas converge as all cases now exhibit lateral spreading

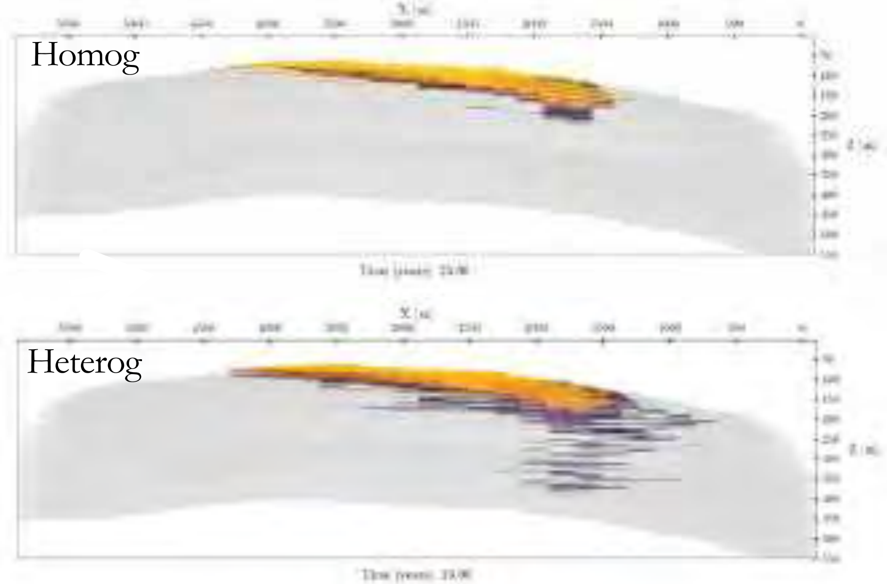


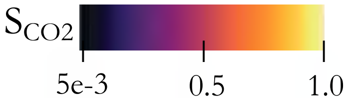
Footprint Area = The area of CO_2 plume when projected onto horizontal plane

Capillary Heterogeneity Leads to Increased Rates of Lateral Migration through Thin Channelling



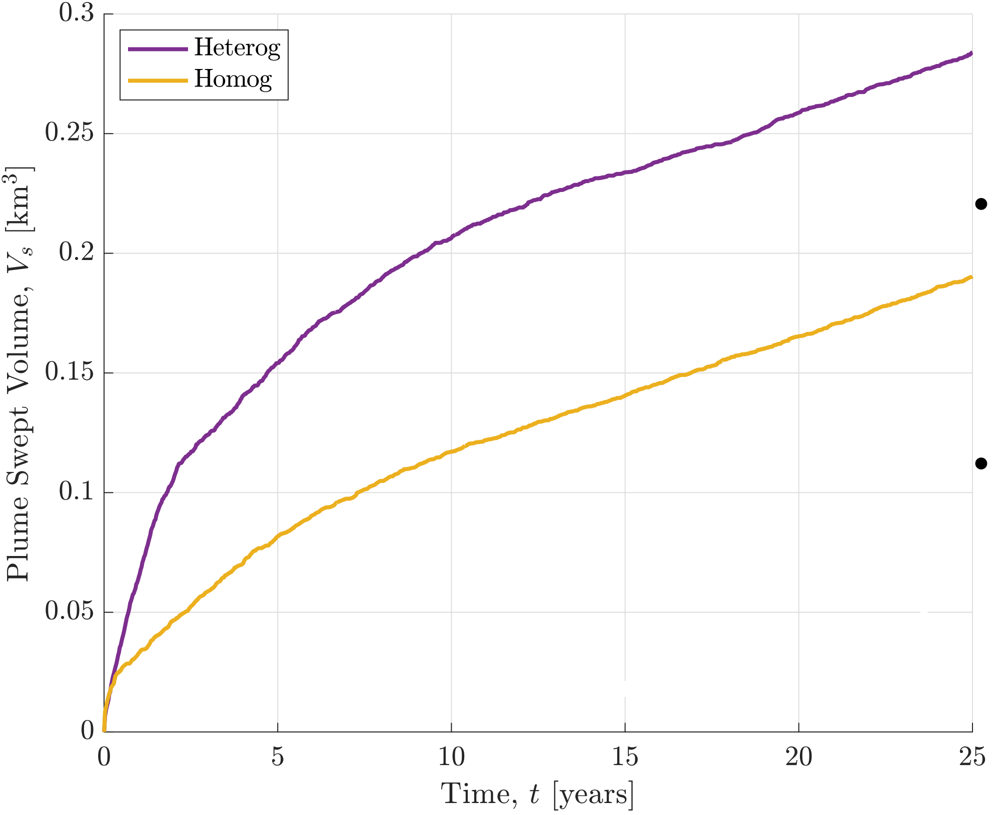
4. CO_2 channels develop and grow with time, increasing the footprint area. CO_2 migrates laterally significantly faster in heterogeneous case





Footprint Area = The area of CO_2 plume when projected onto horizontal plane

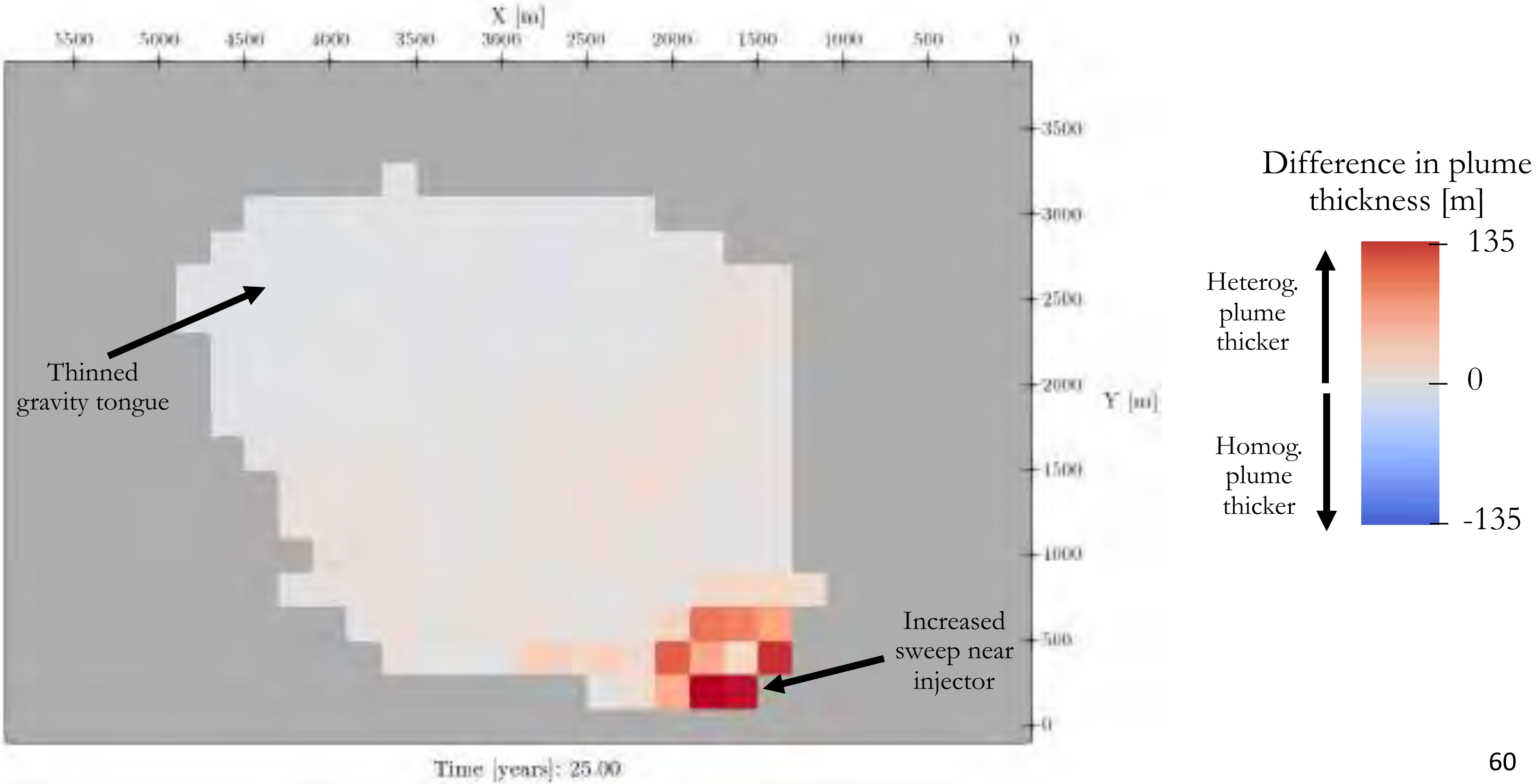
Capillary Heterogeneity Improves Sweep Efficiency through Thin Channelling



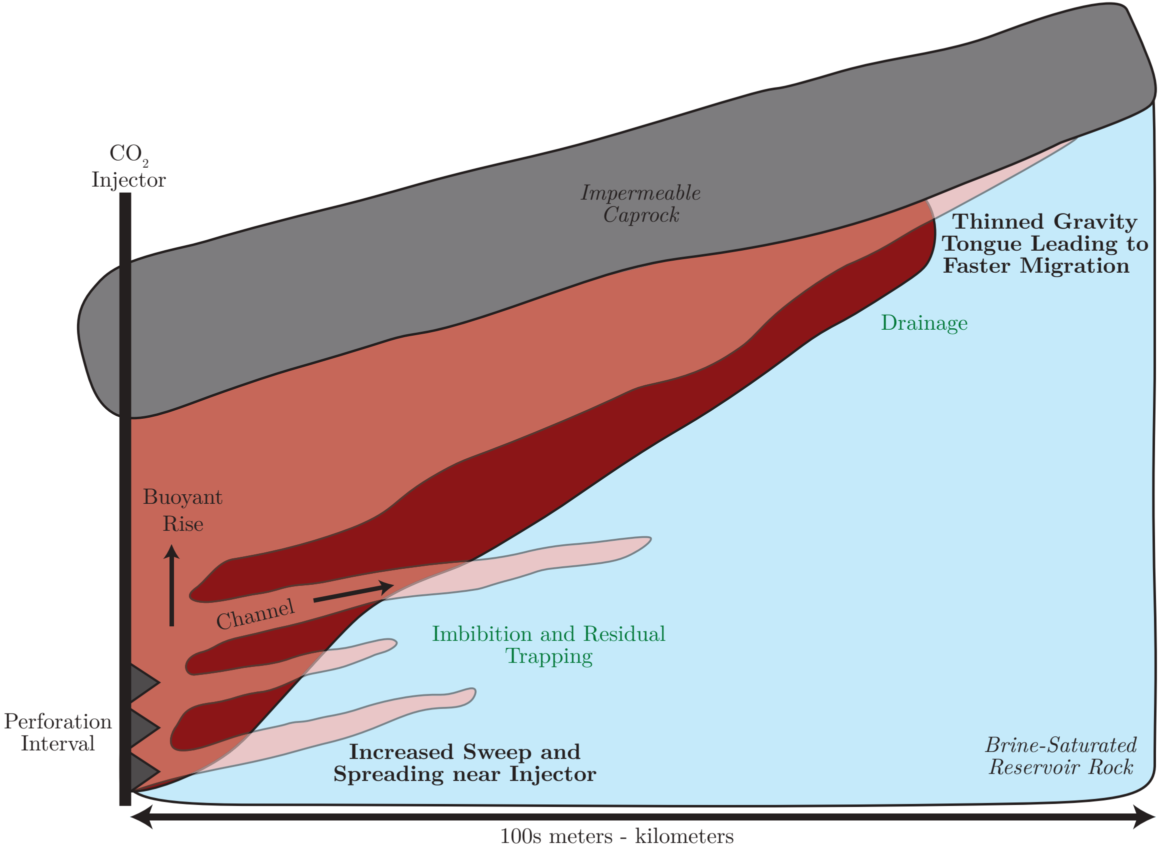
- Capillary heterogeneity results in a significant increase in the plume swept volume due to channel formation
- Relative permeability anisotropy is the leading control on the flow behaviour

Plume Swept Volume = Volume of grid blocks invaded by CO_2

Capillary Heterogeneity Improves Sweep Efficiency through Thin Channelling



Capillary Heterogeneity Has Crucial Implications For CCS Operations



1. Design injection to maximise spreading and trapping near the injector

2. Include potential for faster anisotropic plume migration in uncertainty estimates

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Thank you for your attention!

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Thank you