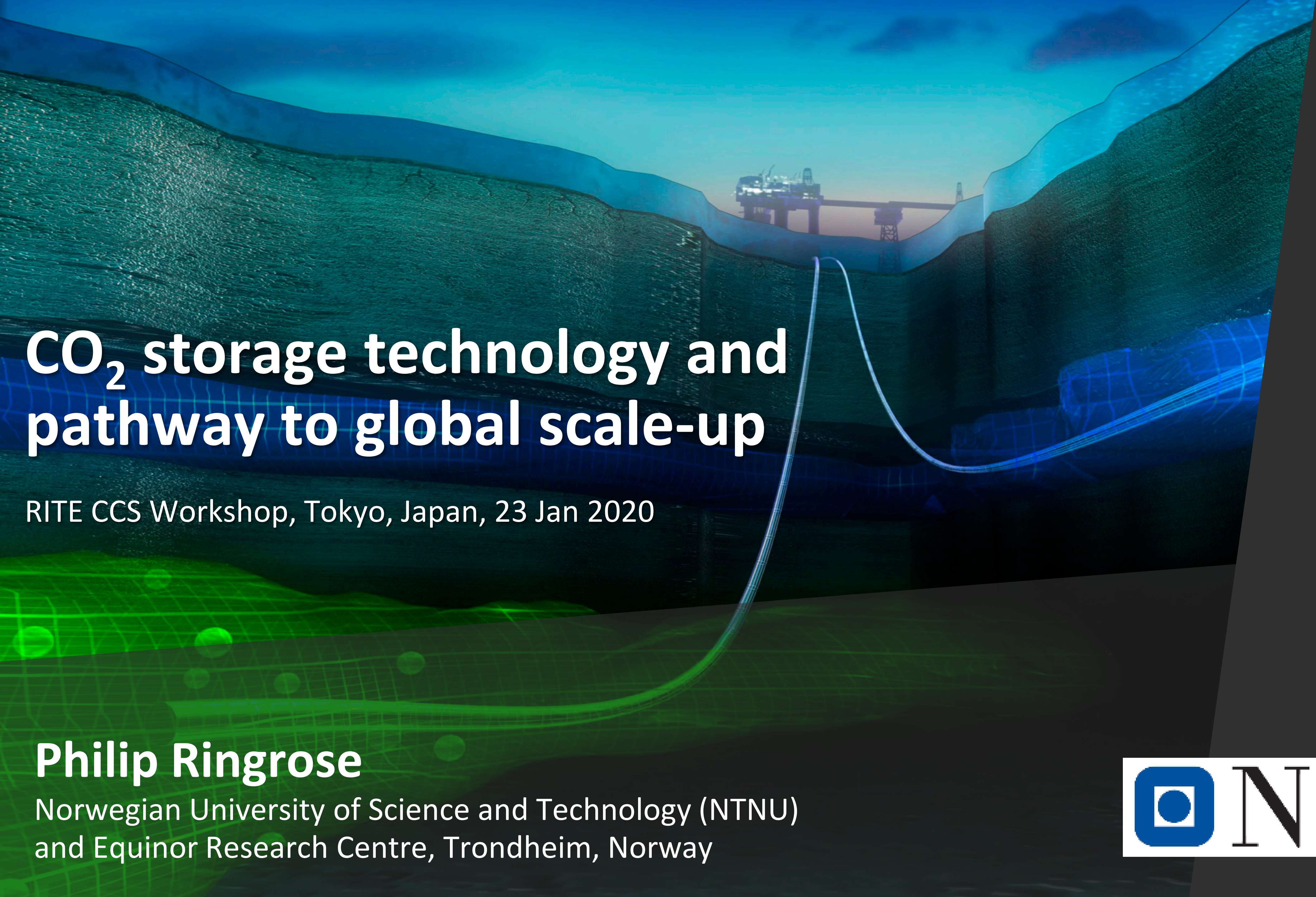


CO_2 storage technology and pathway to global scale-up

RITE CCS Workshop, Tokyo, Japan, 23 Jan 2020

Philip Ringrose
Norwegian University of Science and Technology (NTNU)
and Equinor Research Centre, Trondheim, Norway

equinor

NTNU

CO_2 Storage technology

Keeping greenhouse gases safely underground

Can the world really go ‘low Carbon’ and deliver on the Paris agreement?

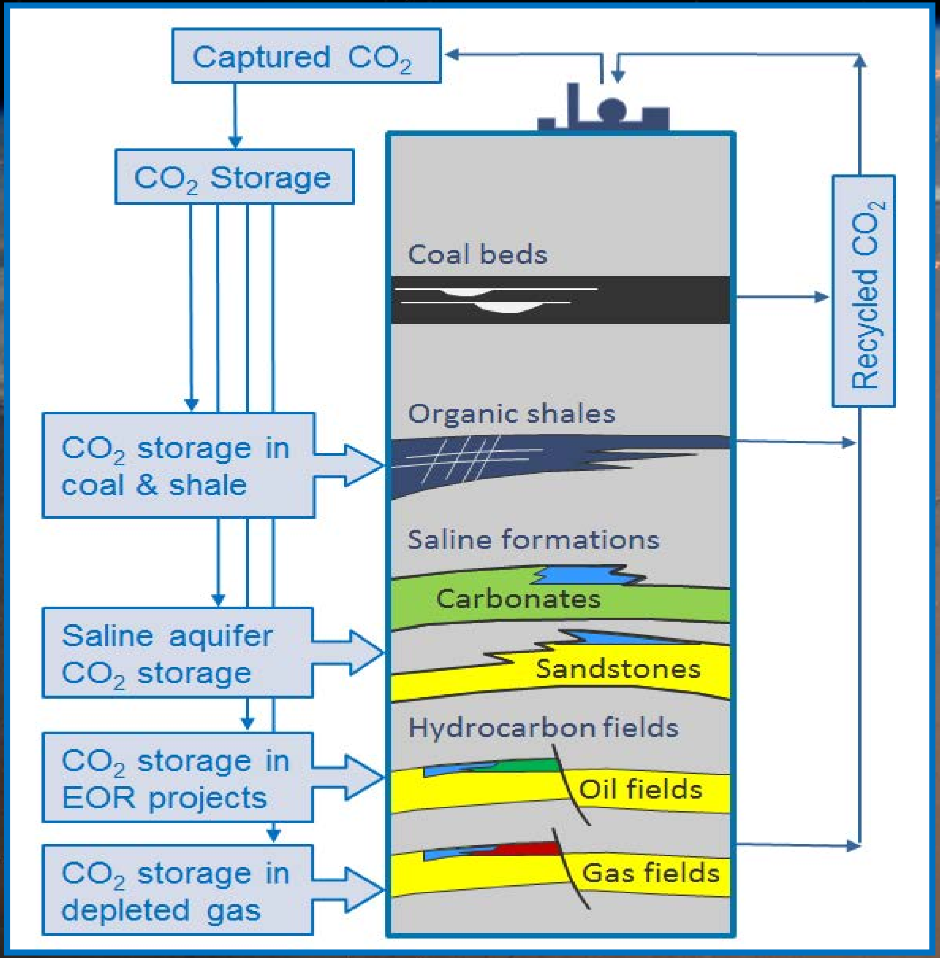
Talk Outline:

- The emerging CCS hub in Norway
- Insights into saline aquifer CO_2 storage
- Pathway to global scale up
- Summary

Night time Sahara –Tim Peake 21may2016 - Copyright ESA & NASA

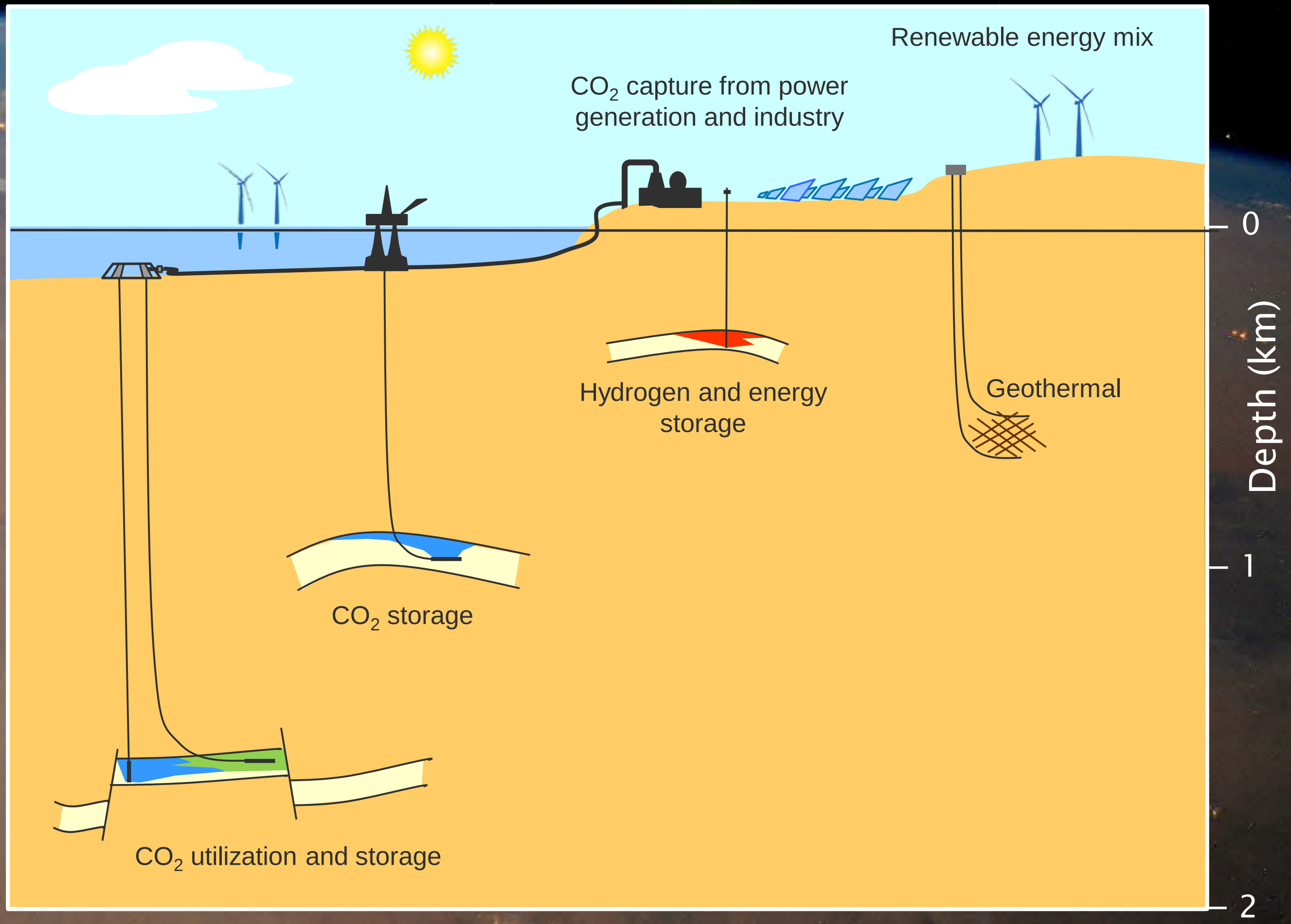
The low Carbon energy mix

CCS – essential and unattractive(?)



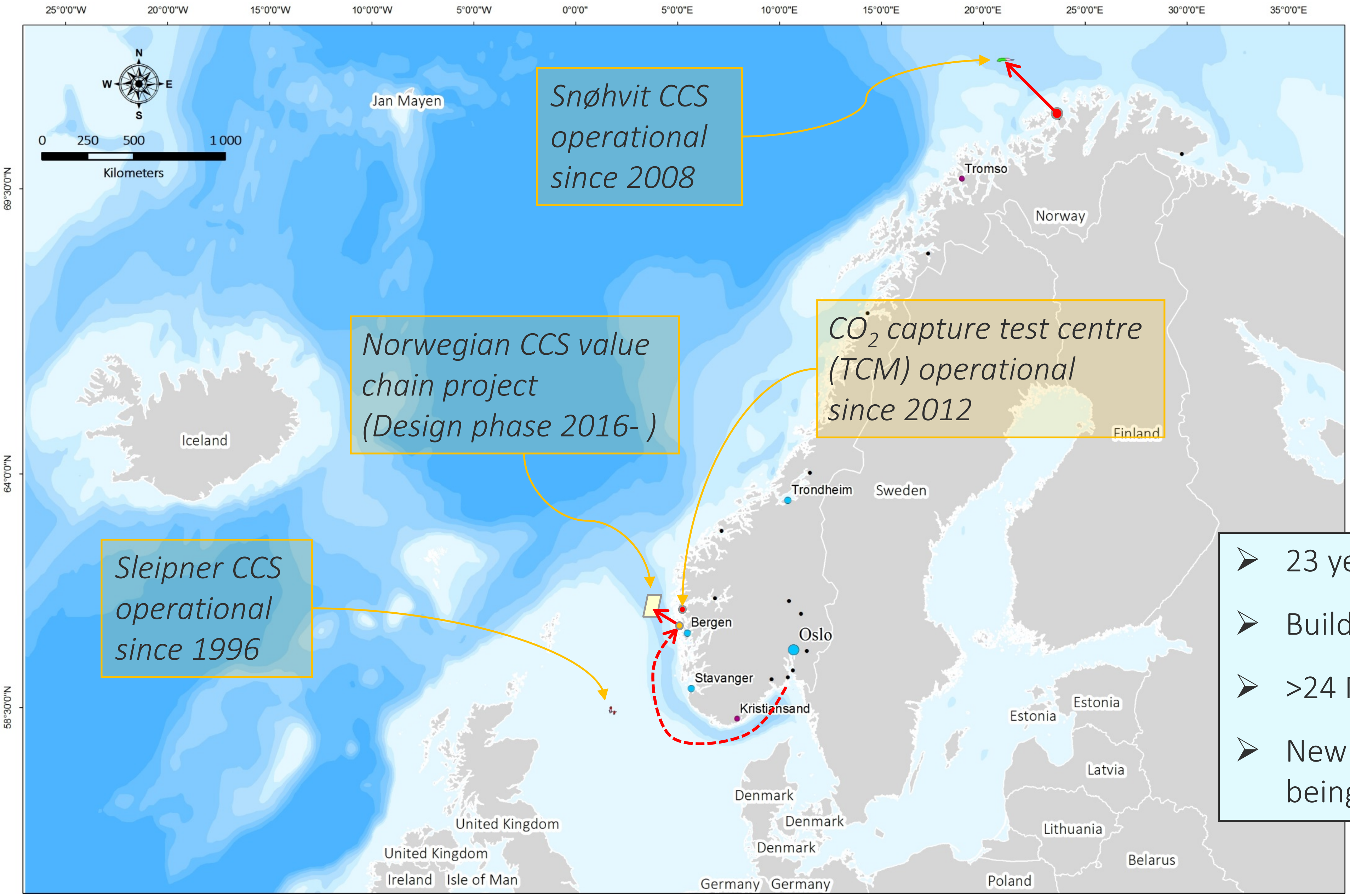
Cavanagh & Ringrose 2014

Renewable energy – attractive and essential



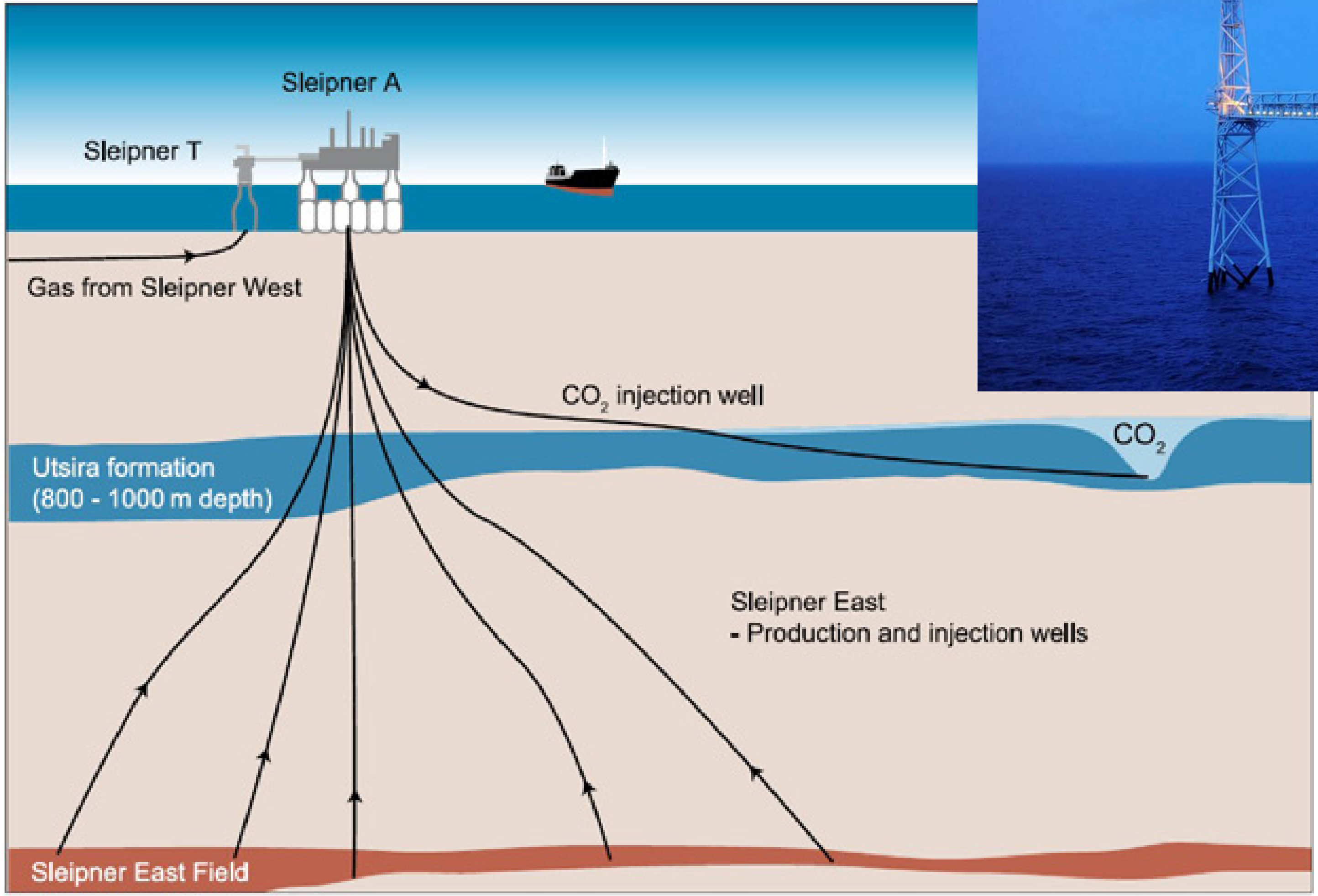
Ringrose 2018

Norway CCS: Building on experience



- 23 years of operations
- Building confidence in CCS
- >24 Mt CO_2 stored
- New full-scale CCS project being developed

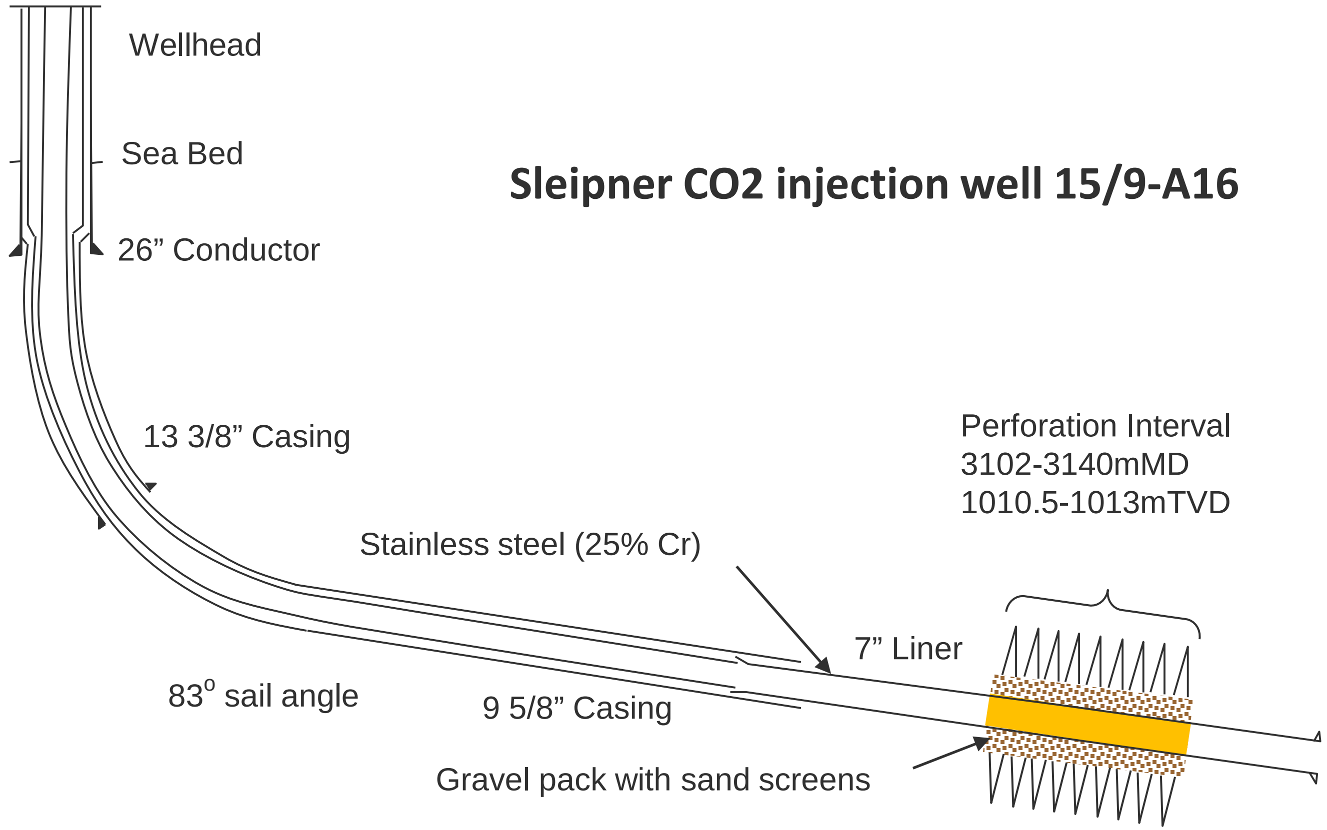
Sleipner Project Summary



- CCS part of gas field development
- Amine capture from natural gas
- 0.9 Million tonnes stored per year
- Injection started in Sept. 1996
- 23 years assurance monitoring
- Sleipner platform processing CO_2 from Gudrun field from 2017

Sleipner CO_2 Injection Well Design

- Long-reach horizontal well with stainless steel components has provided stable injection for 22 years



Hansen et al. 2005

- Demonstrates value of engineering design

Monitoring the subsurface at Sleipner

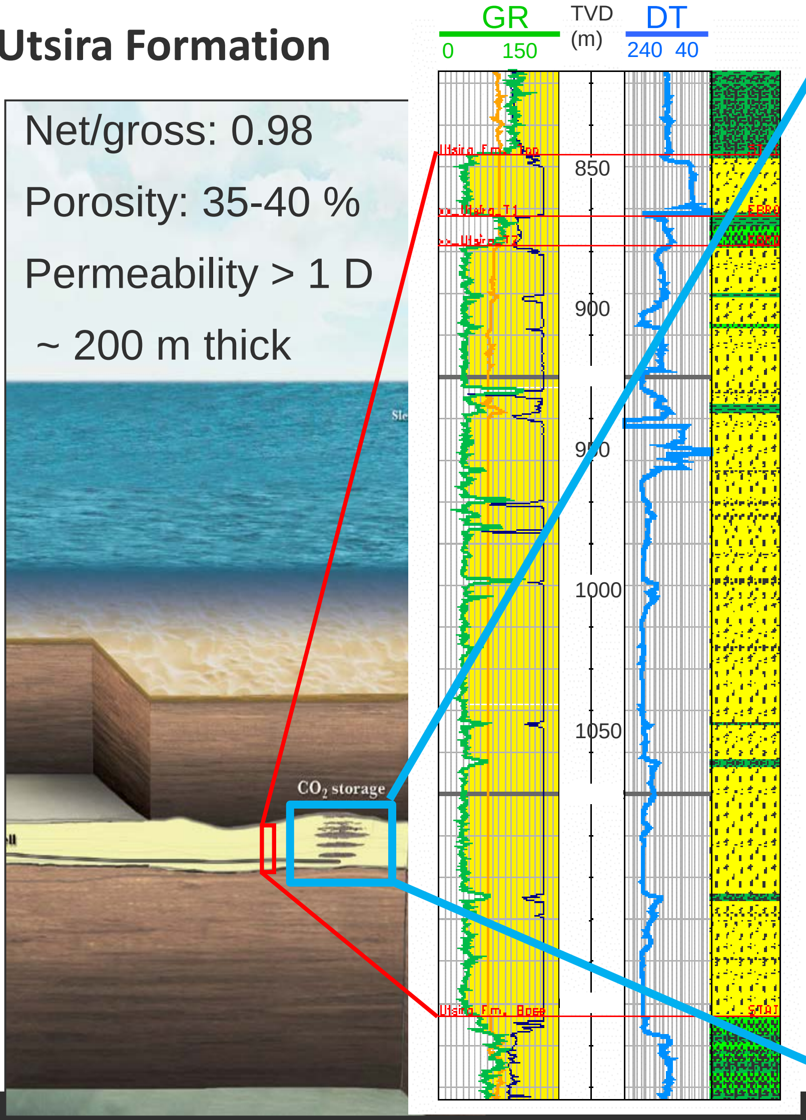
Utsira Formation

Net/gross: 0.98

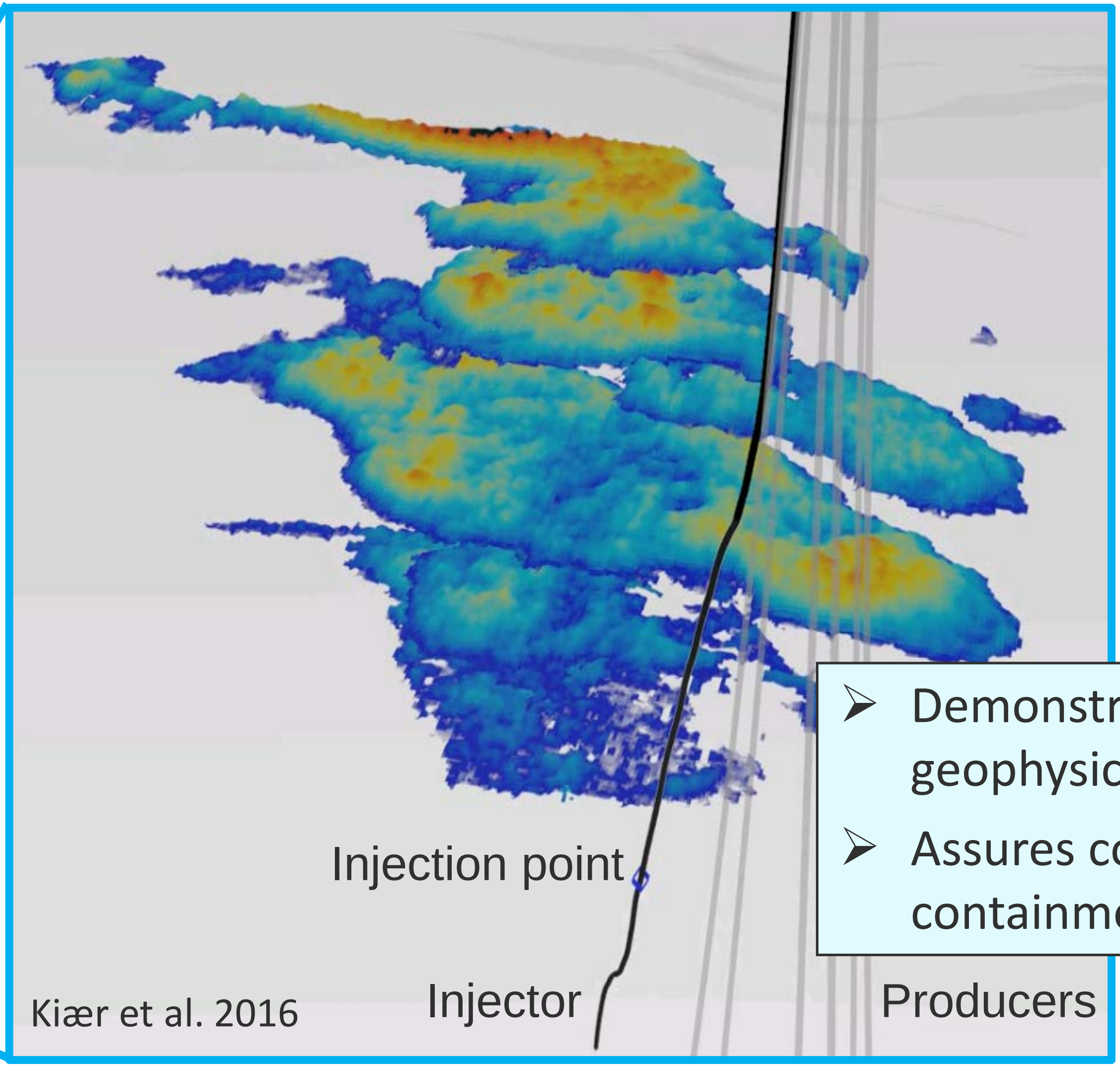
Porosity: 35-40 %

Permeability > 1 D

~ 200 m thick



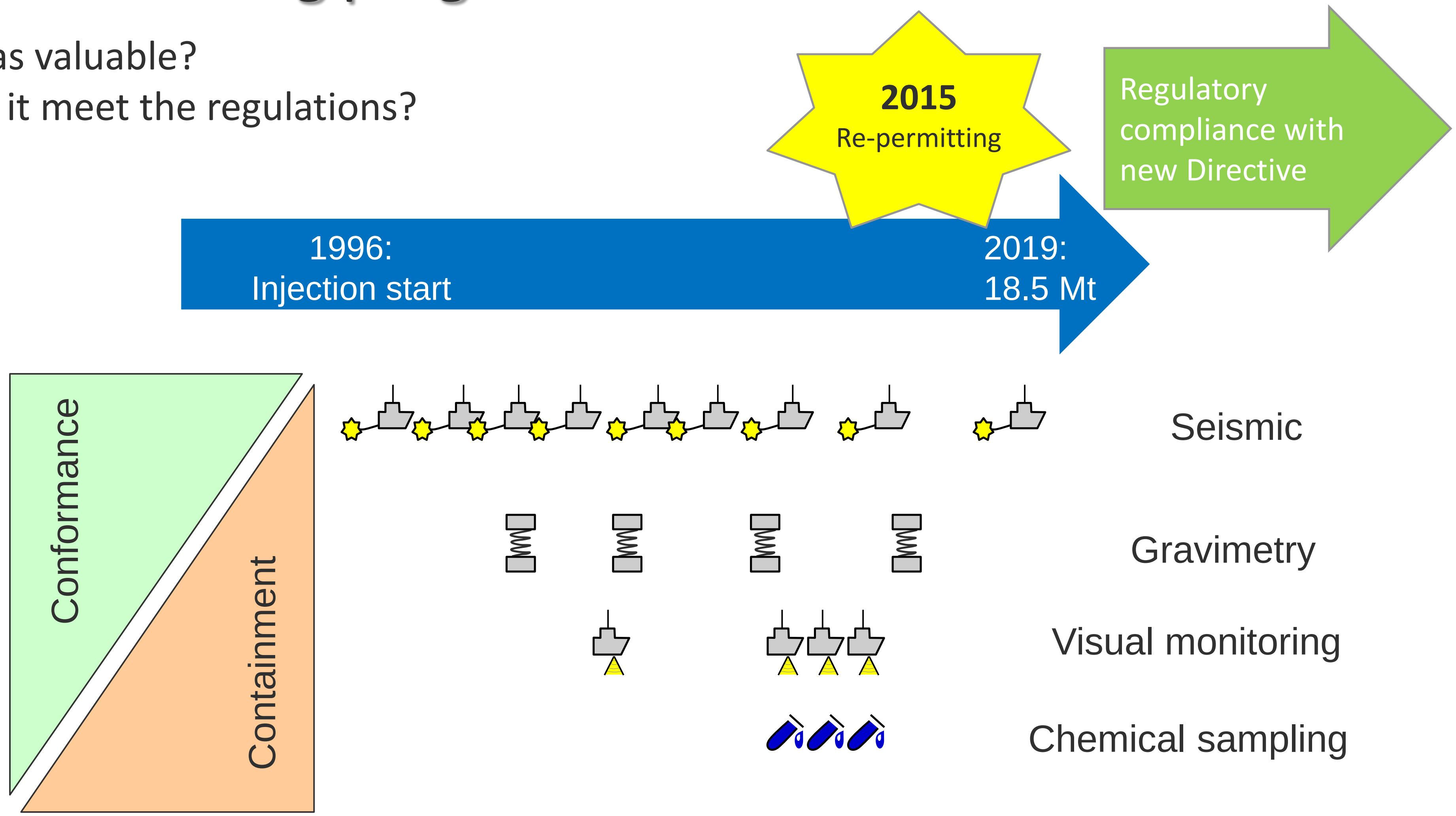
Insights from geophysical time-lapse monitoring



- Demonstrates value of geophysical monitoring
- Assures conformance and containment

Sleipner Monitoring programme review

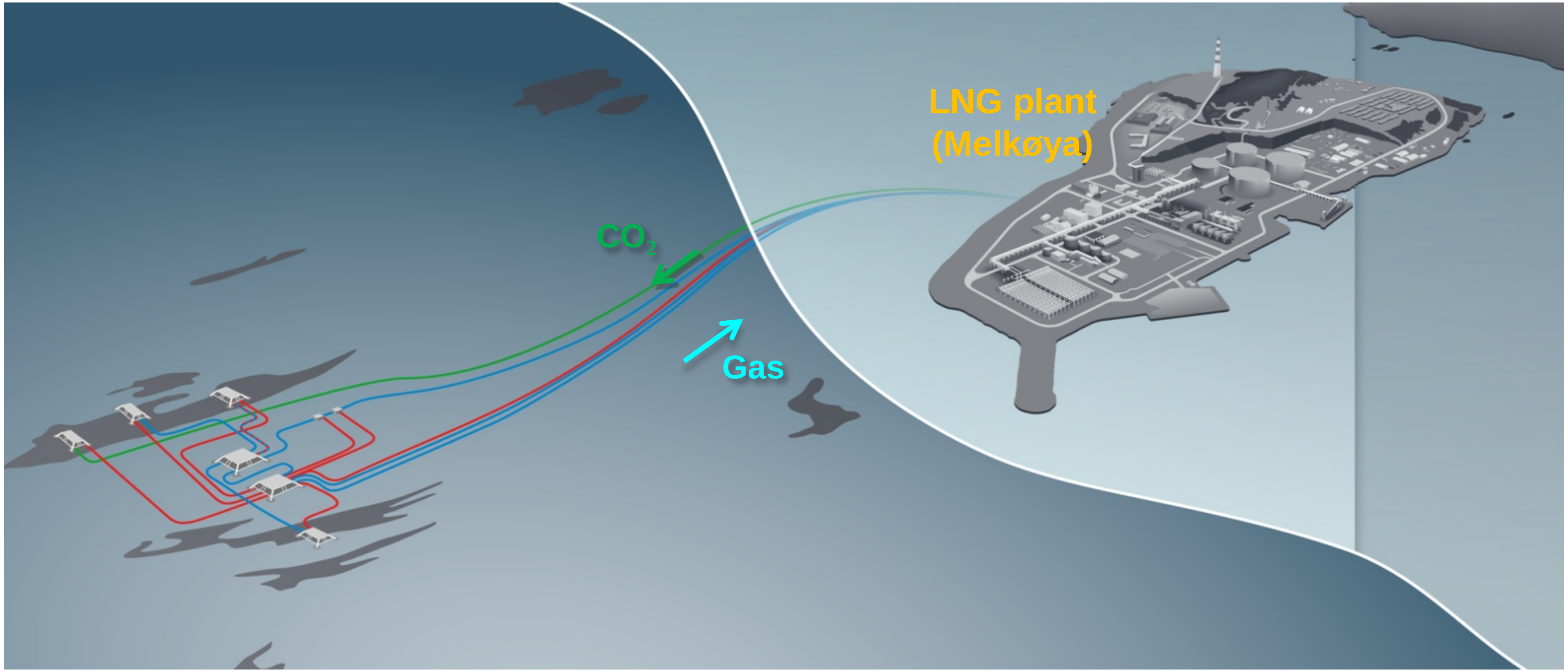
- What was valuable?
- How did it meet the regulations?



Furre et al. 2017

Snøhvit Project Summary

- First onshore capture - offshore storage project (combined with LNG)
  - 150km seabed CO_2 transport pipeline
  - Saline aquifers c. 2.5km deep adjacent to gas field
  - CO_2 stored initially in the Tubåen Fm. (2008-2011) and then in the Stø Fm. (2011-)

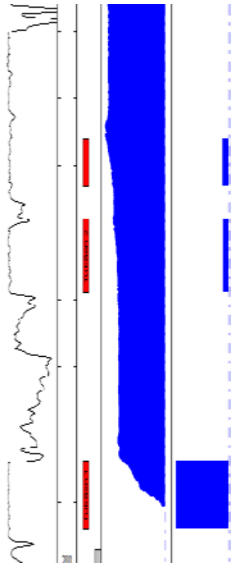


Monitoring the subsurface at Snøhvit

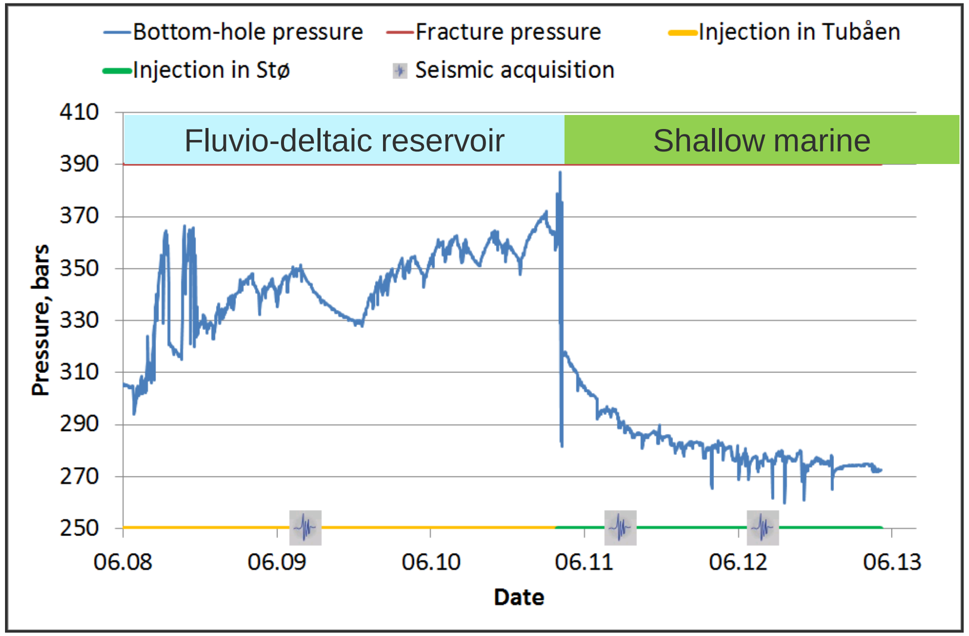
- Successful well intervention guided by monitoring data
  - Rising pressure due to geological barriers led to **well intervention**
  - Integrated use of geophysical monitoring and down-hole gauges
  - Deployed back-up option in the injector well

- Demonstrates value of flexible well design

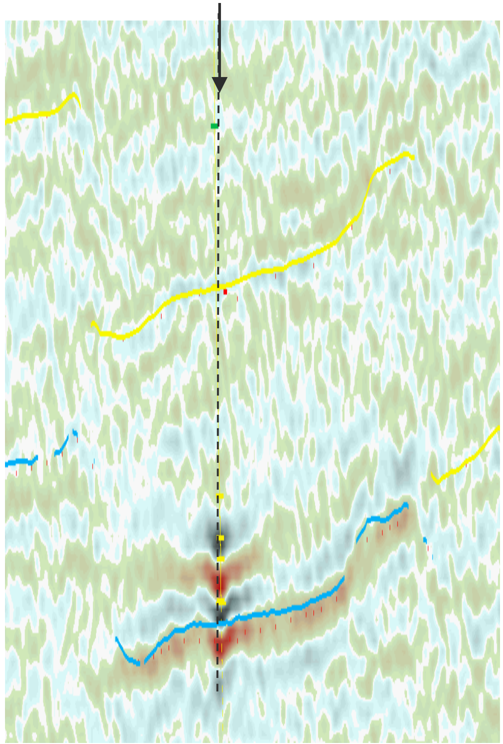
Down-hole data:
Downhole flow log



Down-hole pressure data



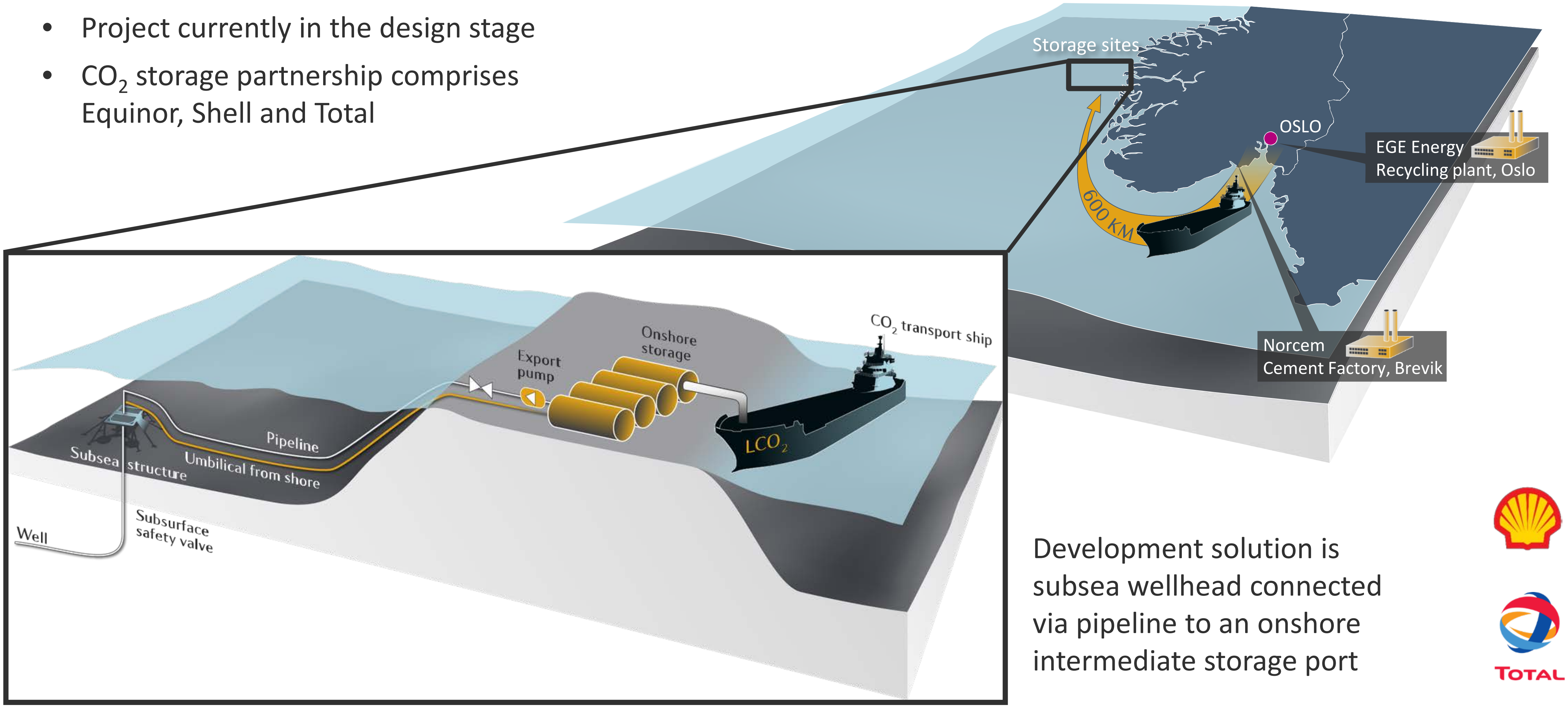
Time-lapse seismic
(Amplitude difference)



Hansen et al. 2013; Pawar et al., 2015

The Norwegian CCS Demonstration project

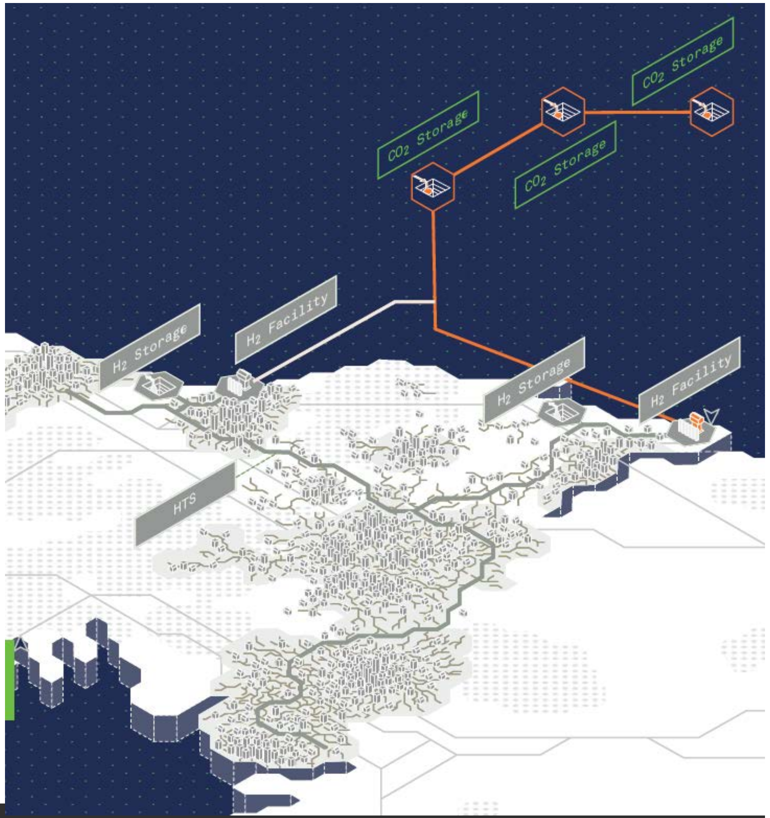
- Project currently in the design stage
- CO_2 storage partnership comprises Equinor, Shell and Total



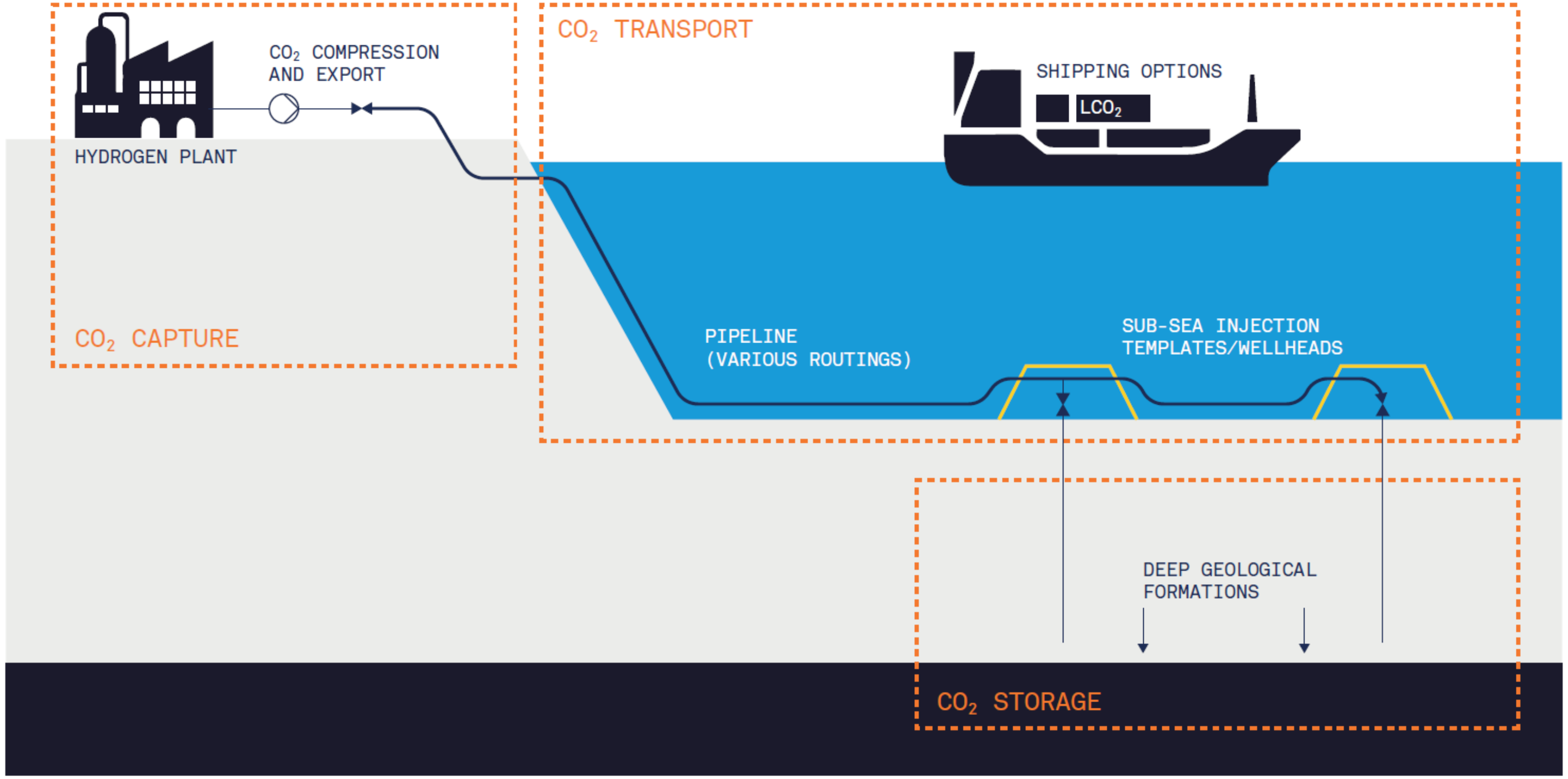
Development solution is subsea wellhead connected via pipeline to an onshore intermediate storage port

H21 Hydrogen Project

- System approach to decarbonise northern England using hydrogen (NG to H_2)
- Large-Scale: ~85 TWh giving 17-18 Mt CO_2 reduction per year
- Requires significant scale-up in storage



CO2 capture, transport and storage concept



Full report at https://northerngasnetworks.co.uk/h21-noe

Norwegian CO_2 Storage: Future potential

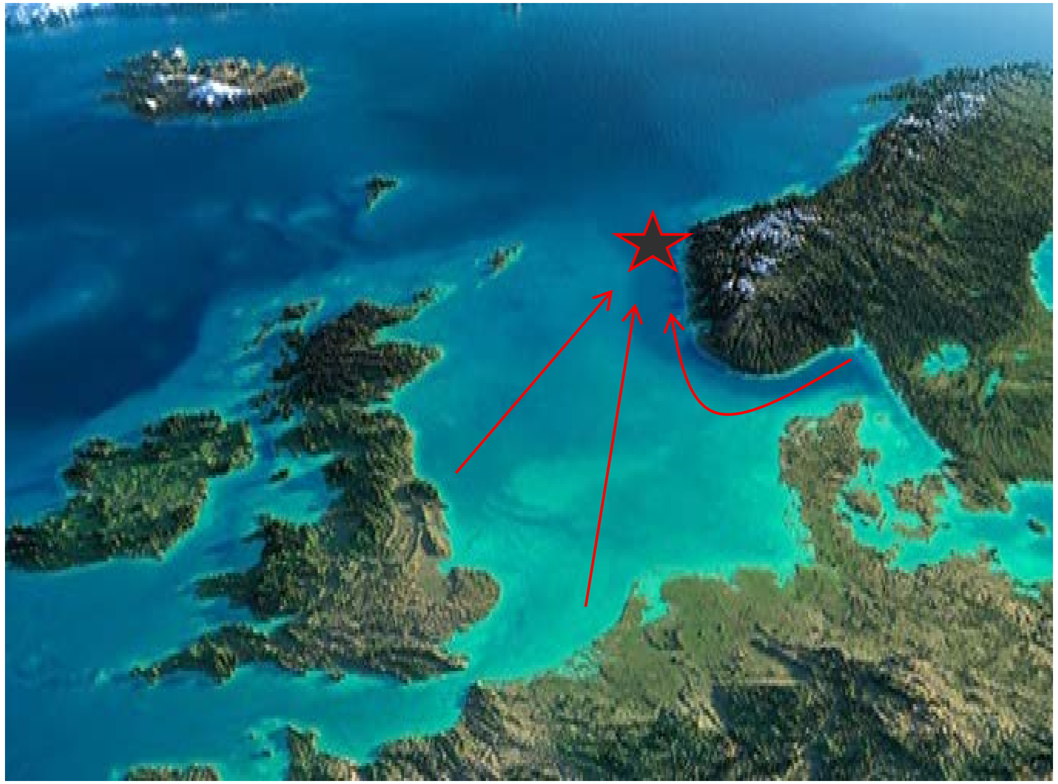
- Reduces risk and threshold for others
- Enables additional CO_2 storage

↓

- Allows stepwise development of CCS from more regional hubs

↓

- Basis for emerging CO_2 value chains:
  - Natural gas to hydrogen
  - CO2 EOR

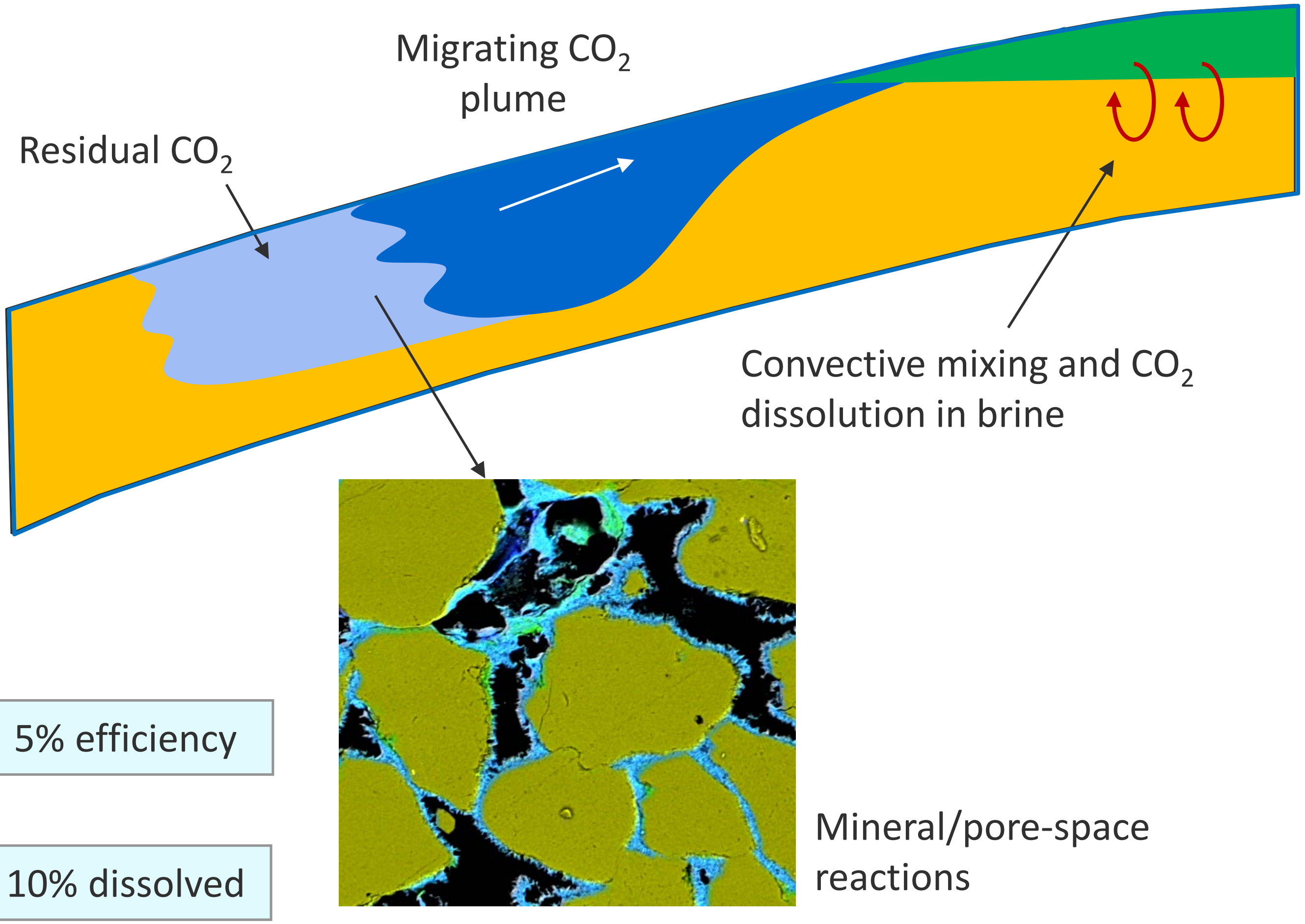


- North Sea CO_2 storage hub:
  A catalyst for roll-out of CCS in Europe?

So what happens underground?

What can we learn from Sleipner about CO_2 trapping mechanisms?

- Physical trapping
- Residual trapping
- CO_2 dissolution
- CO_2 precipitation

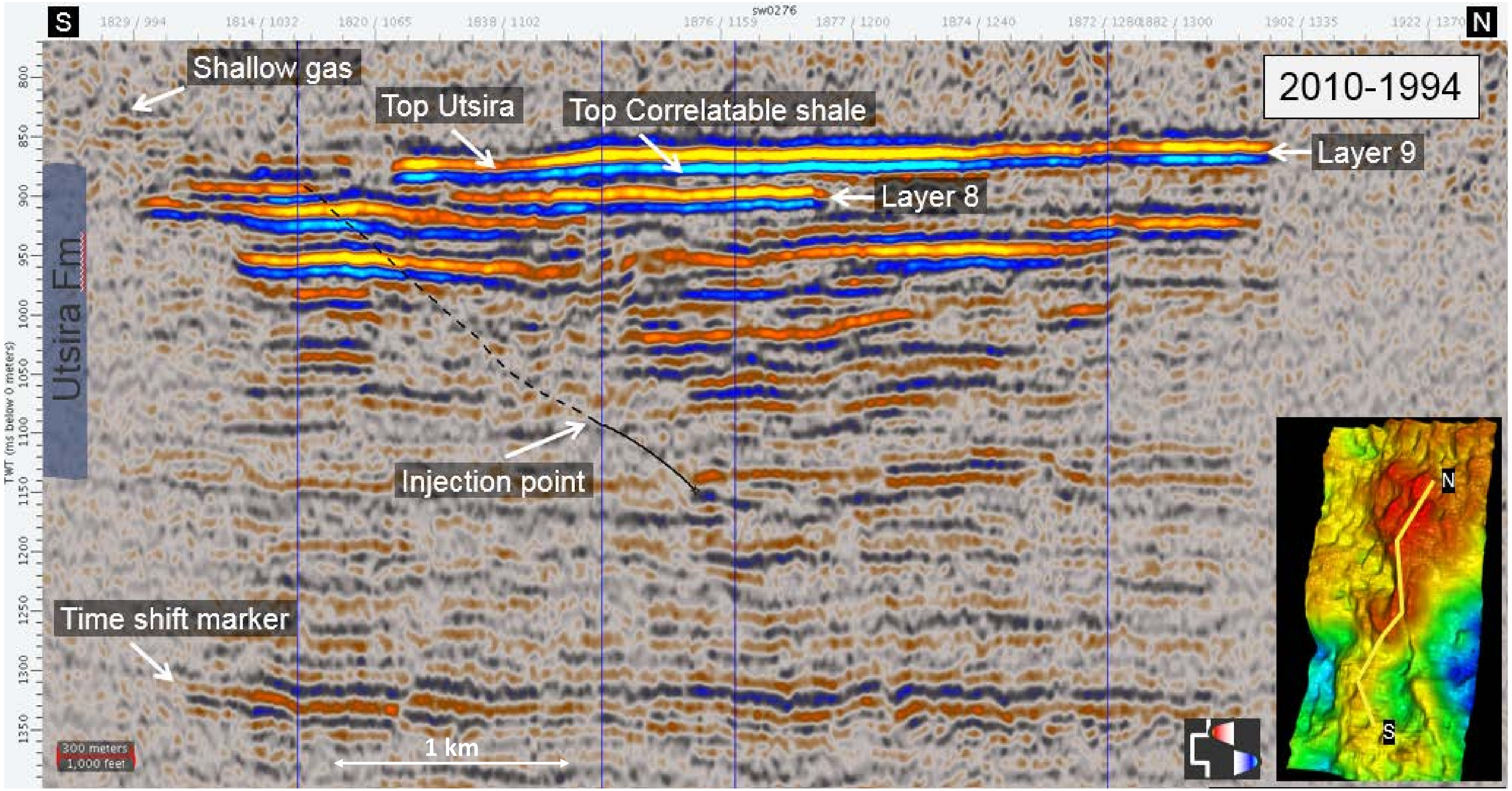


Sleipner CO_2 storage metrics
(as of 2010 seismic survey)

	Mass (Mt)	Fraction of pore space occupied (ε)	
Total injected	12.18	0.048	⇐ 5% efficiency
Free phase	11±0.5	0.044	
Dissolved phase	1.2±0.5	0.004	⇐ 10% dissolved

Ringrose 2018

Sleipner time-lapse difference datasets



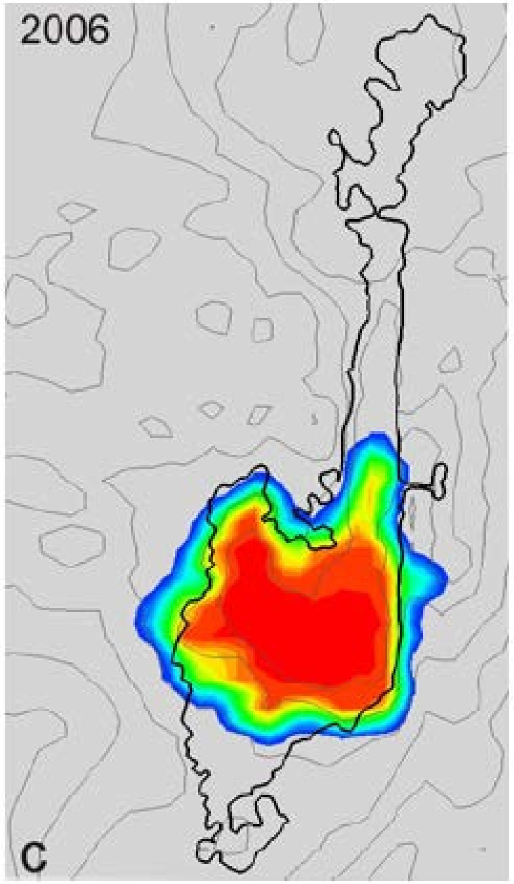
- Sleipner time-lapse seismic data, showing amplitude difference between 2010 and 1994 surveys.
- Bright amplitudes reveal presence of CO_2 complicated by effects of time-shifts and thin layer effects (Furre et al. 2015).

Brief history of CO_2 plume modelling at Sleipner

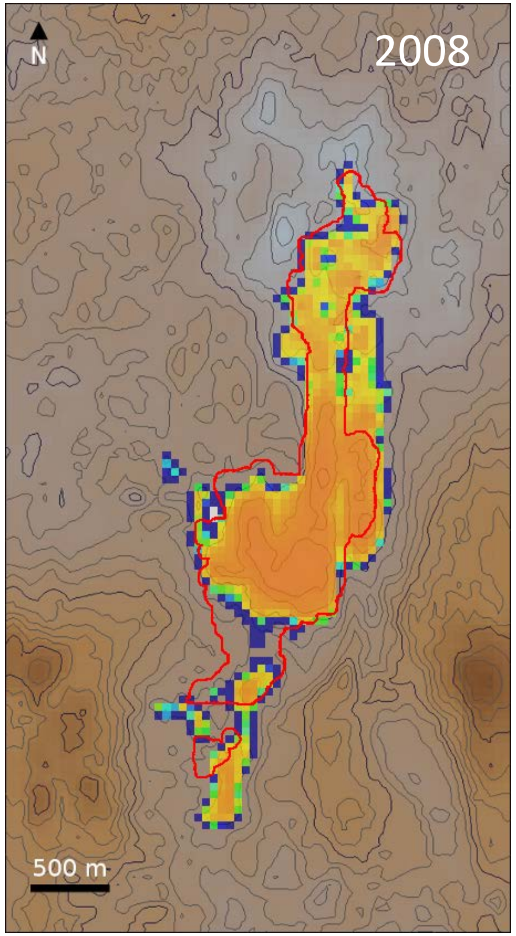
Layer 9 models

Early 5-layer model

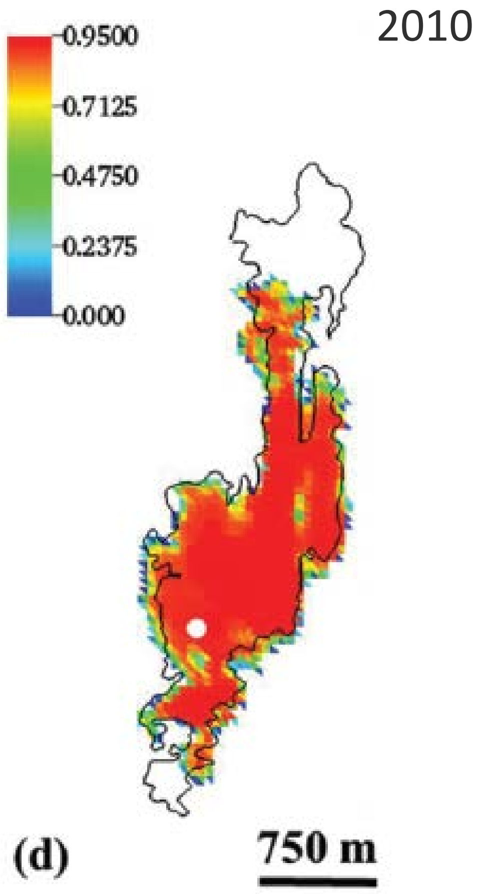
Lindeberg et al. 2000



Chadwick & Noy (2010)



Cavanagh (2013)



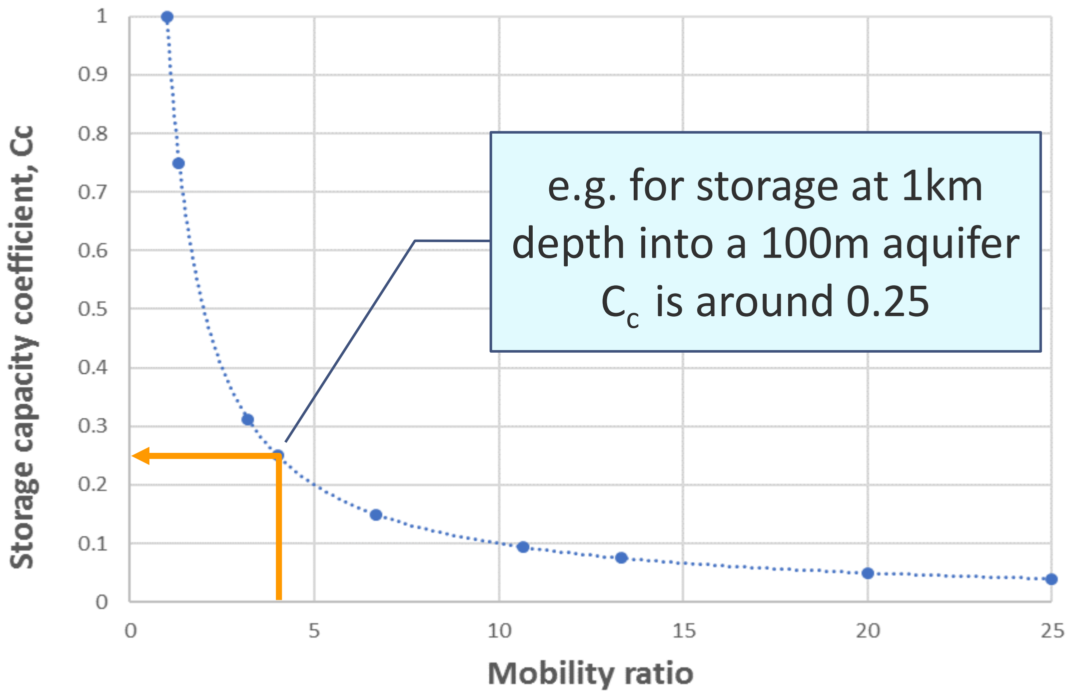
Williams & Chadwick, 2017

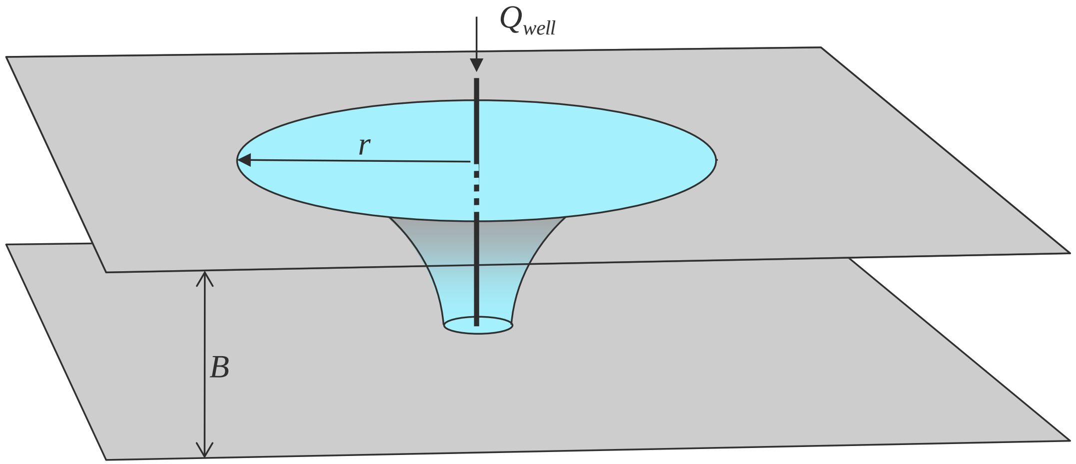
Analytical models for a CO_2 plume

- For a vertical well injecting at a rate Q_{well} into a horizontal saline aquifer unit, with thickness *B*, the CO_2 plume will expand with a 'curved inverted cone' geometry with a radius, *r* (Nordbotten et al. 2005).
- When the flow is viscous dominated:

Mobility ratio

$$r_{max} = \sqrt{\frac{\lambda_c}{\lambda_b}\frac{Q_{well}\, t}{\pi B \phi}}$$

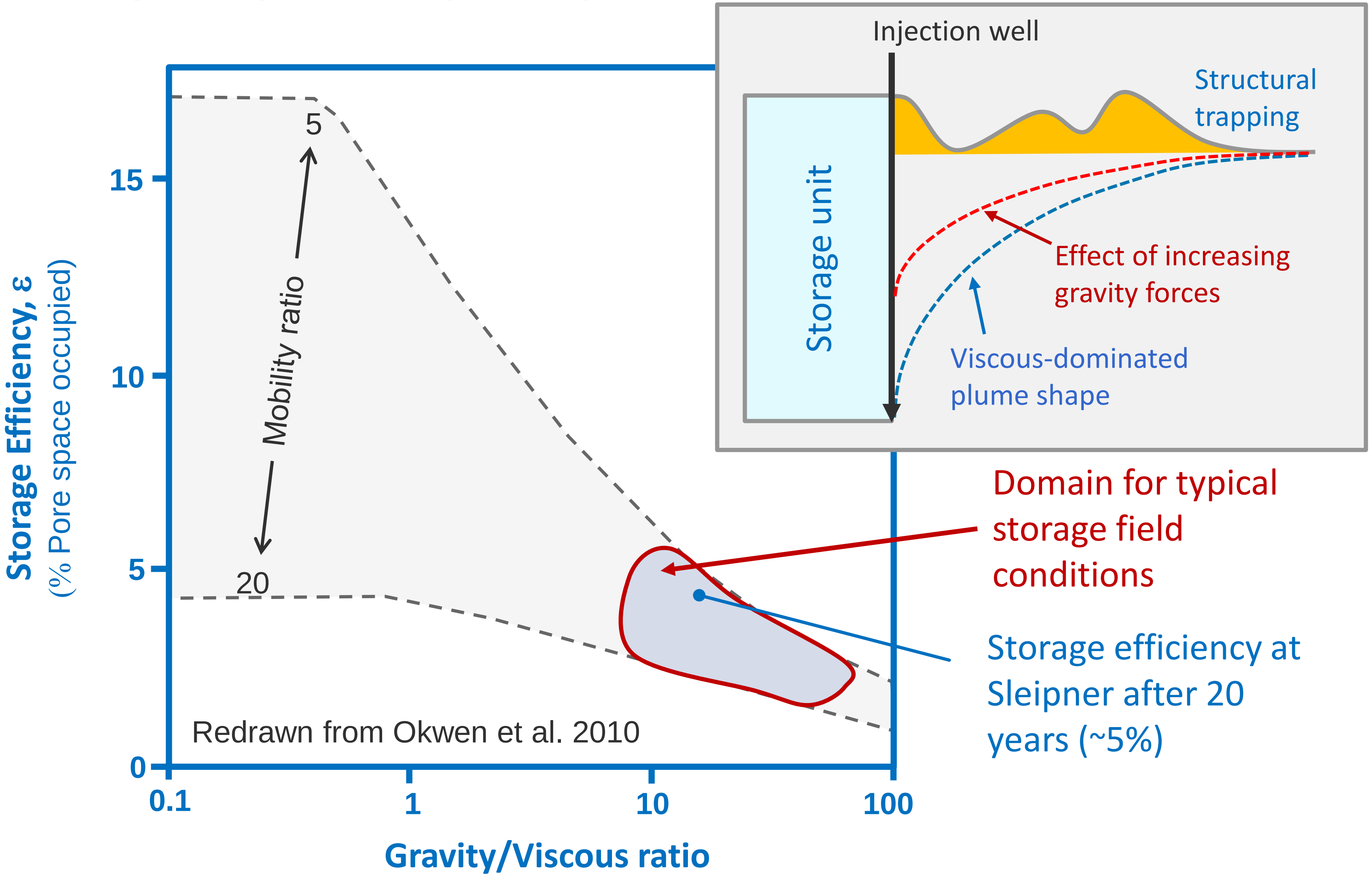




However, the shape of the cone and the efficiency depends on the gravity/viscous ratio:

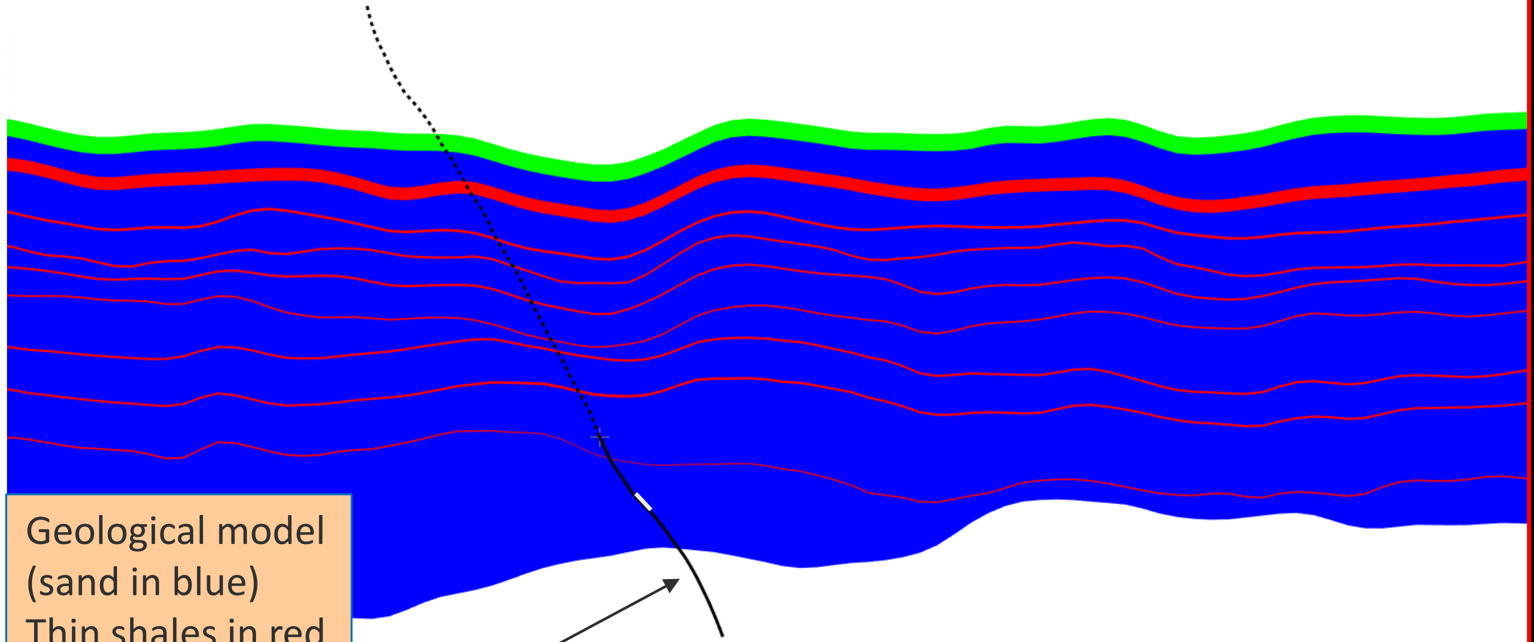
$$\Gamma = \frac{2\pi\, \Delta\rho\, k\, \lambda_b\, B^2}{Q_{well}}$$

Effects of buoyancy on capacity



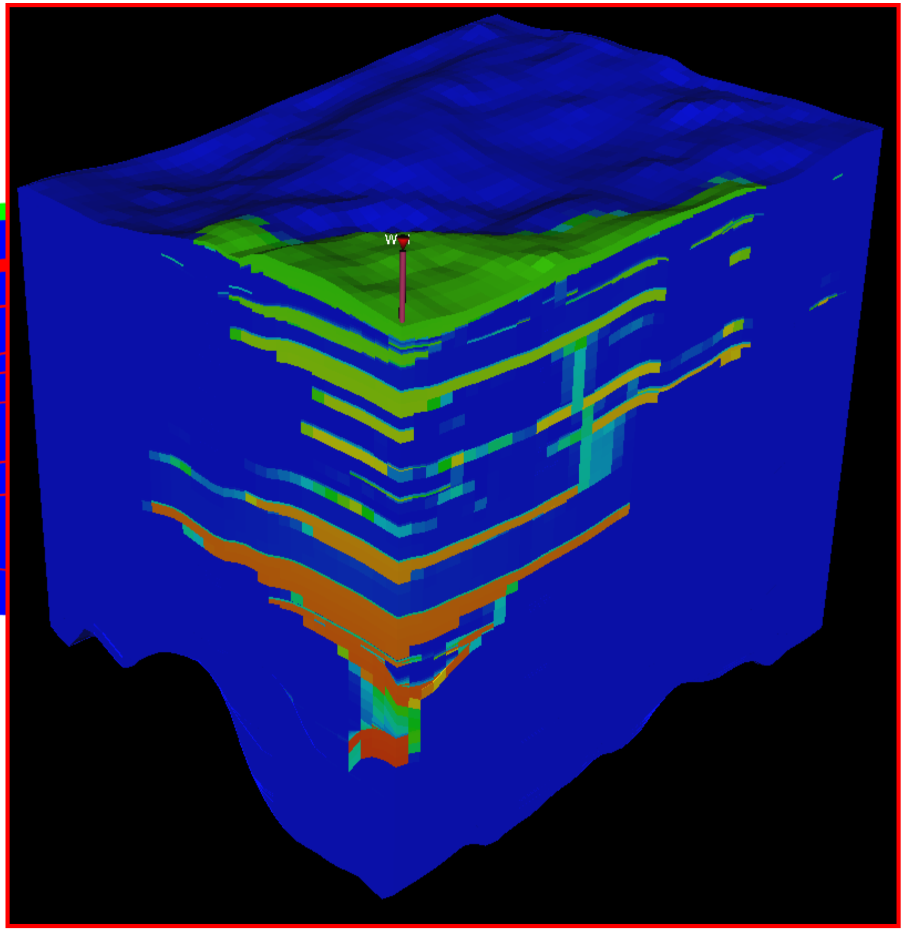
Modelling the Sleipner case

Updated Sleipner reference model now released



Geological model (sand in blue)
Thin shales in red
Caprock in green)

Deviated injection well path (15/9-A-16) with injection interval in light blue



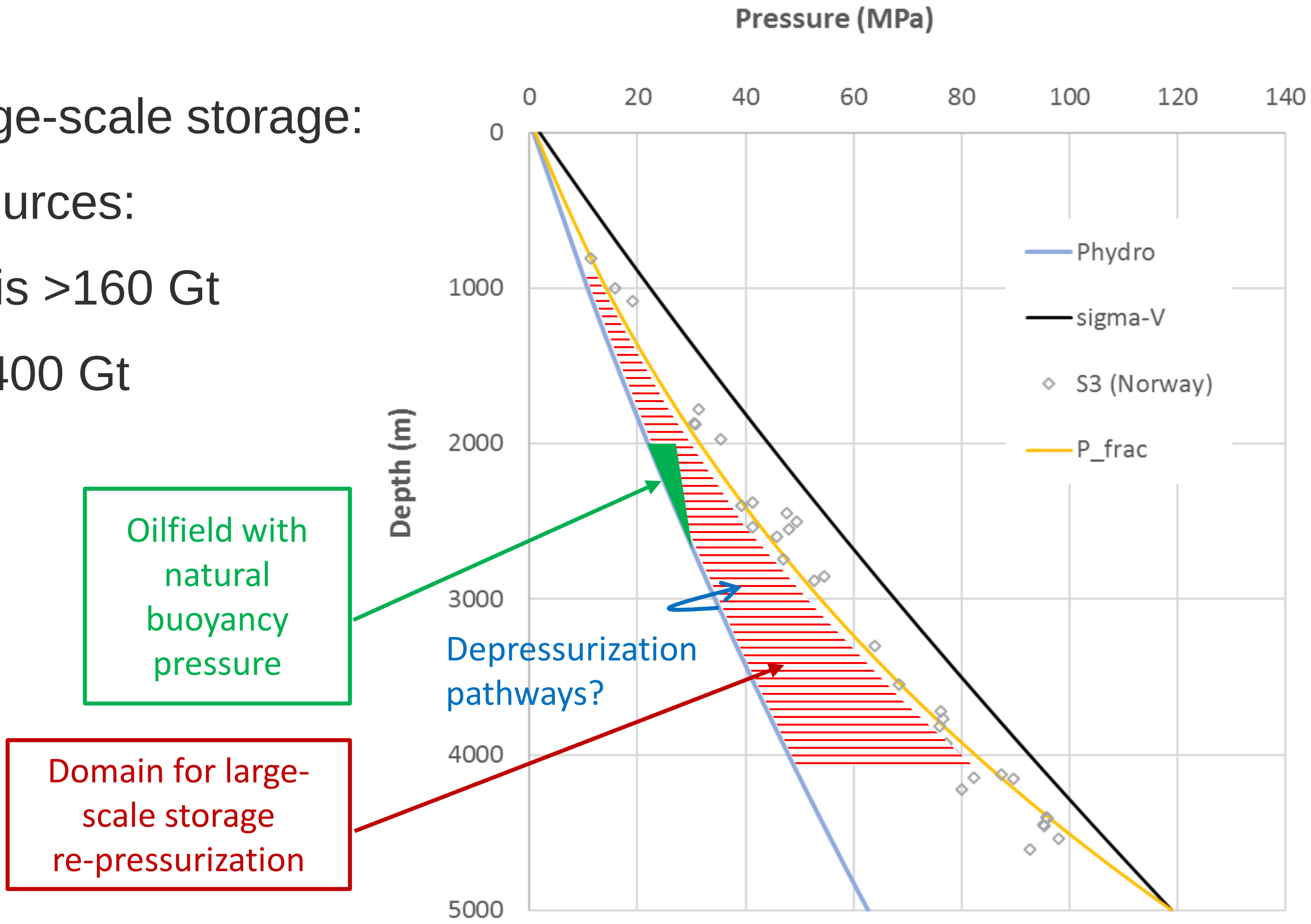
Example multi-phase flow simulation of CO_2 plume at Sleipner (Nazarian et al. 2013)

Sleipner Reference dataset via the CO_2 storage datashare initiative
https://www.sintef.no/en/projects/co2-storage-data-consortium-sharing-data-from-co2-storage-projects/

Pathway to large-scale global storage

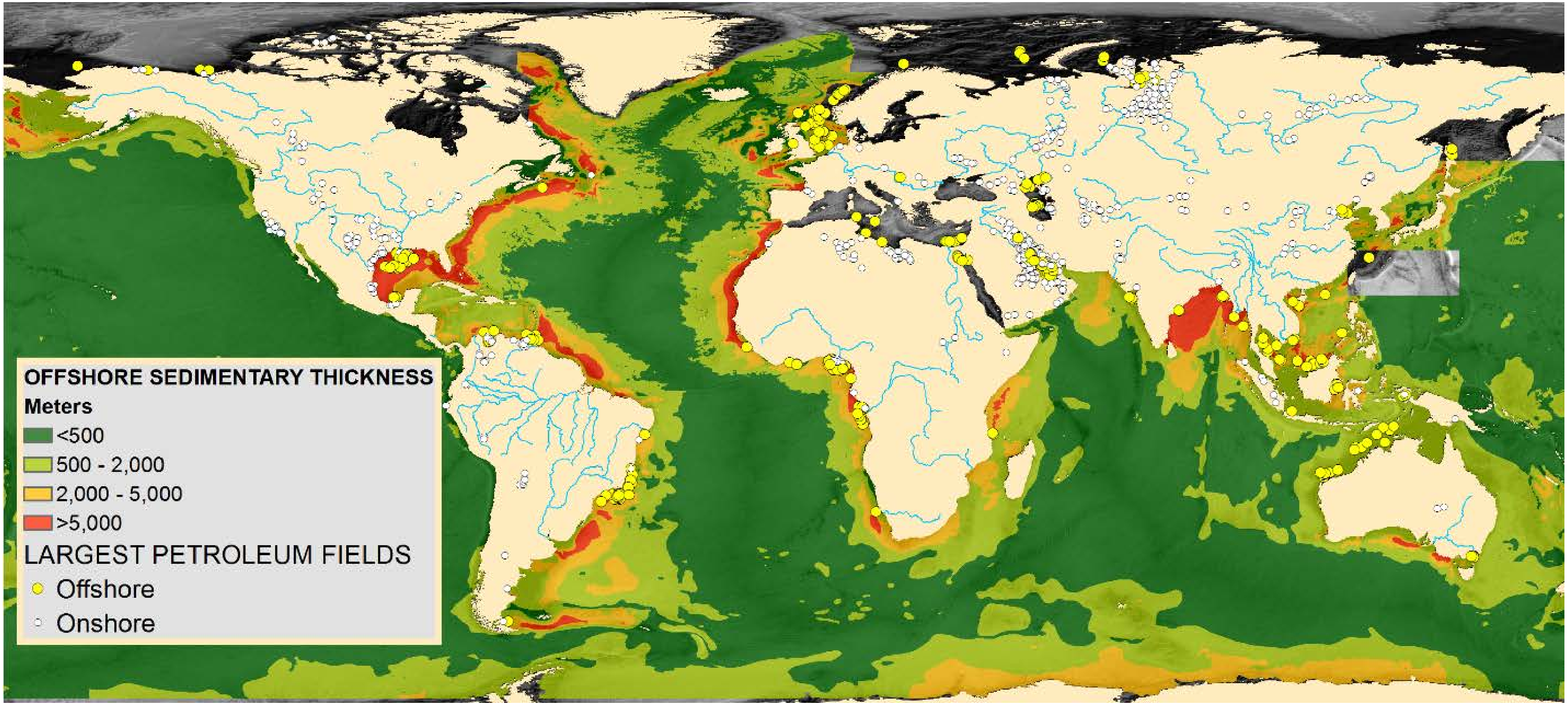
Much discussion about the ‘do-ability’ of large-scale storage:

1. Many nations have mapped storage resources:
   - North Sea basin CO_2 storage resource is >160 Gt
   - North American storage resource is >2400 Gt
   - So far we have only used 0.05 Gt of these resource (globally)
2. However, large-scale storage will require a pressure management approach
3. Design and optimization will be key to scale-up



Ringrose & Meckel (2019); minimum stress data from Bolaas and Hermanrud (2003)

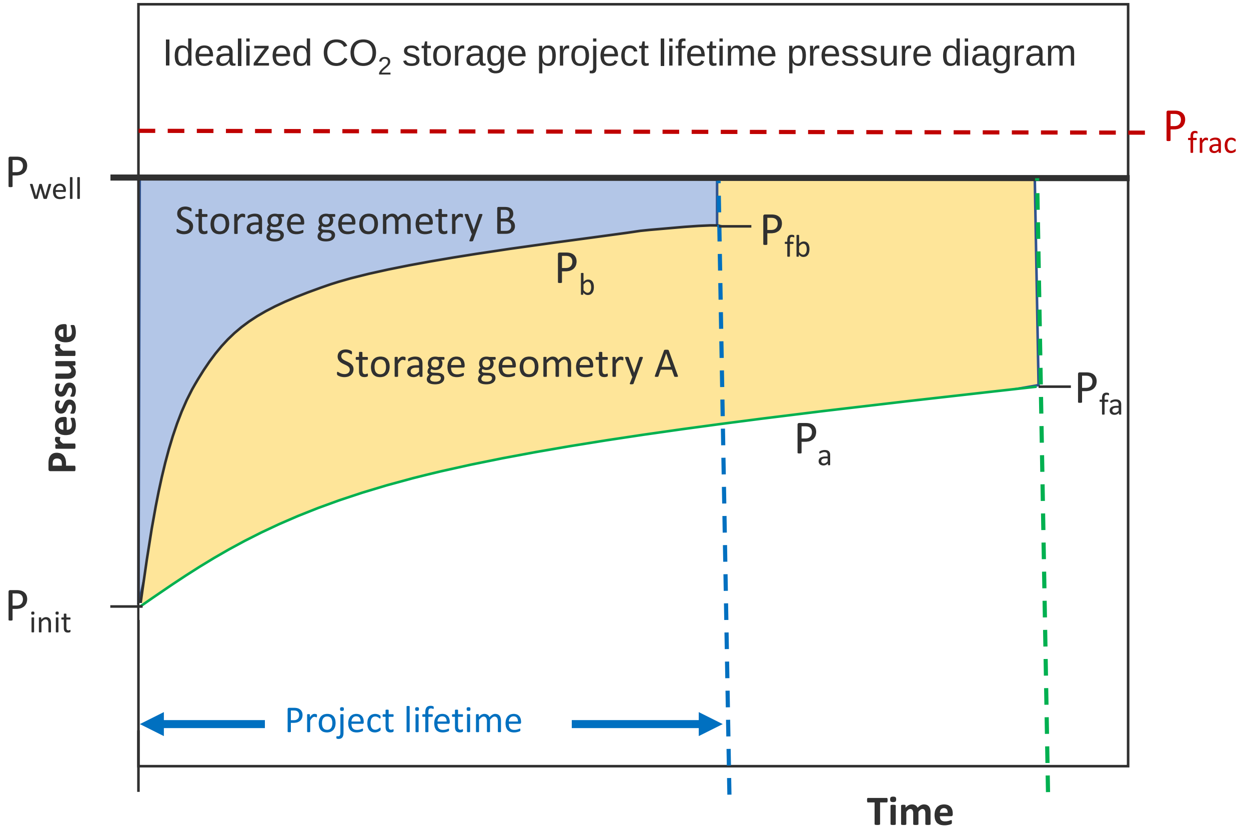
Global offshore resources



Global distribution and thickness of sediment accumulations on continental margins, with largest oilfields and main river systems

Design model for global storage development

➢ Initial and final pressure per well can be used to estimate capacity



Generic 'basin ΔP' approach:

Integration of the injectivity equation over the project lifetime:

$$V_{project} = I_C \left[p_{well} - p_{init} + \int_i^f A\, p_D(t_D) \right] + F_b$$

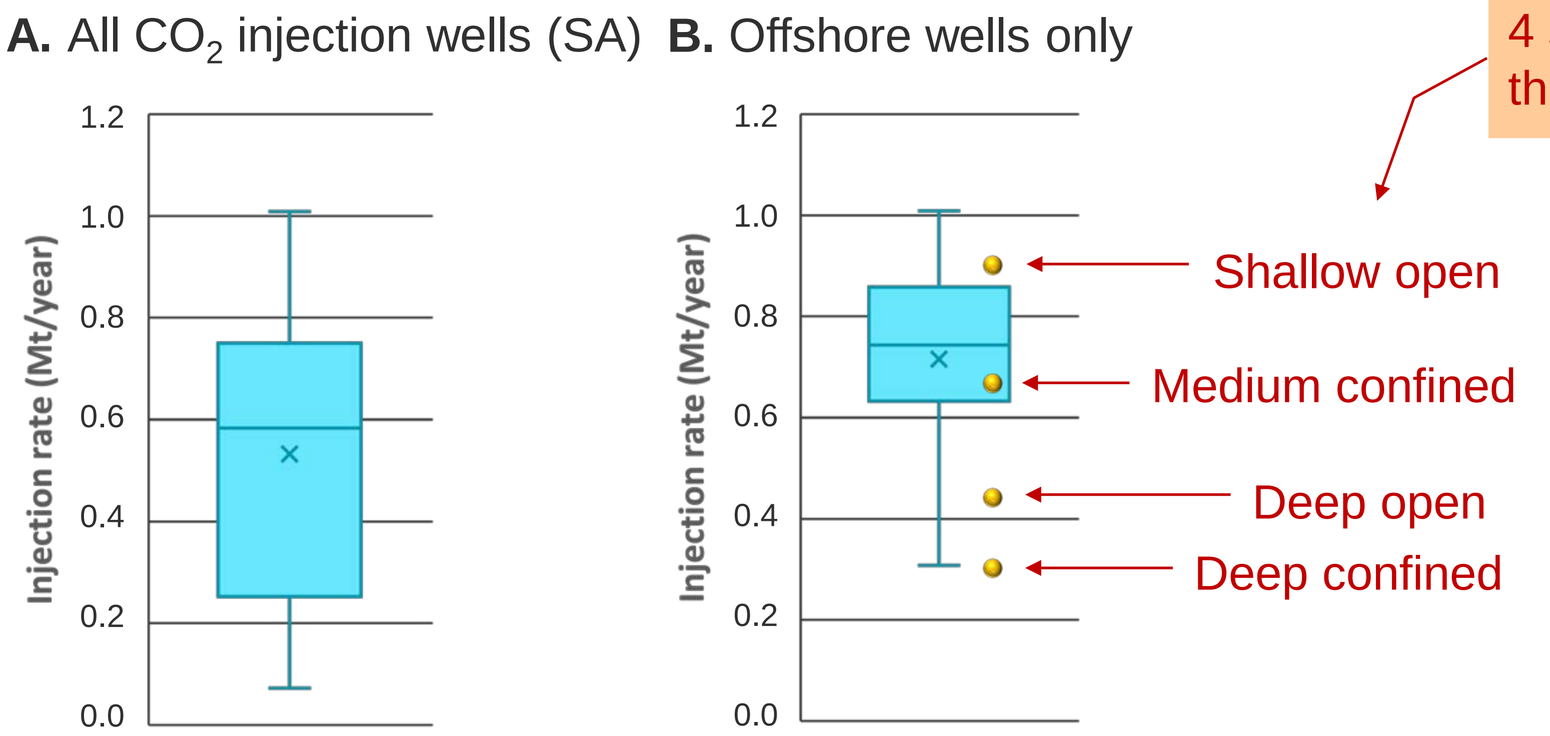
where,

$V_{project}$	= estimated volume stored
I_c	= injectivity
P_{well}	= injection well pressure
P_{init}	= initial reservoir pressure
$Ap_D(t_D)$	= characteristic pressure function
F_b	= volume flux boundary condition

Ringrose & Meckel (2019)

We also need to know well delivery rates

- CO_2 injection well data set (60 years of injection from 9 wells)



4 scenarios modelled to illustrate the range of expected behaviours

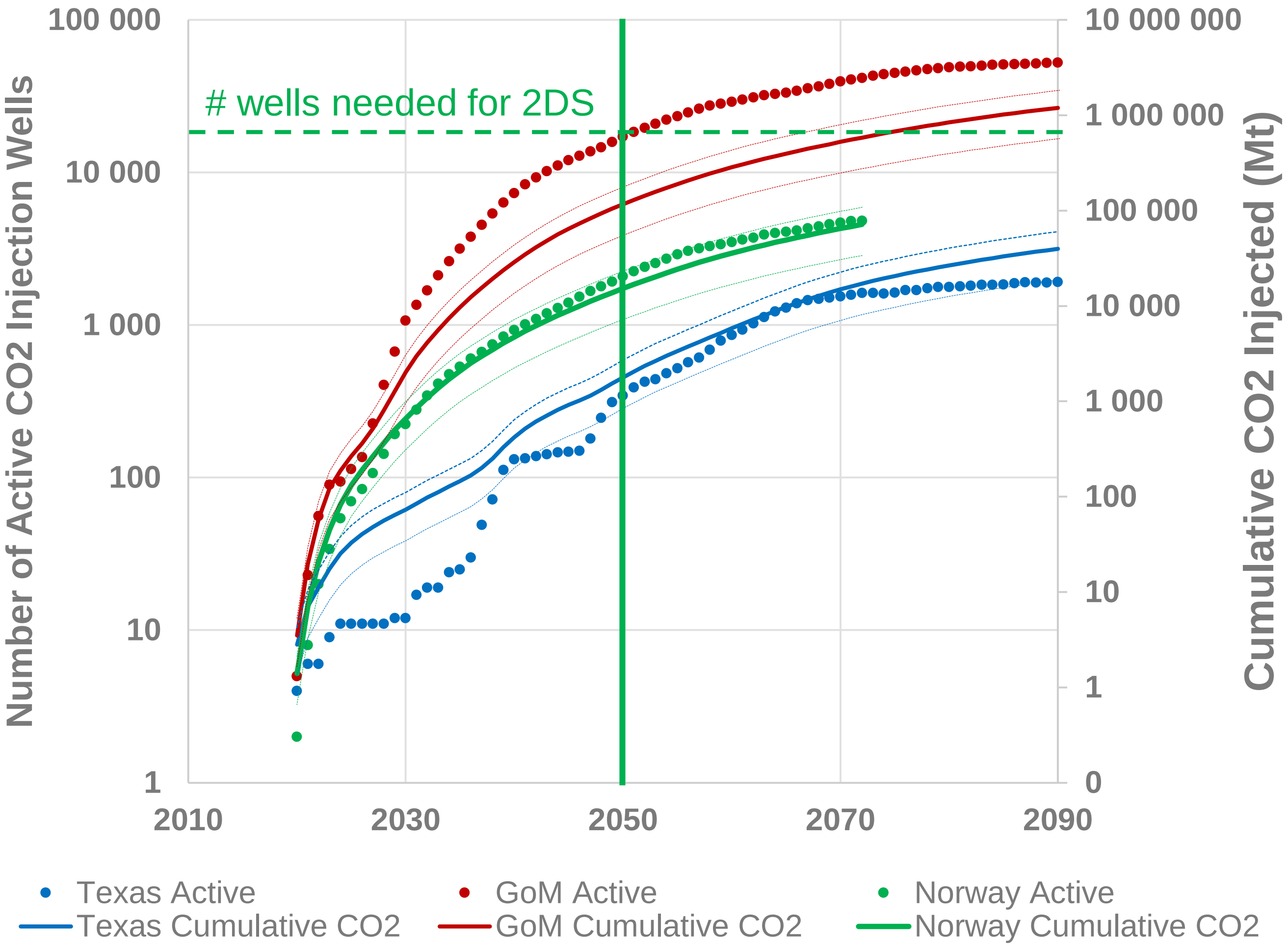
Statistics used for global basin forecasts:

- P90 = 0.33 Mt/year
- P50 = 0.70 Mt/year
- P10 = 1.06 Mt/year

Application of ΔP method to basin-scale developments

- Projected growth of CO_2 injection wells based on historical hydrocarbon well developments.
- Concept captures industrial maturation phases for global CO_2 storage
- Uncertainty range based on bounds (P10 - P90) from empirical injection rates

Main finding:
We will need ~12,000 CO_2 injection wells by 2050 to achieve 2Ds goal



Main findings: Global scale-up

Using historical well development trajectories transposed into a future CO_2 injection industry, we can infer that:

- A single 'Gulf-of-Mexico well development' CO_2 injection model could achieve the 7 Gtpa storage by 2043 and 12 Gtpa by 2050. Cumulative storage in 2050 would be 116 Gt.
- Alternatively, five 'Norway offshore well development' models could achieve the 7 Gtpa storage by 2050. Cumulative storage in 2050 would be 73 Gt.
- Cumulative storage of >100 Gt by 2050 is most efficiently achieved with 5-7 regions pursuing a Norwegian-scale offshore well development model:
  - Resources are equitably distributed and would likely occur in multiple offshore basins close to the main locations of onshore capture

It will only take a fraction of the historic worldwide offshore petroleum well development rate to achieve the global requirements for geological storage of captured CO_2 under the 2DS scenario

Summary

1. The emerging CCS hub in Norway should help stimulate multiple CO_2 capture projects in NW Europe
2. Sleipner and Snøhvit projects give valuable insights for future saline aquifer CO_2 storage
3. Geopressure capacity approach quantifies a pathway for global scale up
4. Number of wells needed under the 2DS scenario is only a fraction of the historic worldwide petroleum well development rate

Main References

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- Furre, A-K, Kiær, A., Eiken, O. “CO_2-induced seismic time shifts at Sleipner.” *Interpretation* 3.3 (2015): SS23-SS35.
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- Nazarian, B., Held, R., Høier, L., & Ringrose, P. (2013). Reservoir management of CO2 injection: pressure control and capacity enhancement. *Energy Procedia*, *37*, 4533-4543.
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