Ensuring safe storage operations: learning from Sleipner and Snøhvit

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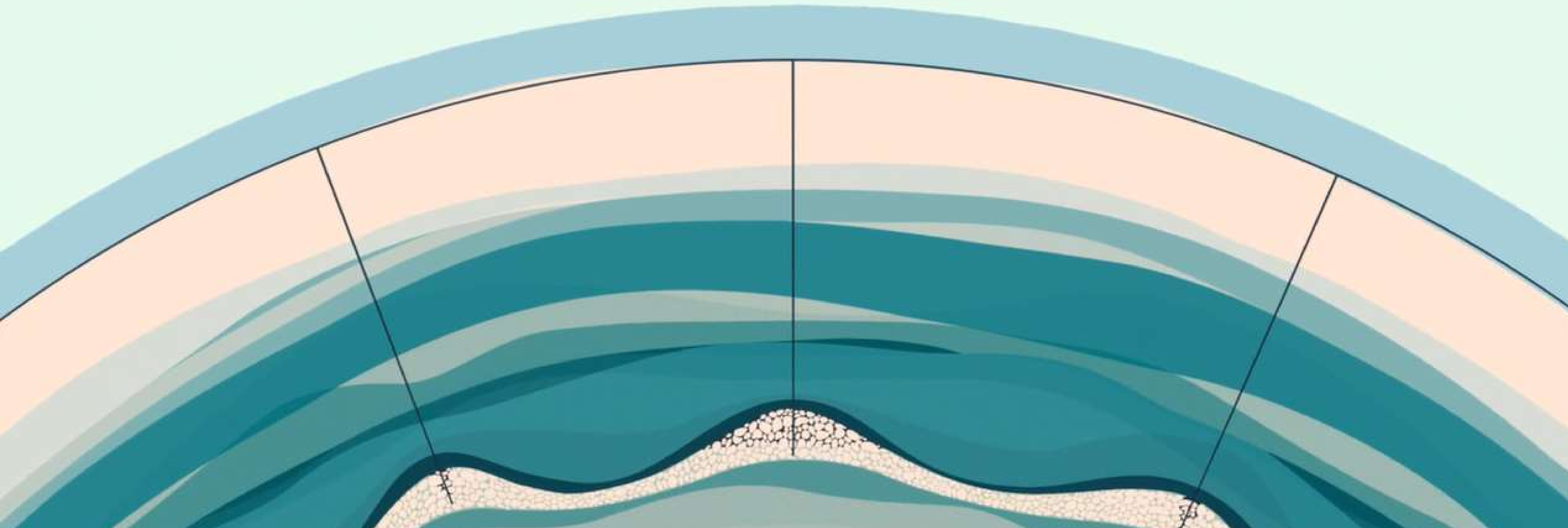


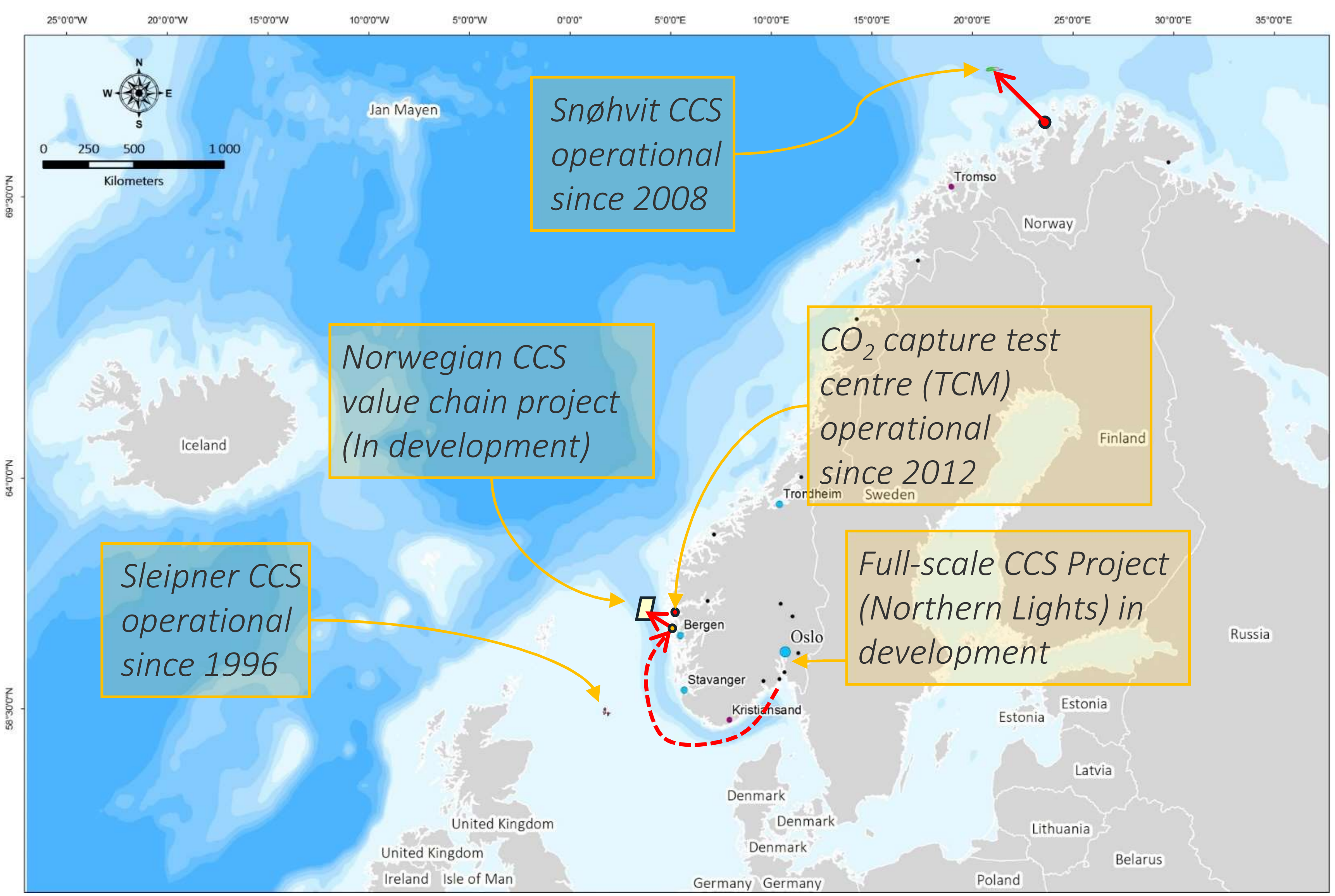
Summary CCS in Norway

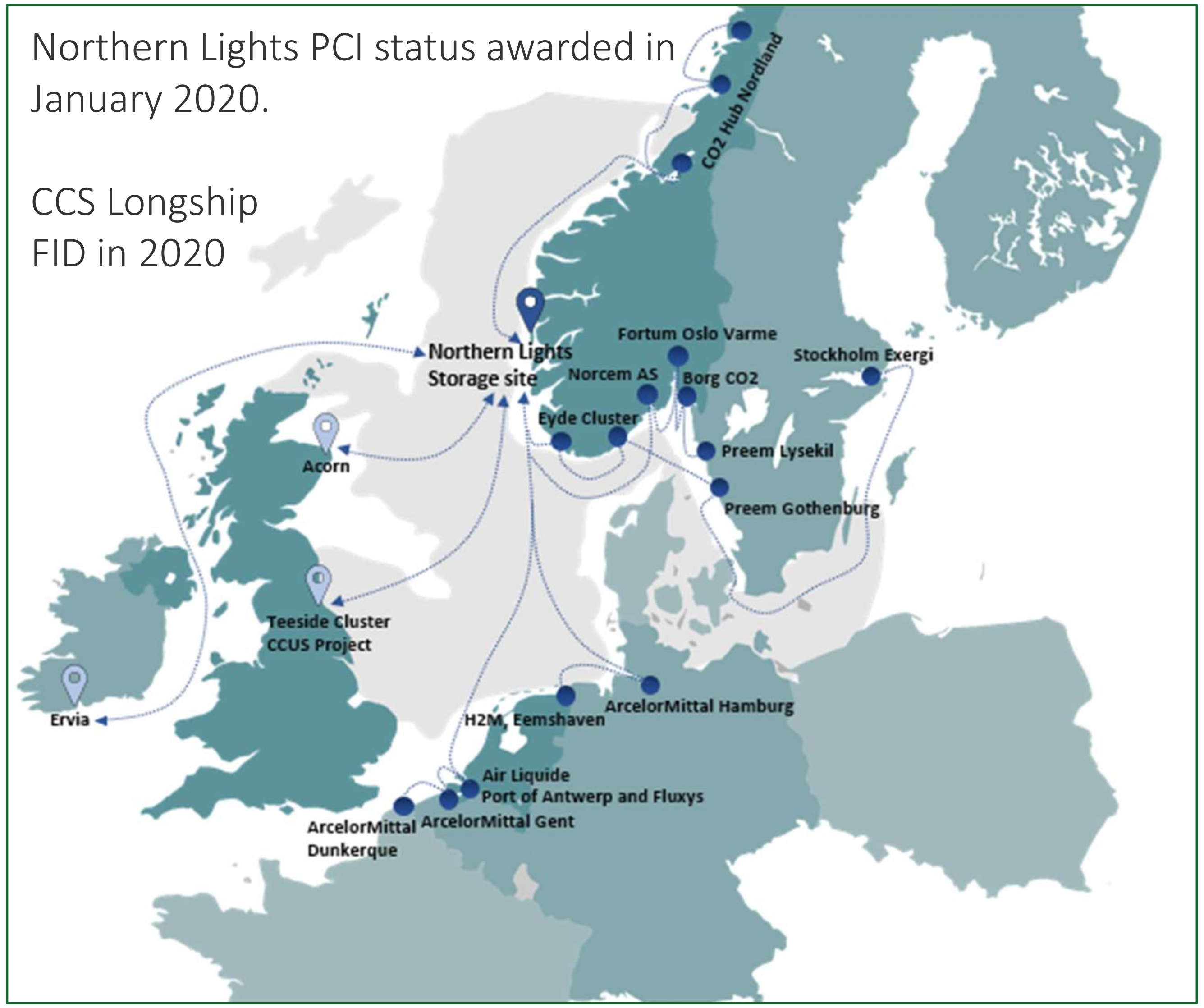
Building on experience

- 24 years of operations
- >24 Mt CO_2 stored

Supporting decarbonisation

- Open storage concept
- Incipient CCS hub

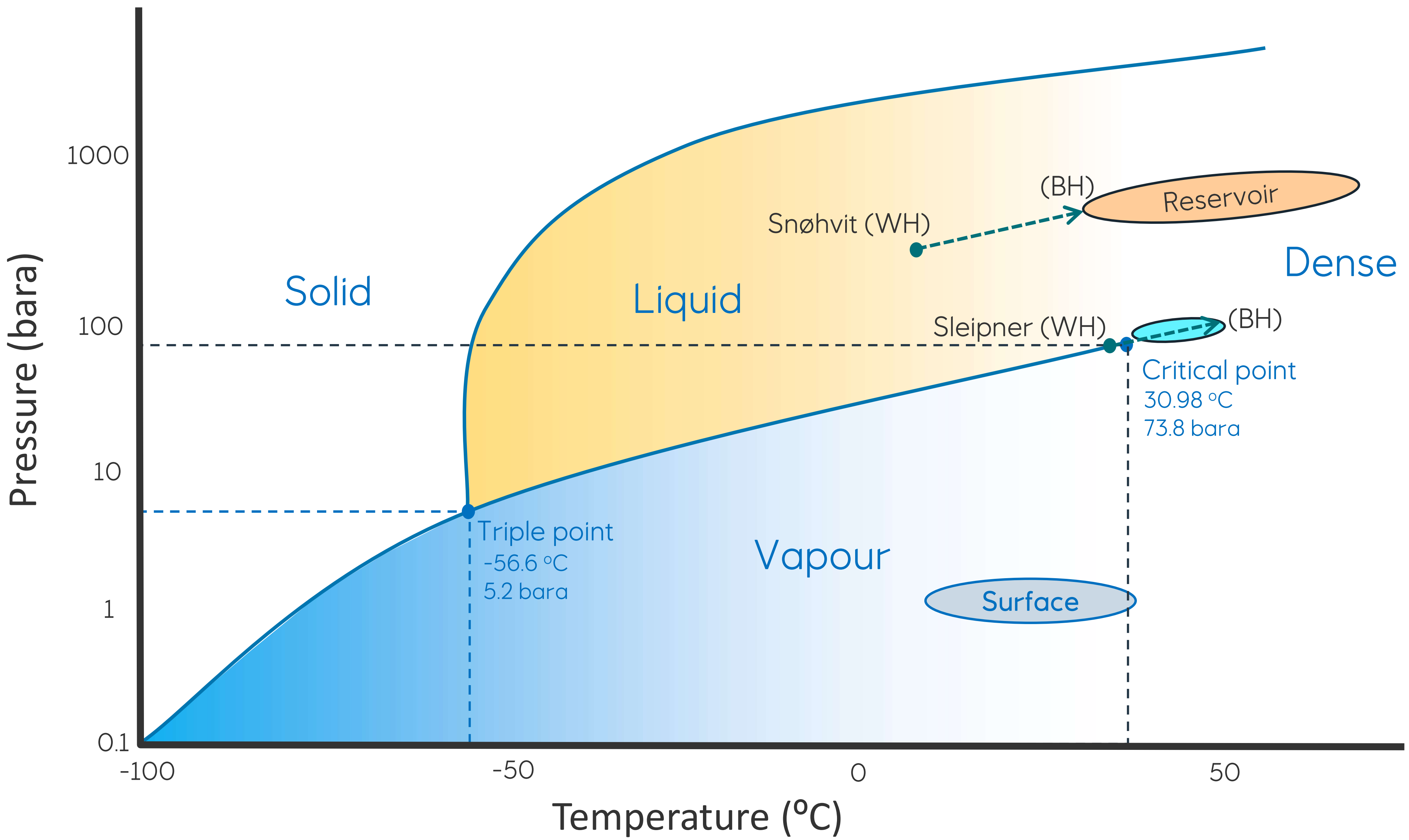




CO_2 injection from the molecule's point of view

Understanding facilities and well operations on the phase diagram

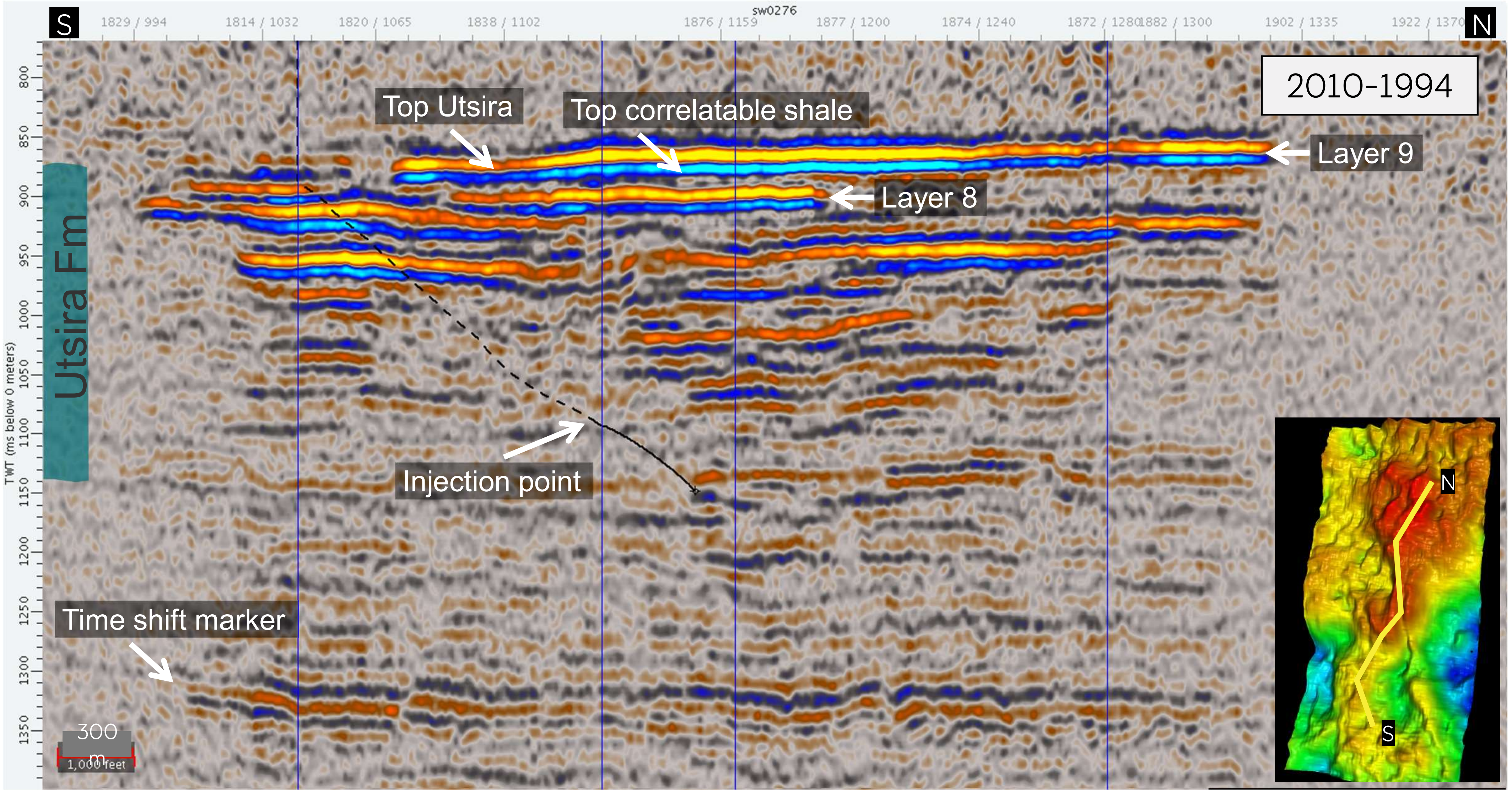
- Sleipner operations very close to the triple point
- Snøhvit is much deeper and into the liquid/dense envelop
- CO_2 at Snøhvit warms up into the formation and cools the rocks – possible nearwell thermal fractures
- CO_2 at Sleipner cools down in the reservoir – leading to significant changes in density



Seismic imaging of CO_2 plume at Sleipner

Time-lapse seismic imaging at Sleipner has been very successful:

- Has informed researchers and operators about the 'physics of the storage process' (insights)
- Has been vital for convincing the authorities and the public about successful storage (conformance)

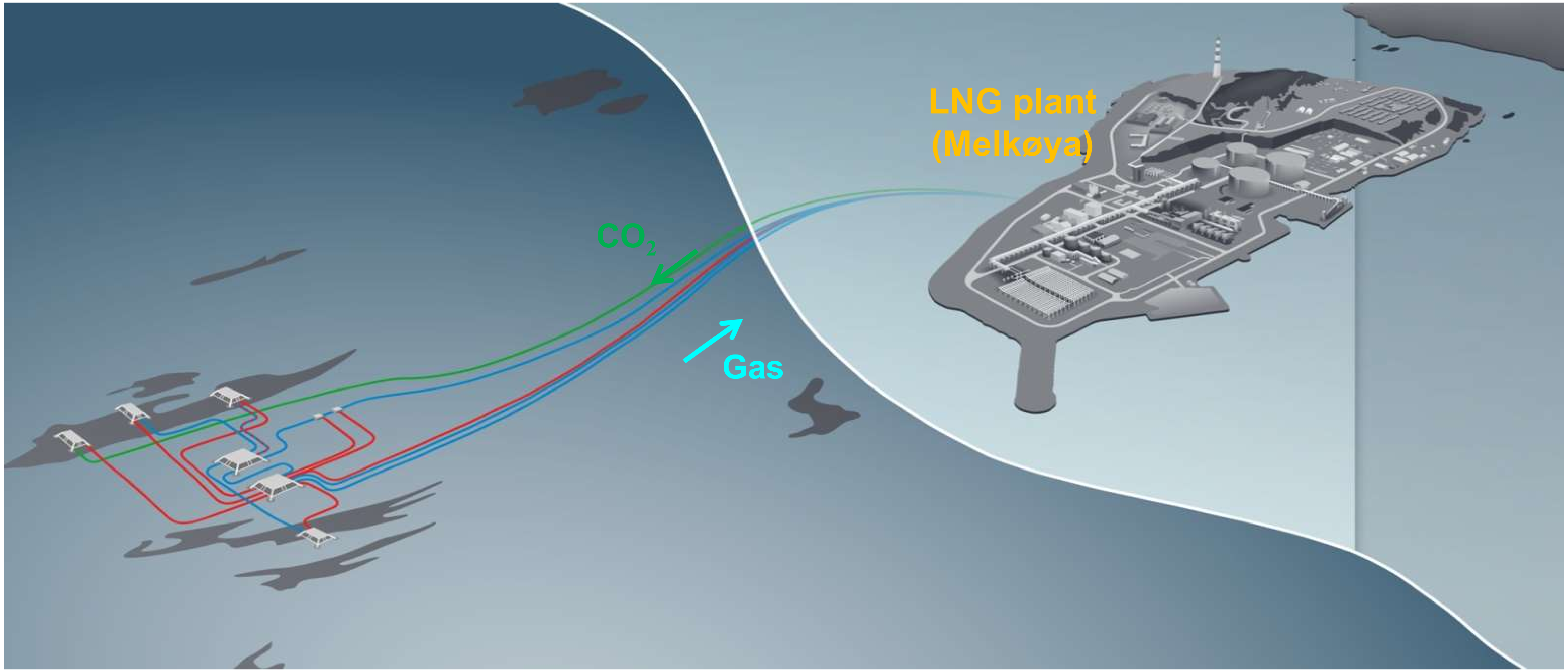


Seismic section (N-S) at Sleipner showing time-lapse amplitude-difference data when comparing 2010 and 1994 surveys. Modified from Furre et al. (2015)

Snøhvit CCS 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-)



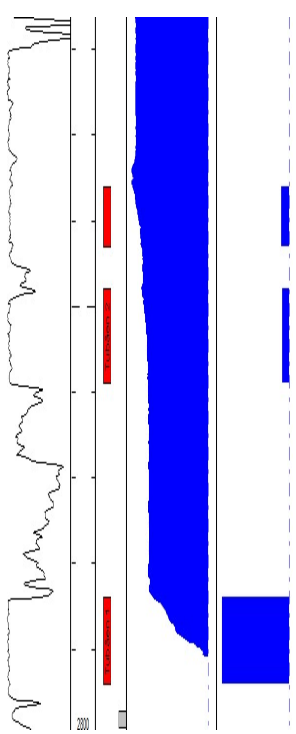
Monitoring the subsurface at Snøhvit

➢ Successful well intervention guided by monitoring data

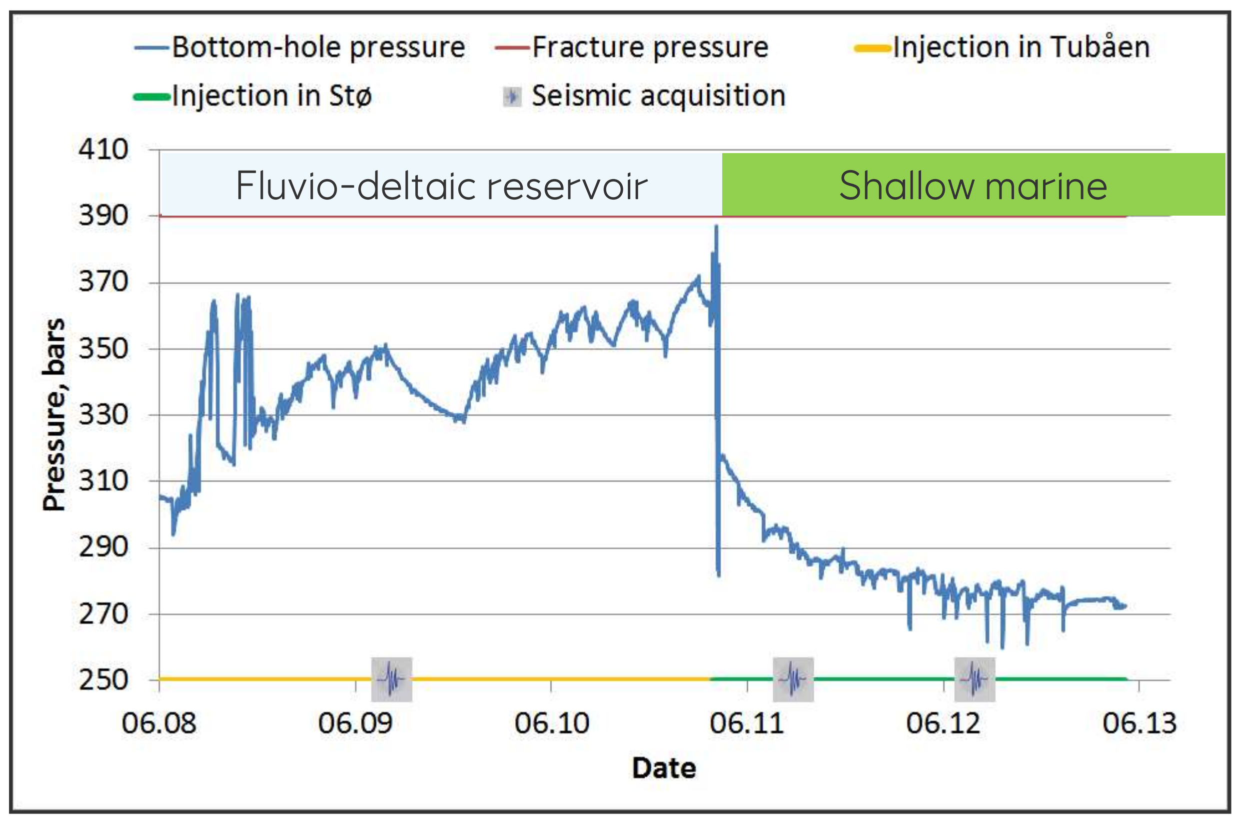
- Initial injectivity challenges mainly due to salt drop-out effect
- Rising pressure due to geological barriers led to well intervention
- Integrated use of geophysical monitoring and down-hole gauges
- Deployed back-up option in the injector well (modified completion)

➢ Demonstrates value of flexible well design

Down-hole data:
PLT flow log

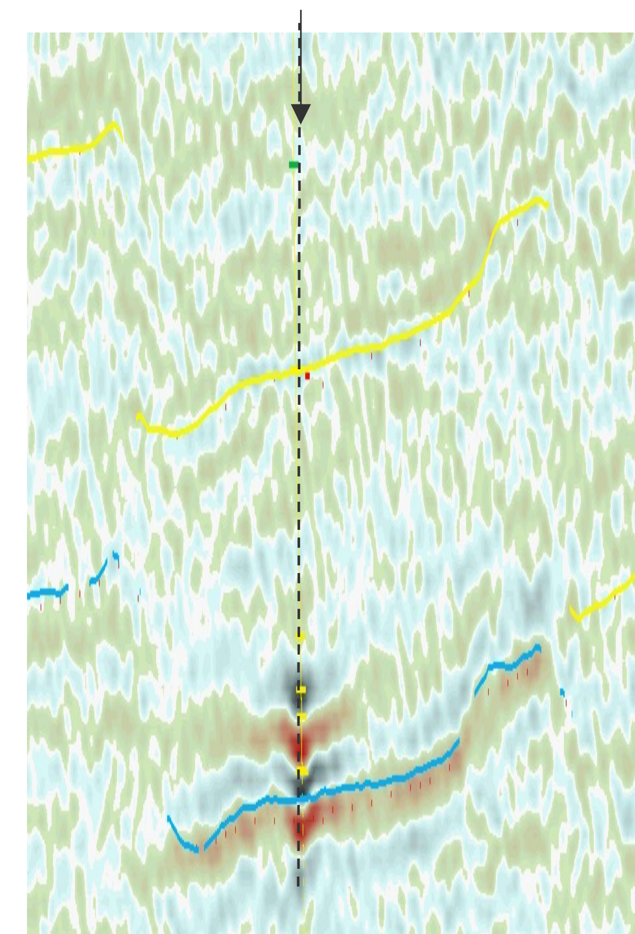


Down-hole pressure data

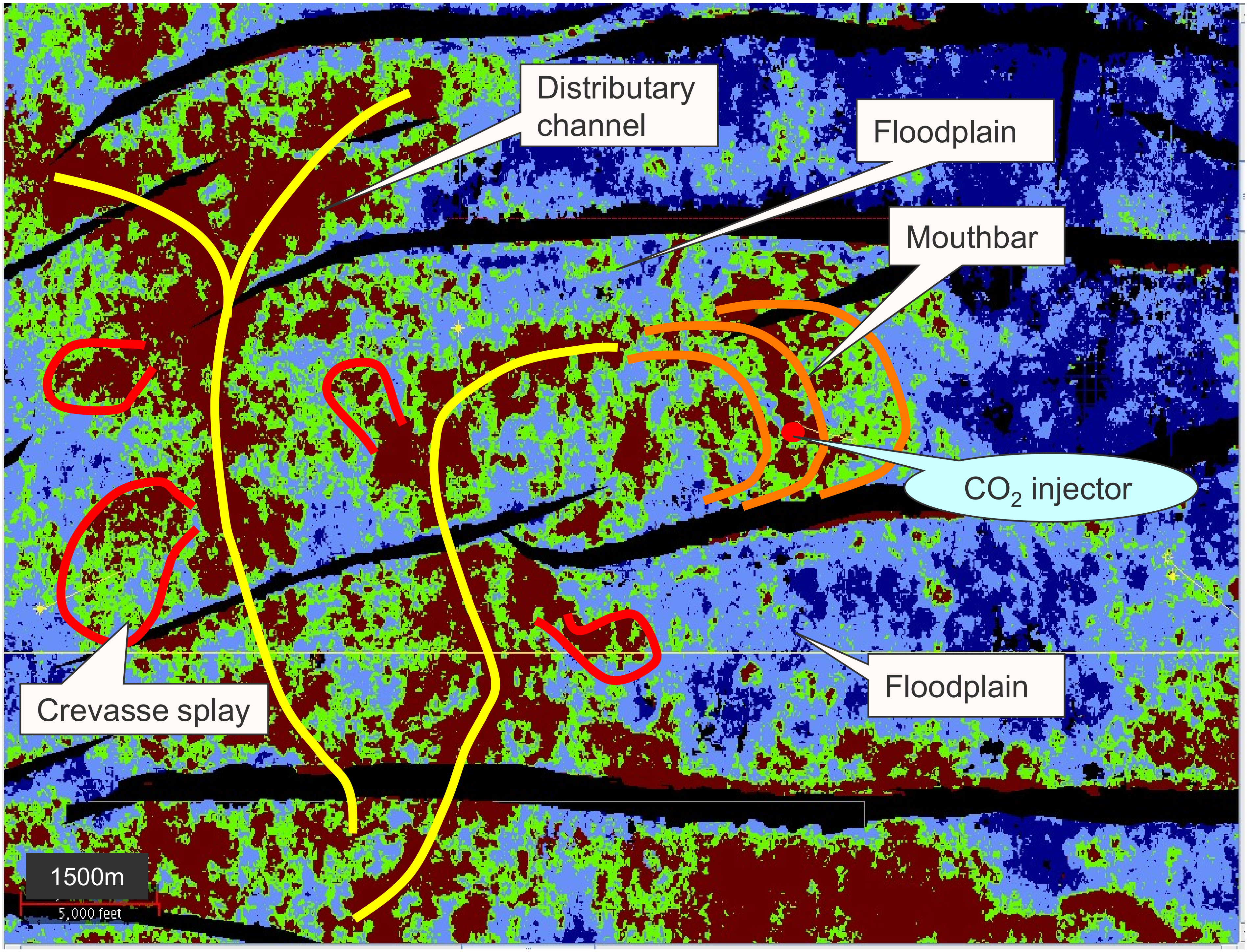


Hansen et al. 2013; Pawar et al., 2015

Time-lapse seismic
(Amplitude difference)



Geological surprises around the Snøhvit injector (F-2 H)



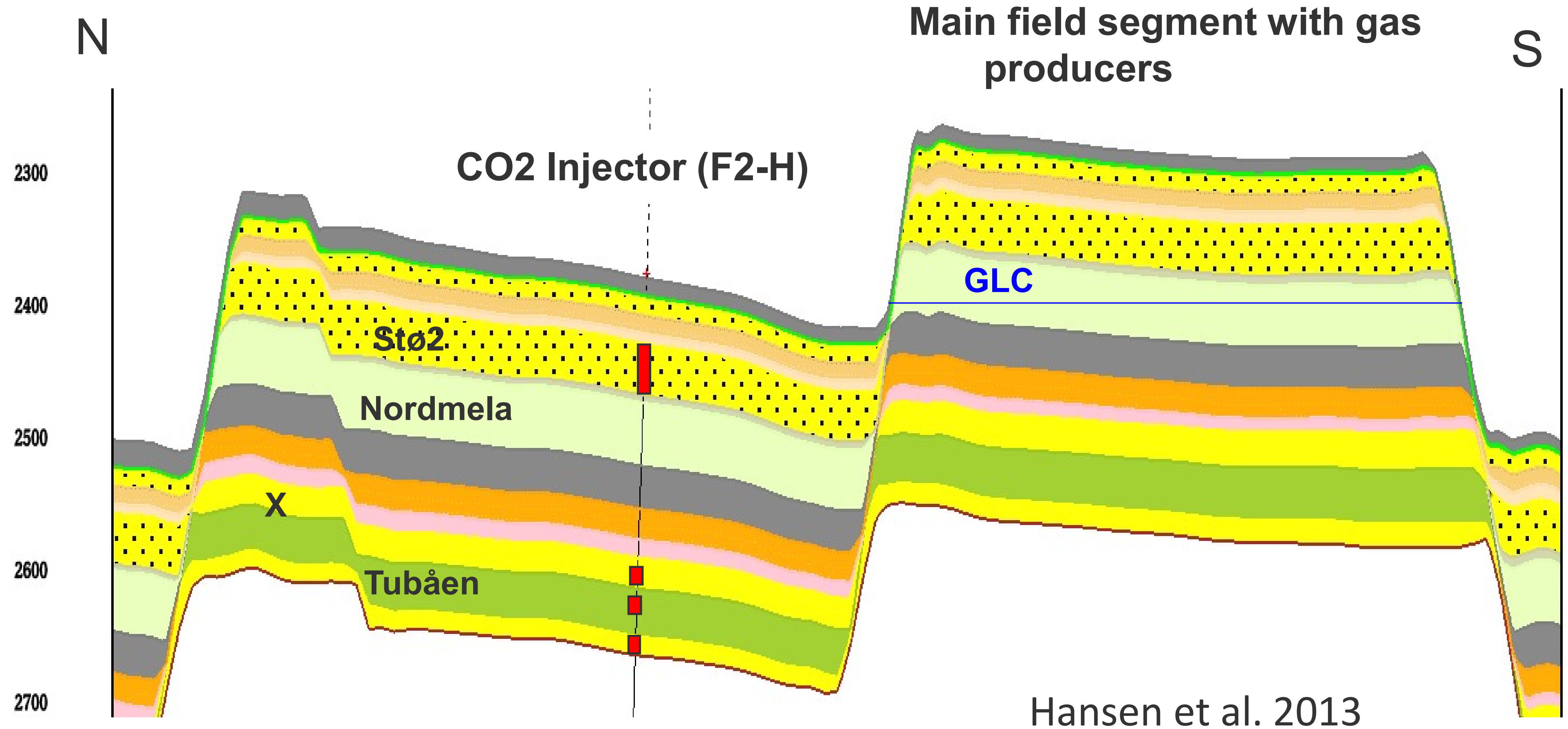
Tubåen Fm reflector at the Snøhvit CO_2 injection site:

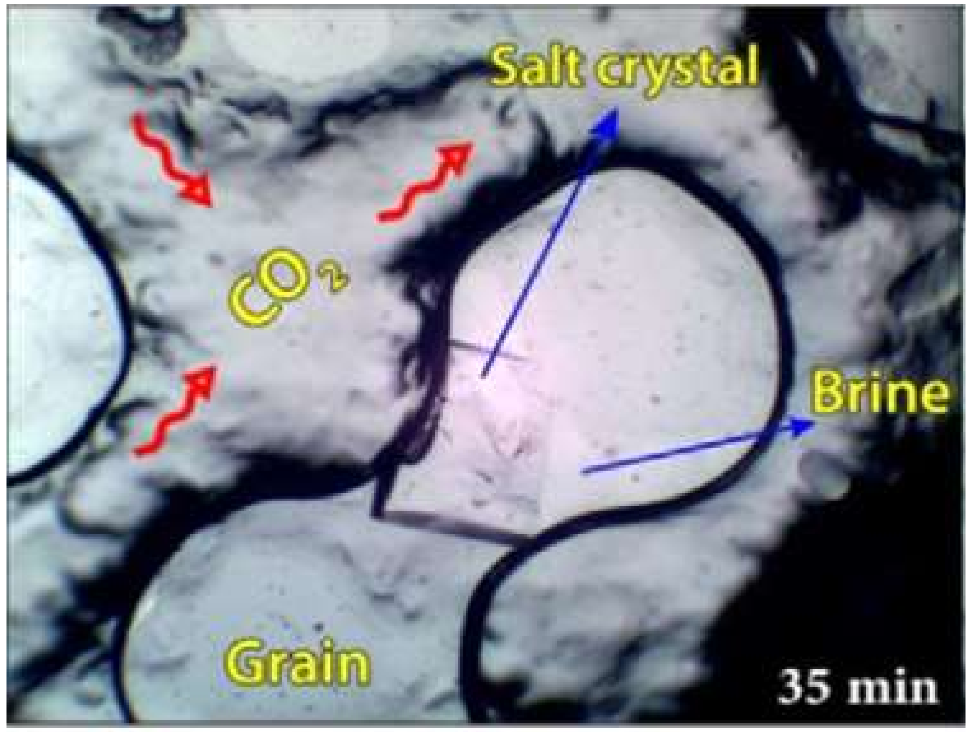
Acoustic impedance map annotated with depositional features related to the interpreted depositional environments (brown and green colours show higher acoustic impedance indicating higher sand fraction). Black features are faults.

Interpretation of well-test pressure data at Snøhvit which revealed the presence of a partial flow barrier at around 100m from the injection well and another barrier at around 3000m from the well (Hansen et al. 2013).

Snøhvit CO_2 injection history

- CO_2 injection into the Tubåen Formation until April 2011
- Injection then diverted into the Stø Formation following well intervention
- 6.5 Mt injected by end 2019 (1.1 Mt injected into Tubåen)
- Continuing stable injection of CO_2
- Second CO_2 injector G-4 H currently used to inject in Stø Fm





Example lab analysis of salt precipitation during injection of CO_2
Miri et al (2015)
IJGGC

Near-well bore damage effects probably a mix of salt drop out and fines migration

But how do we know if storage is safe in the long term?

1. There are many natural stores of CO_2 in volcanically active regions of the world:
   - Bravo Dome in New Mexico contains 1.6 Gigatons of CO_2 which has been there for approximately 1.3 million years (Sathaye et al. 2014. PNAS)
2. Humans (especially the Romans!) have been living alongside natural CO_2 vents for 1000's of years
3. Study of a 400-thousand-year-old leaky fault in a CO_2 volcanic region (Paradox Basin Utah) shows a maximum leakage rate of around 870 tonnes/yr - at the Crystal Geyser tourist spot! (Burnside et al. 2013; Geology, 41, 471-474)

So the most leaky fault on earth (in a volcanic region) is equivalent to annual emission of 100 Norwegians!

Natural CO_2 vent at Mefitiniella Polla, Italy. The seep has claimed animal lives but no human fatalities have occurred.
Photo from SCCS
http://www.sccs.org.uk/features/italyseeps.html

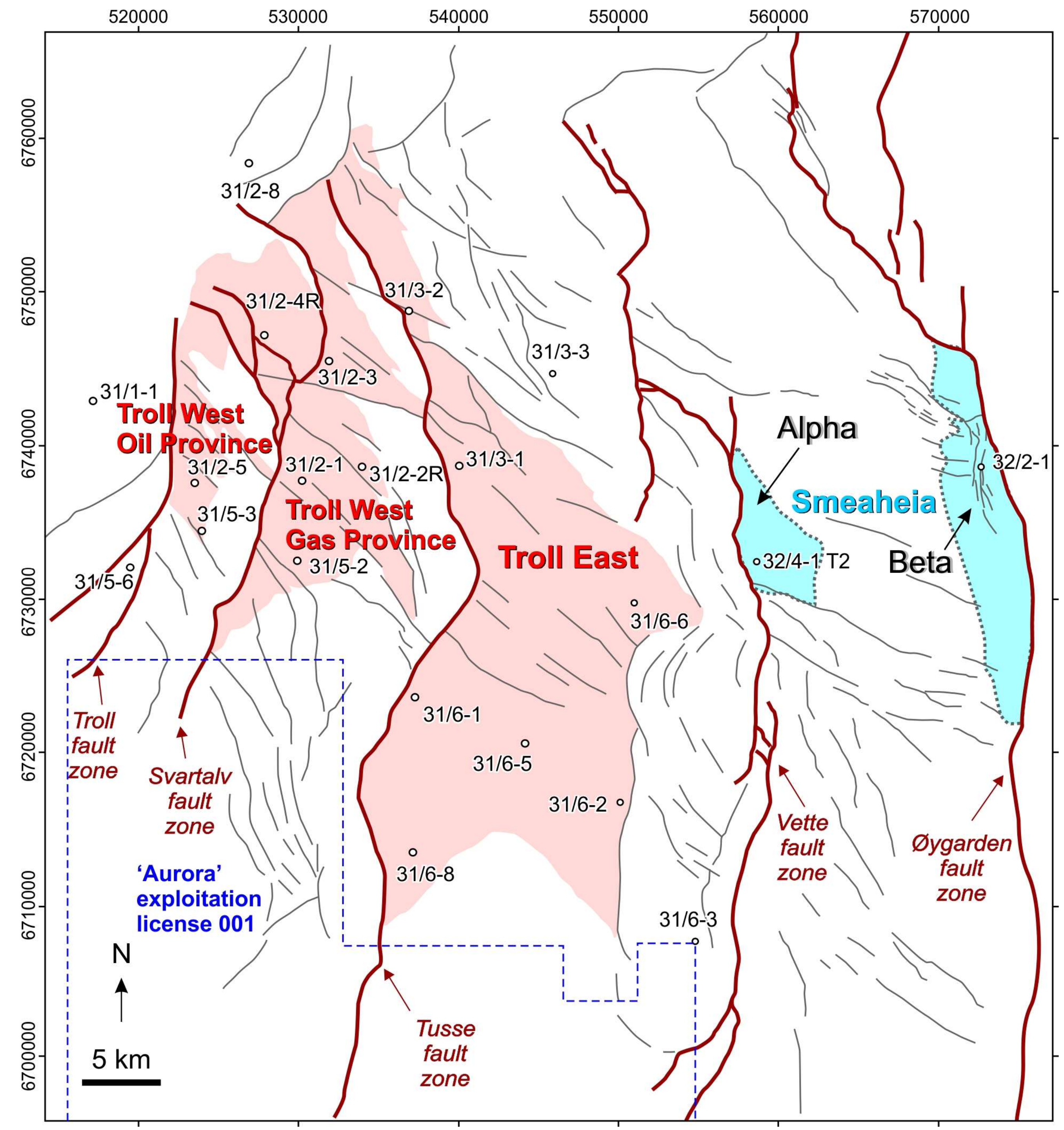
Quantifying storage risks

In support of the Northern Lights project and for future storage scale up, Equinor and many research and industry partners are working on:

- Fault mapping from seismic
- Fault seal and fault permeability
- Pressure communication
- 3D geological modelling
- Geomechanics and strain
- Micro-seismic monitoring
- Flow simulation

Maturing new prospects:

- This risk assessment is being used to mature new stores for future scale-up
- Northern Lights + +



Long Wu et al (2019), EAGE Fault & Top Seal Conference

Five main arguments regarding storage safety

1. The climate protection argument:
   'Putting CO_2 in deep geological formations is a lot safer and better than putting the same CO_2 into the atmosphere.'
2. The physical basis argument:
   'CO_2 is trapped in microscopic rock pores by the same process that has trapped natural gas for millions of years.'
3. The operational experience argument:
   'We know from more than 20 years of operations at Sleipner that CCS works.'
4. The geophysical monitoring argument:
   'We can see where the CO_2 is (with some uncertainty) and show it is safely stored in the intended reservoir unit.'
5. The regulatory compliance argument:
   'We can demonstrate regulatory conformance with the Norwegian and EU CO_2 storage directives.'

From Furre et al. 2019
Building confidence in CCS:
From Sleipner to the Northern Lights Project
First Break 37(7), 83-89.

Is large-scale CCS realistic? What would it take?

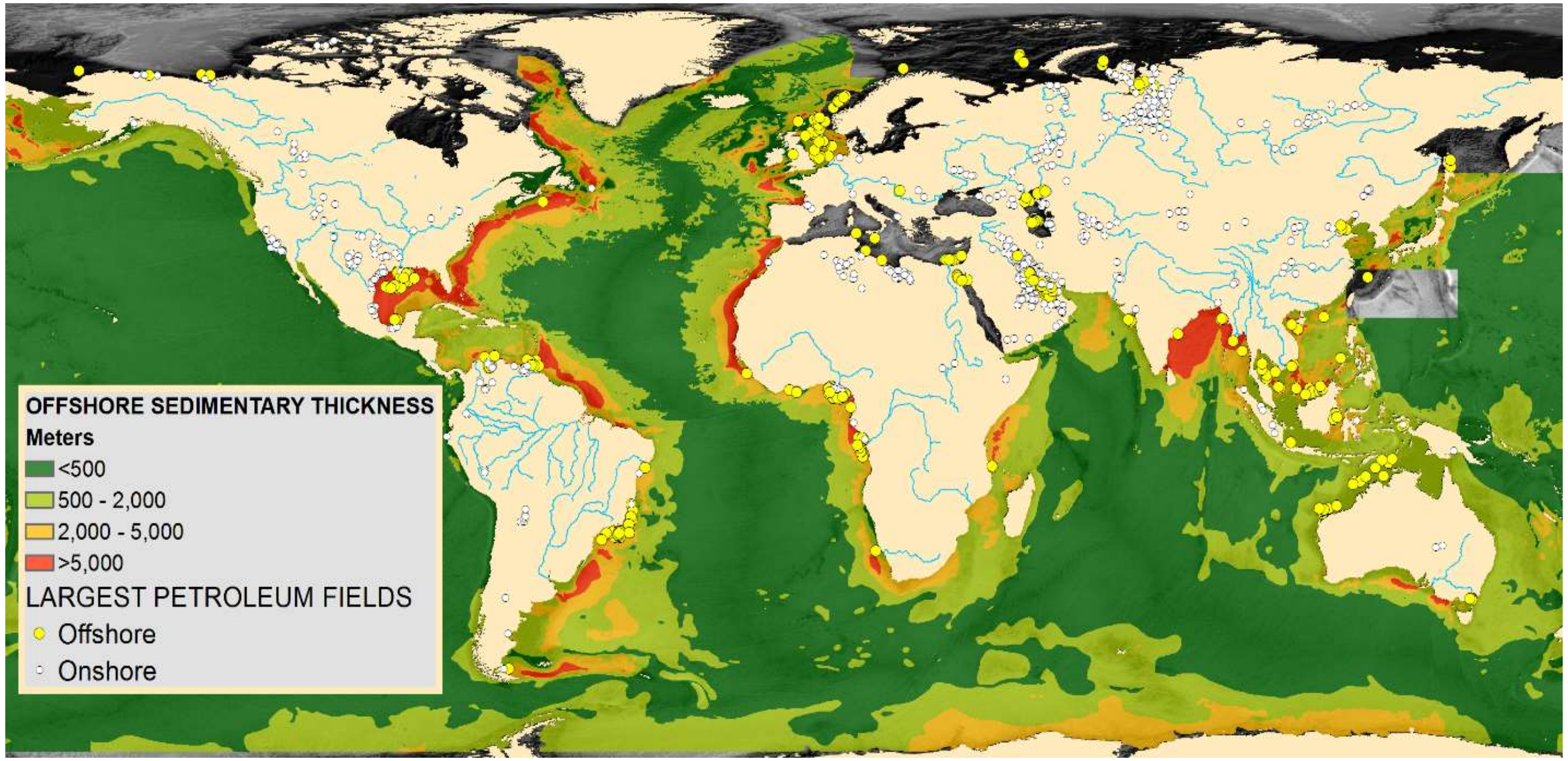
Recent study by Ringrose & Meckel, Scientific Reports (2019) on offshore global CO_2 storage resources
https://www.nature.com/articles/s41598-019-54363-z

- Uses basin geo-pressure approach
- Projected growth of CO_2 injection wells from historical hydrocarbon well developments
- Captures 'industrial maturation' phases for global CO_2 storage

Main Conclusion:

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

Each continental 'CCS hub' will need 100-200 wells in the next decade



Global distribution and thickness of sediment accumulations on continental margins, with largest oilfields and main river systems (Ringrose & Meckel, 2019)

Open

Concluding remarks

- Long track record of successful CCS operations offshore Norway
  - Important for validating and verifying storage concepts
- Storage operations and Sleipner and Snøhvit give valuable insights for future projects
  - Flexible well design for coping with 'geological surprises'
- Long-term geological storage risks are well studied (and very small)
  - Monitoring and site verification (conformance, containment) programmes are important
- Northern Lights project has clear scale-up pathway (from 1.5 Mtpa to >5Mtpa)
- Global scale-up of storage needs:
  - Requires ~12,000 CO_2 injection wells by 2050 to achieve 2DS goal
  - 'European CCS cluster' will need about 100 wells in the next decade

Open