CO_2 injection operations: Insights from Sleipner and Snøhvit

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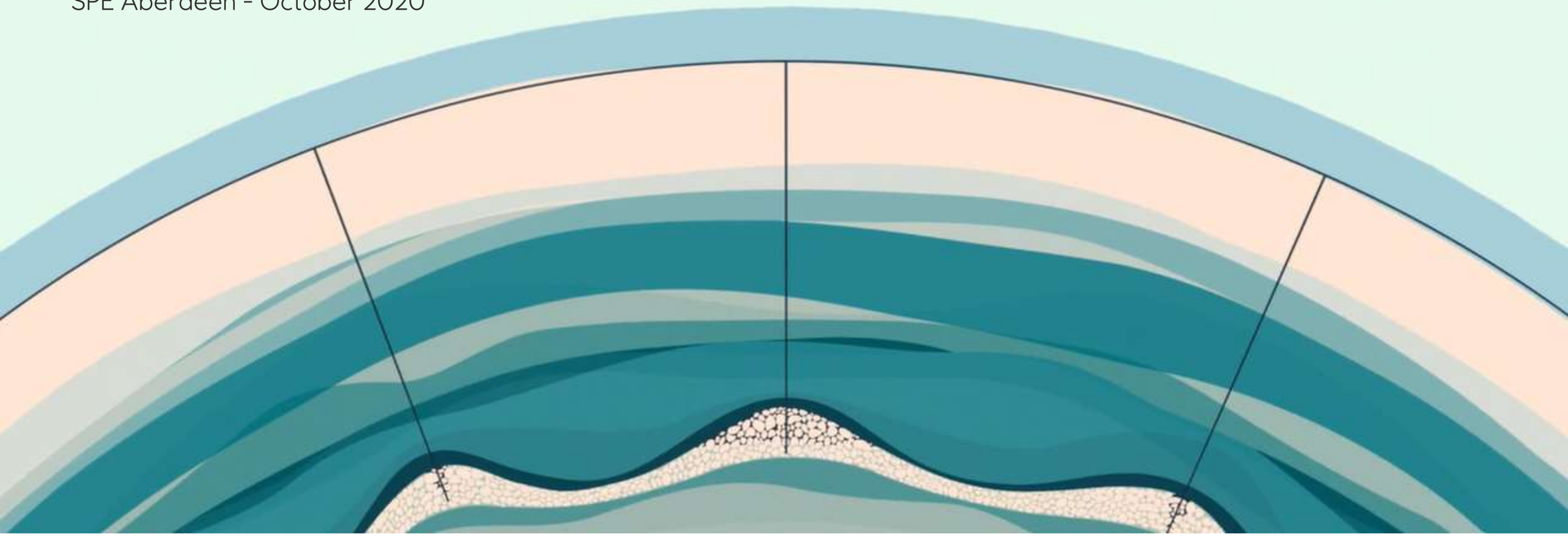


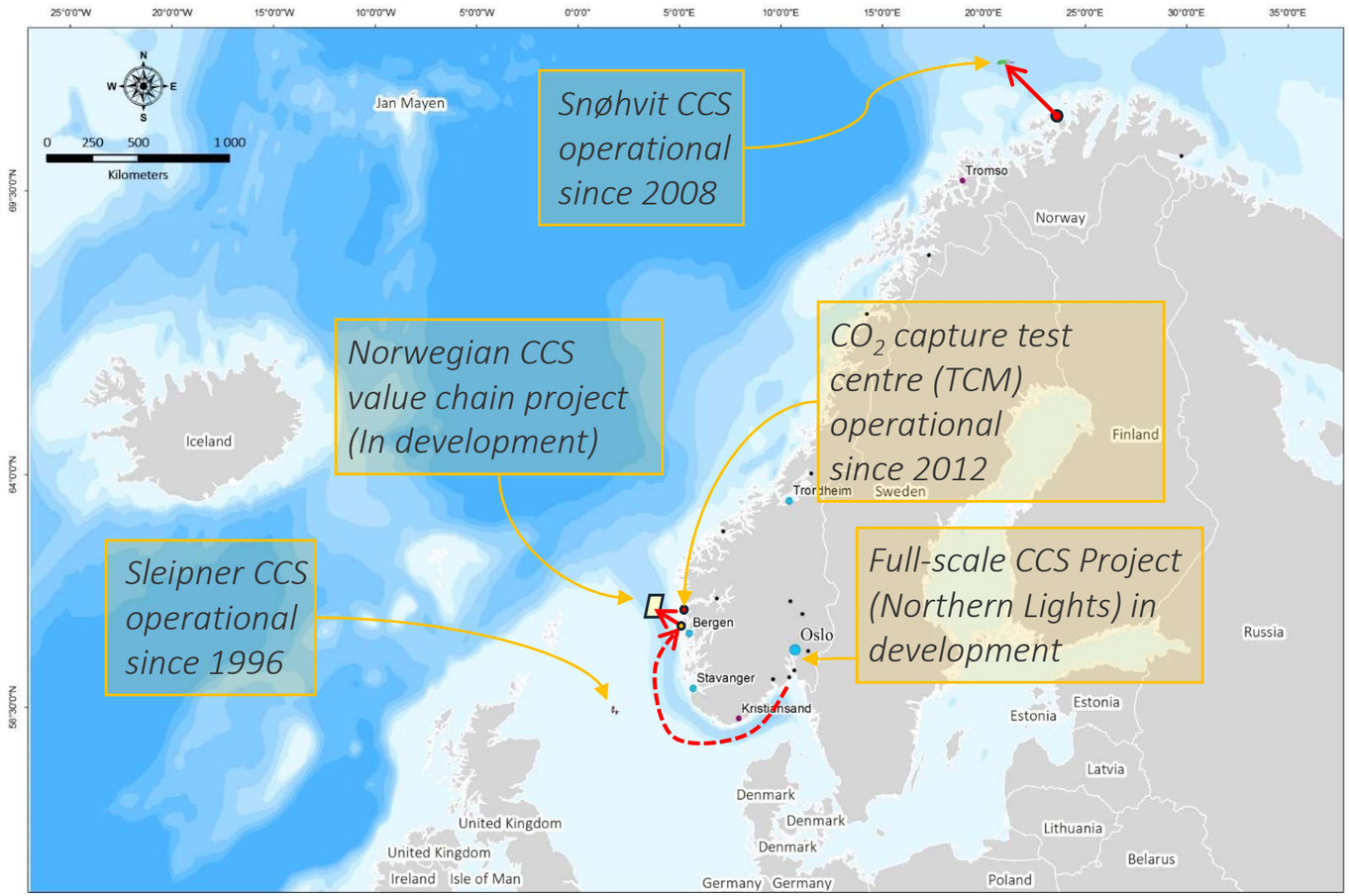
Summary CCS in Norway

Building on experience

- 23 years of operations
- >24 Mt CO_2 stored

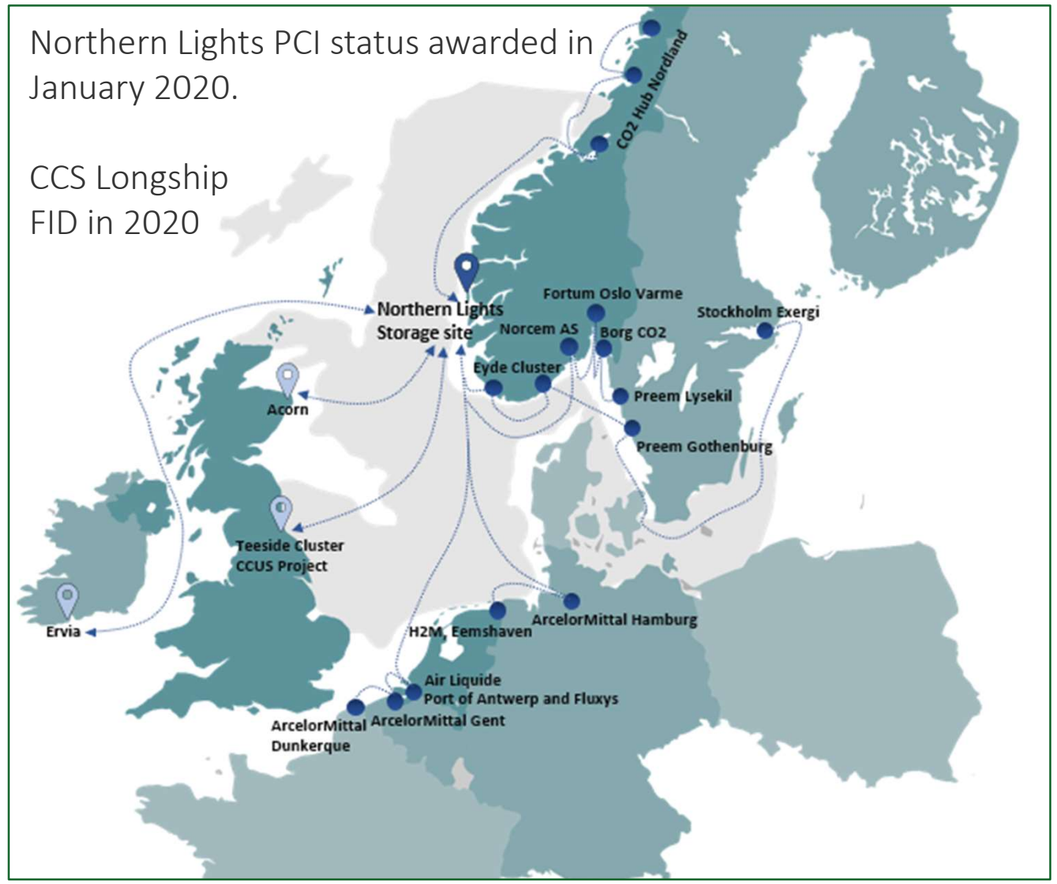
Supporting decarbonisation

- Open storage concept
- Incipient CCS hub



Northern Lights PCI status awarded in January 2020.

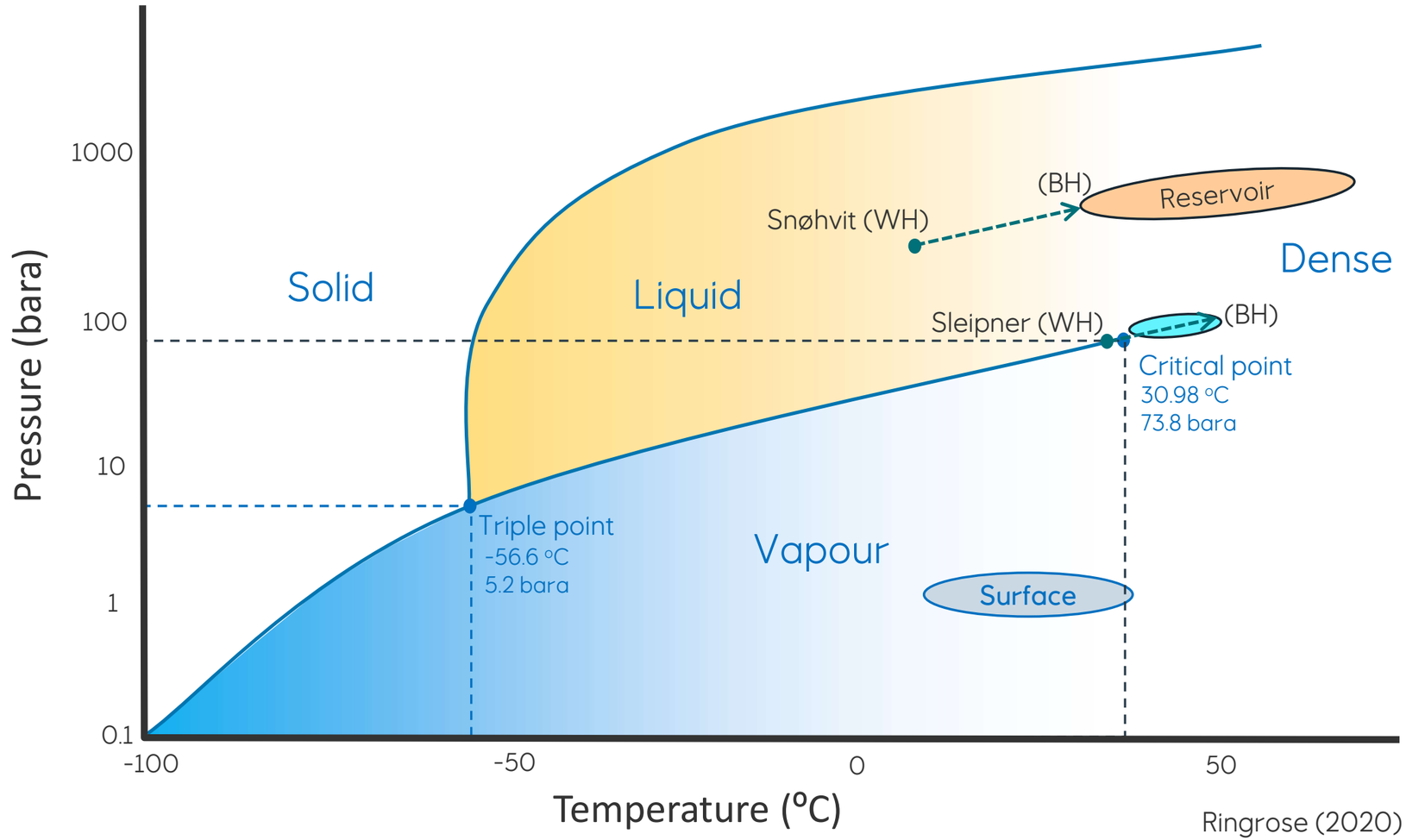
CCS Longship FID in 2020



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

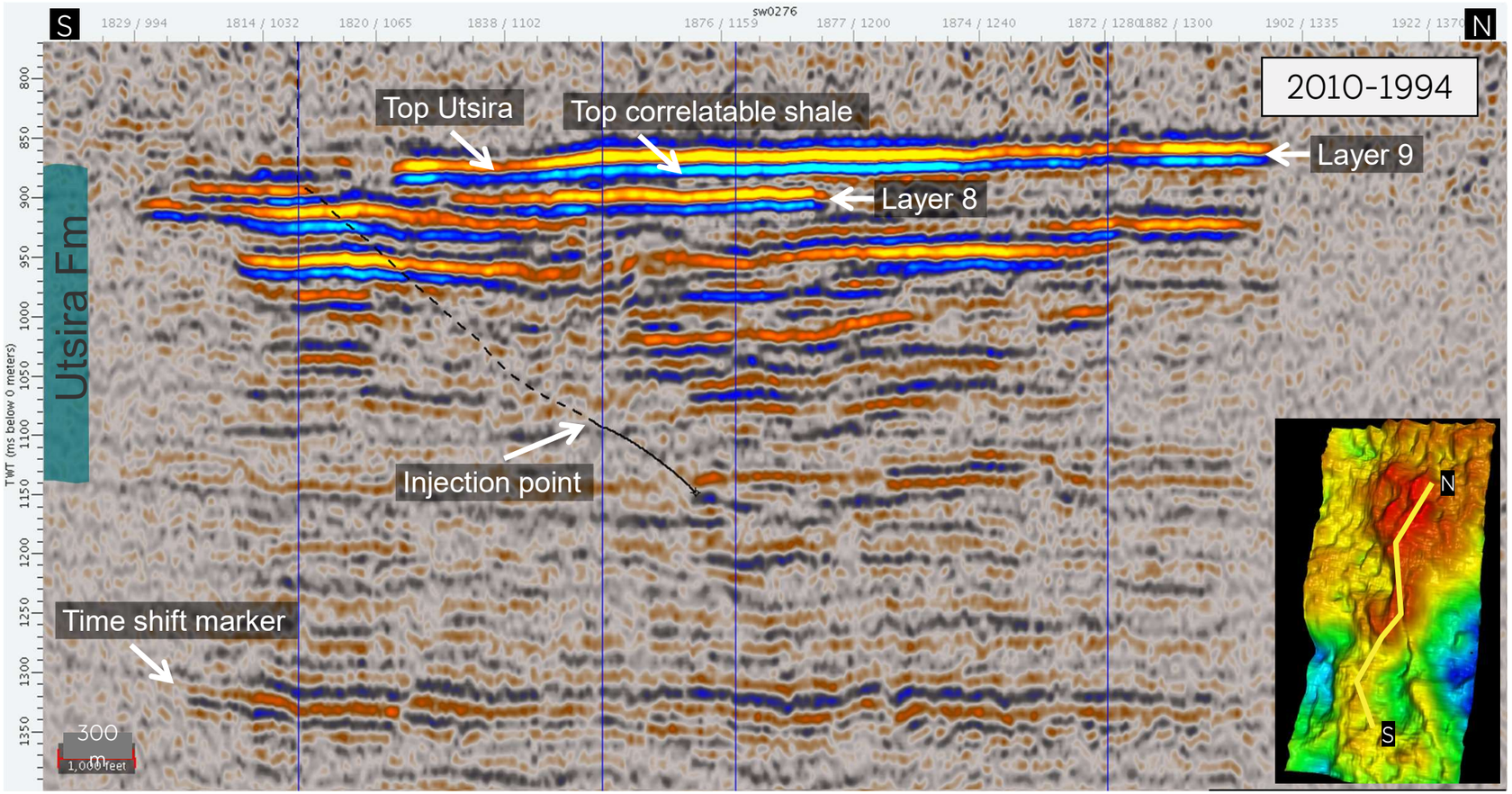


Ringrose (2020)

Seismic imaging of CO_2 plume at Sleipner

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

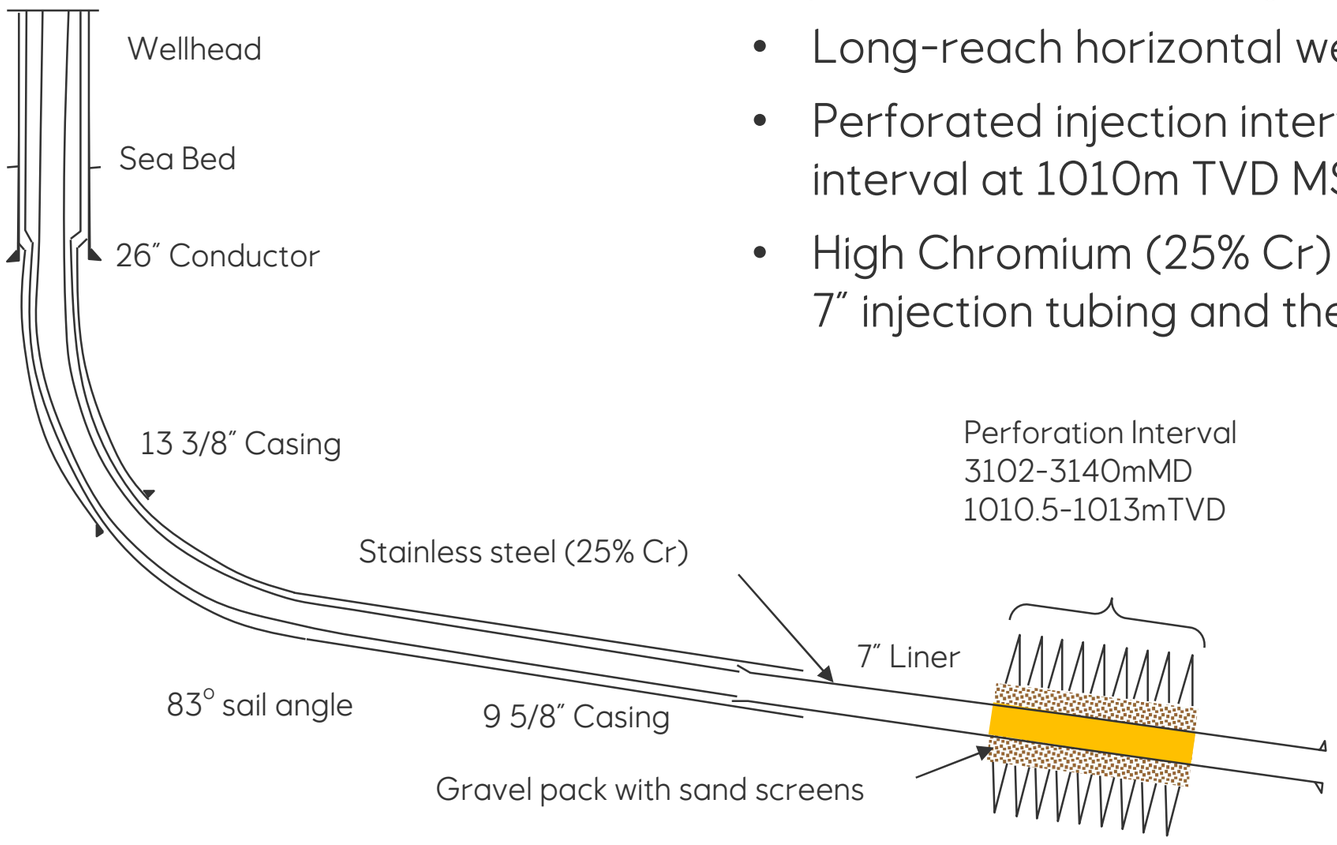
- Has informed researchers and operators about the 'physics of the storage process' (insights)
- Has been vital for convincing the authorities and the public about successful storage (conformance)



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

Sleipner CO_2 Injection Well Design

Long-reach horizontal well with stainless steel components has provided stable injection for 24 years



Sleipner CO2 injection well 15/9-A16 Hansen et al. 2005

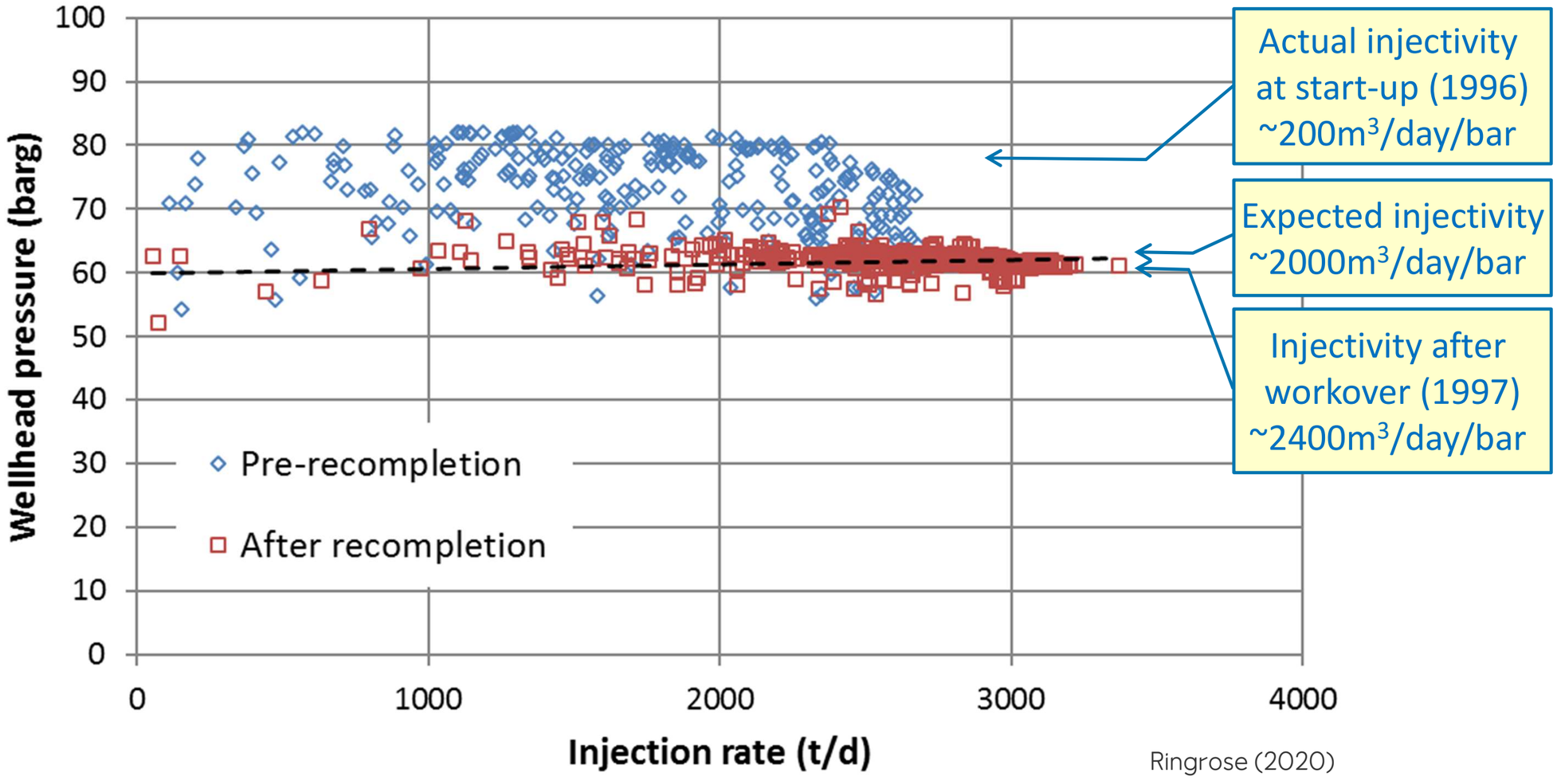
Key elements of the design:

- Long-reach horizontal well with a sail angle of 83°
- Perforated injection interval of 38m with the top of the injection interval at 1010m TVD MSL
- High Chromium (25% Cr) stainless steel was used for the 7″ injection tubing and the exposed sections of the 9 5/8″ well casing.

However, there were initial injection problems due to sand influx which were solved by re-perforation of the injection interval and installation of sand screen and gravel packs (as shown here) and described by Hansen et al. 2005

Start-up phase injectivity analysis at Sleipner

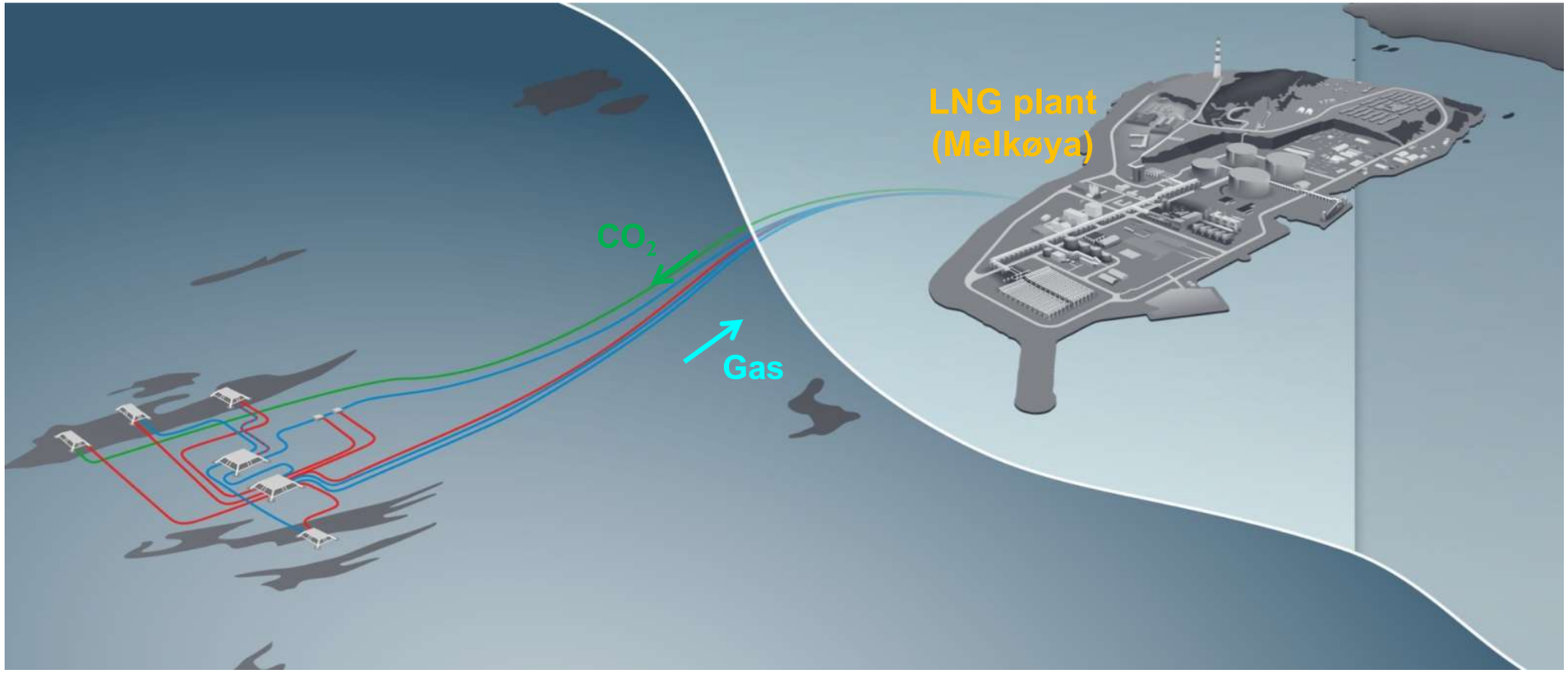
Sleipner injection data (1996-1999)



Ringrose (2020)

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-)



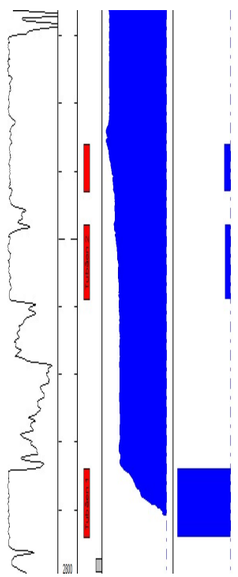
Monitoring the subsurface at Snøhvit

➢ 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)

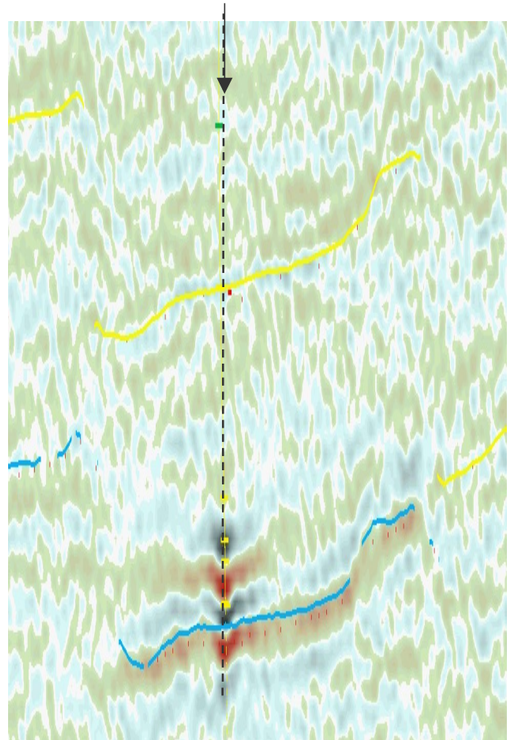
➢ Demonstrates value of flexible well design

Down-hole data:
PLT flow log



Down-hole pressure data

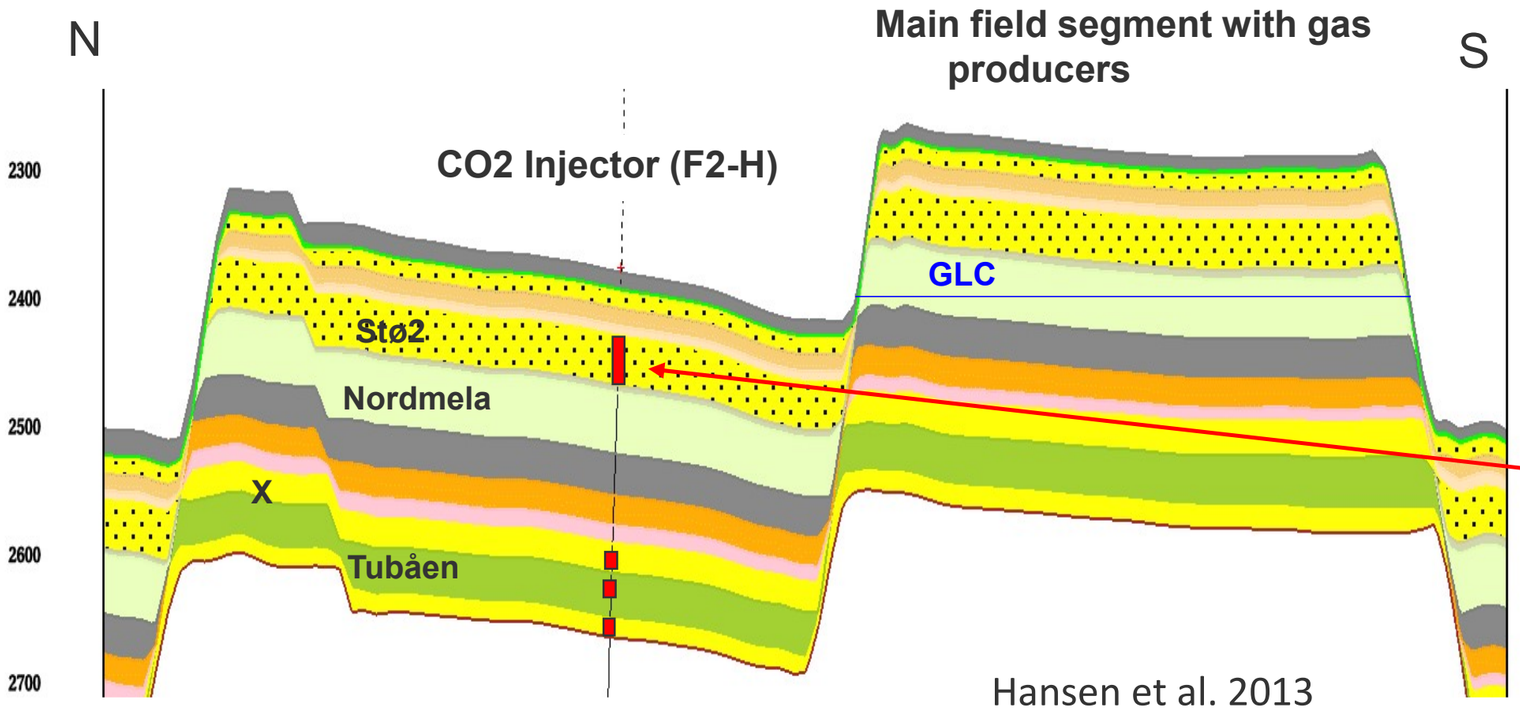
Time-lapse seismic
(Amplitude difference)



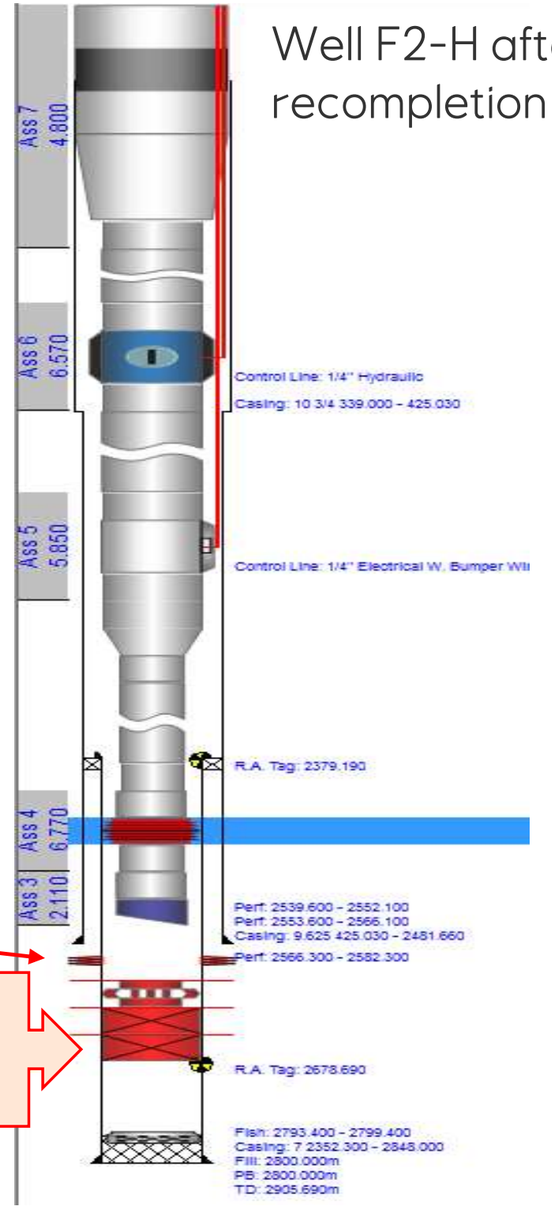
Hansen et al. 2013; Pawar et al., 2015

Snøhvit CO_2 injection history and status

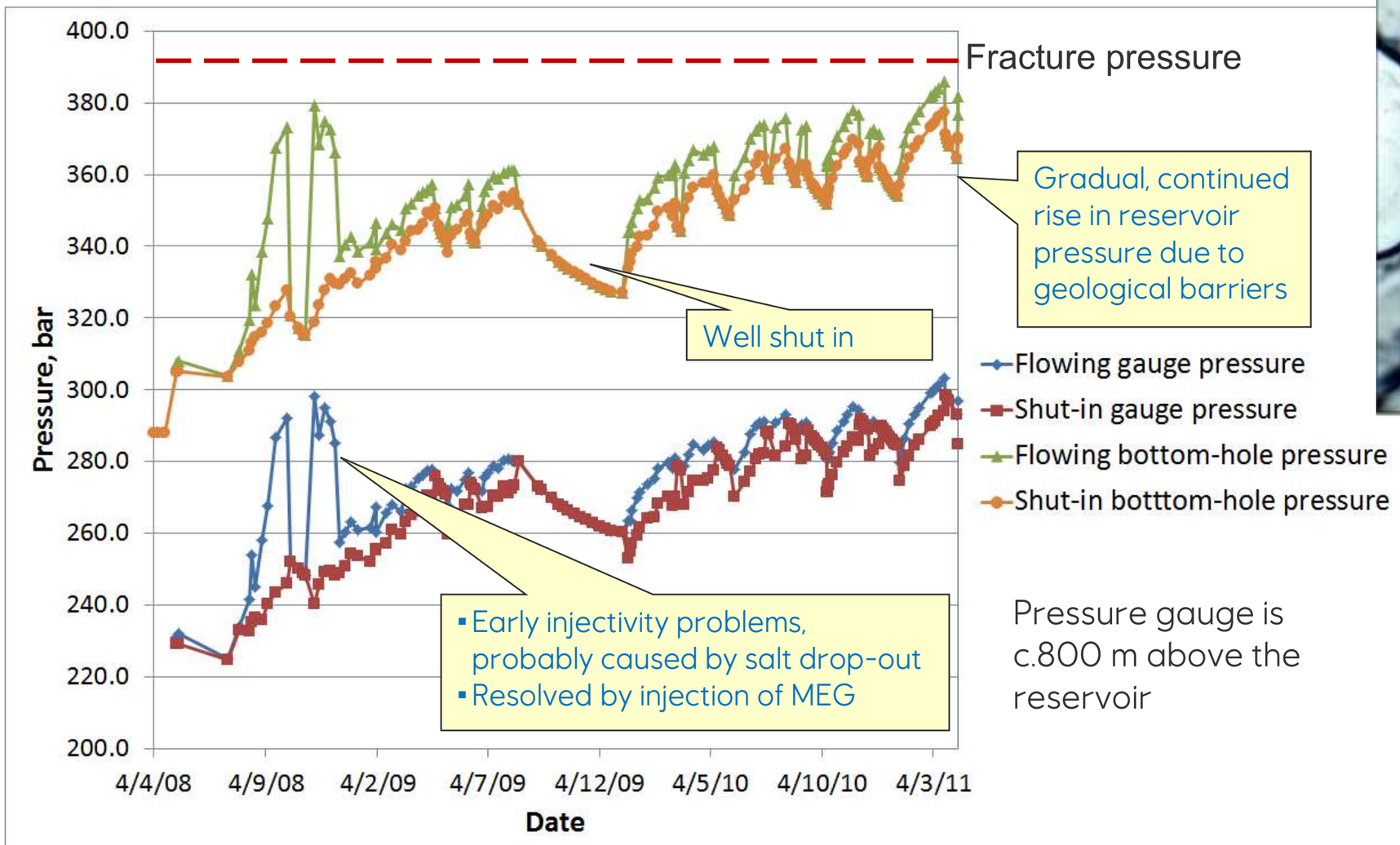
- CO_2 injection into the Tubåen Formation until April 2011
- Injection then diverted into the Stø Formation following well intervention
- 6.5 Mt injected by end 2019 (1.1 Mt injected into Tubåen)
- Continuing stable injection of CO_2
- Second CO_2 injector G-4 H currently used to inject in Stø Fm



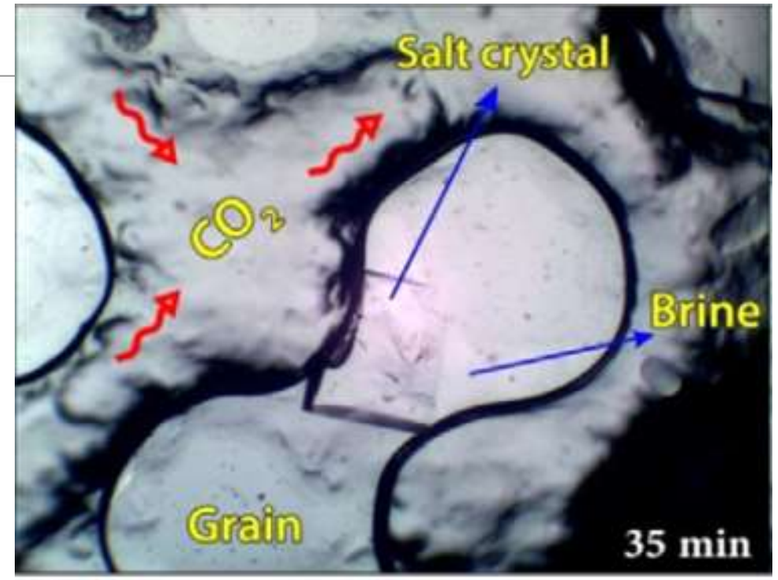
Hansen et al. 2013



Snøhvit Injection pressure history



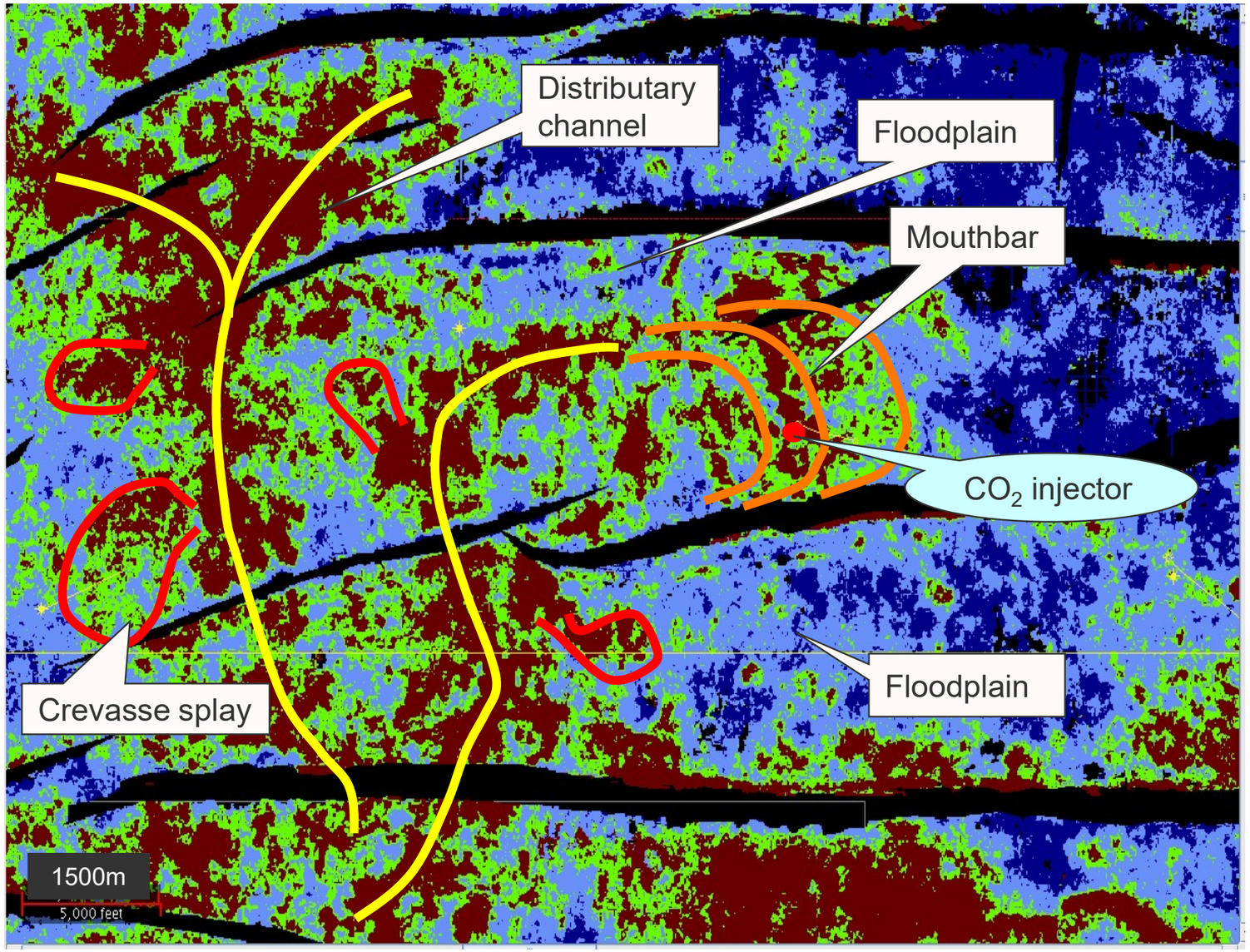
Pressure gauge is c.800 m above the reservoir



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

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).

Summary

- Long, valuable experience with CO_2 injection wells will be useful for future projects
- Phase-behaviour and thermal setting essentially define the injection project's "identity" and inform well-design choices
- Early injection challenges at both Sleipner and Snøhvit were resolved using well interventions
- Geological and geochemical surprises should be expected with CO_2 injection wells
- Flexible well design and planning can effectively handle these challenges

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