Monitoring for offshore storage
What we have learned from 19 years of operations

Philip Ringrose

Statoil ASA, Trondheim, Norway

US DoE Carbon Storage R&D Project Review Meeting
Pittsburgh, PA, 18-20 August 2015

The big questions for CO_2 monitoring

- What type of monitoring is really necessary?
- Several stakeholder viewpoints:
  1. What is important from an operational point of view?
  2. What is required from a regulatory perspective?
  3. What is in the public interest?
- In response to these questions CO_2 storage projects have developed fit-for-purpose approaches to monitoring.
- The biggest technical challenge is that projects need to monitor:

  the reservoir (saline formations)

  … and the overburden

  … and the regional surface area

  … and the facilities

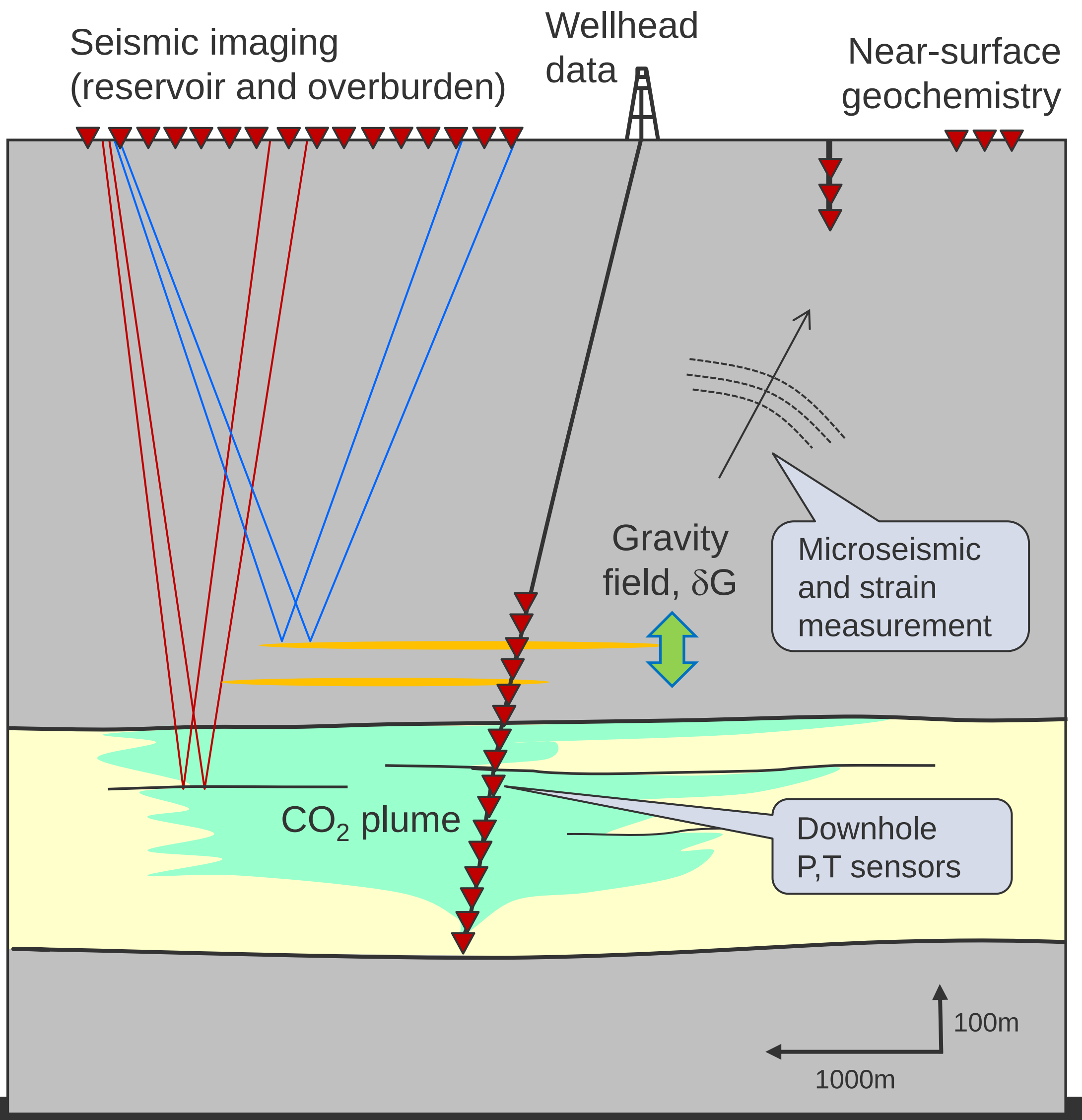
  … and plans for post site closure

With a limited budget!

Ideal CO_2 storage monitoring portfolio

So what should the CO_2 monitoring portfolio look like?

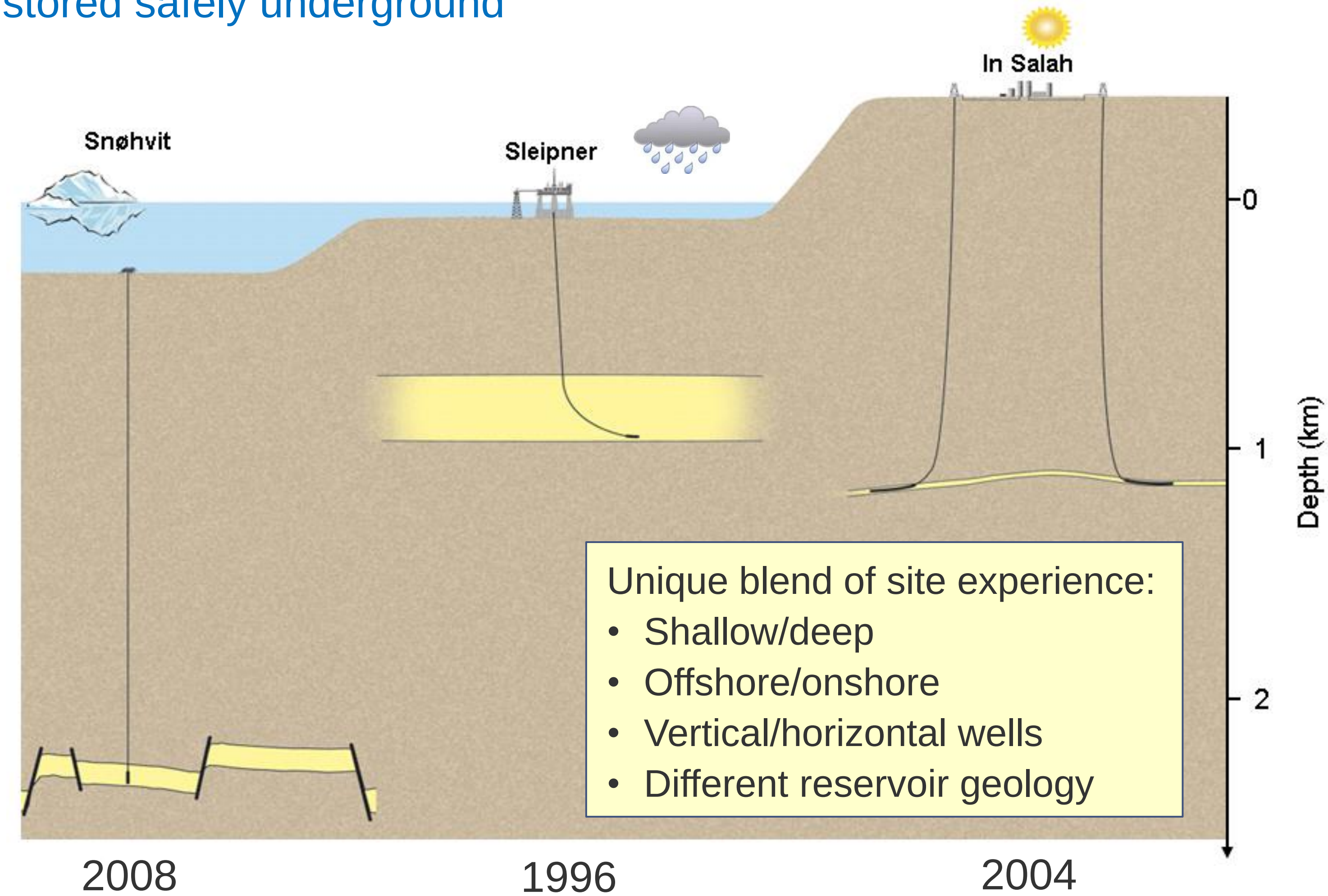
- Geological characterisation
- Standard wellhead and downhole measurements
- Distributed fibre-optic P, T and accoustic sensing
- Low footprint surface seismic nodes – passive & active
- Gravity field monitoring
- Surface gas detectors
- Remote sensing: e.g. InSAR or seabottom sonar
- With significantly lower costs than today



Ringrose 2013

Statoil CO_2 storage projects

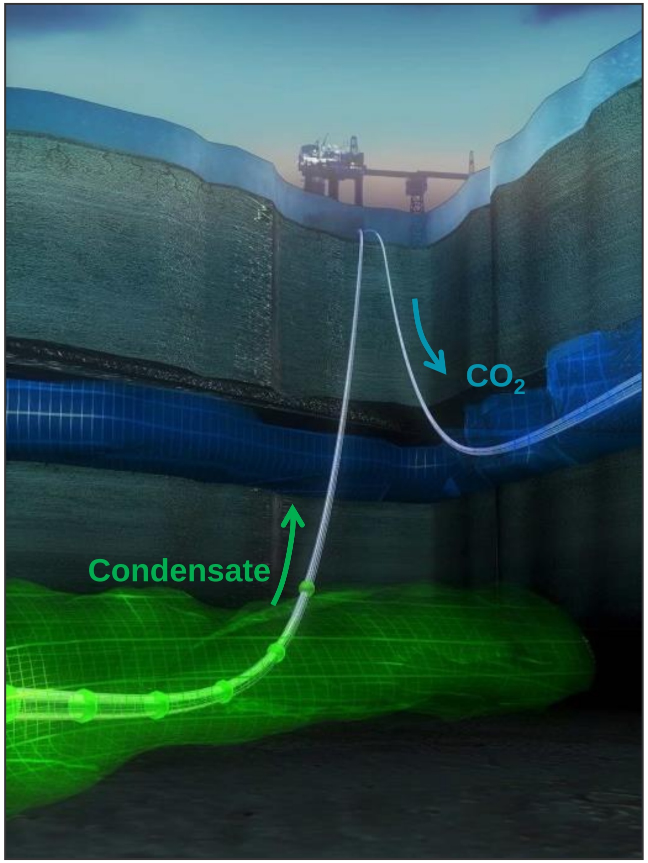
- 22 Mt CO_2 stored safely underground

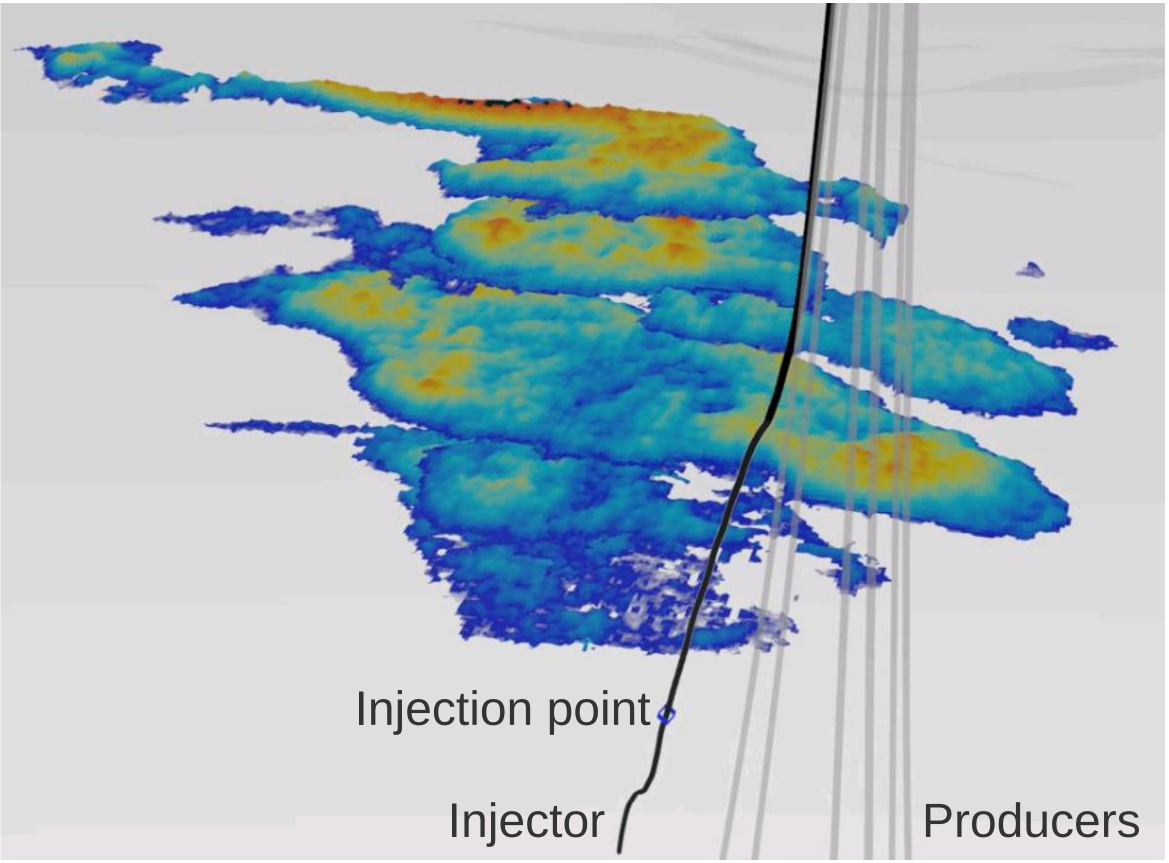


Eiken et al., 2011

The pioneering CCS project at Sleipner

- Confirming the feasibility of geological storage of CO_2
- Demonstrating the value of seismic imaging for monitoring
- Making a strong case for remote geophysical monitoring as the key tool





Furre et al., 2015; Kiær et al., 2015

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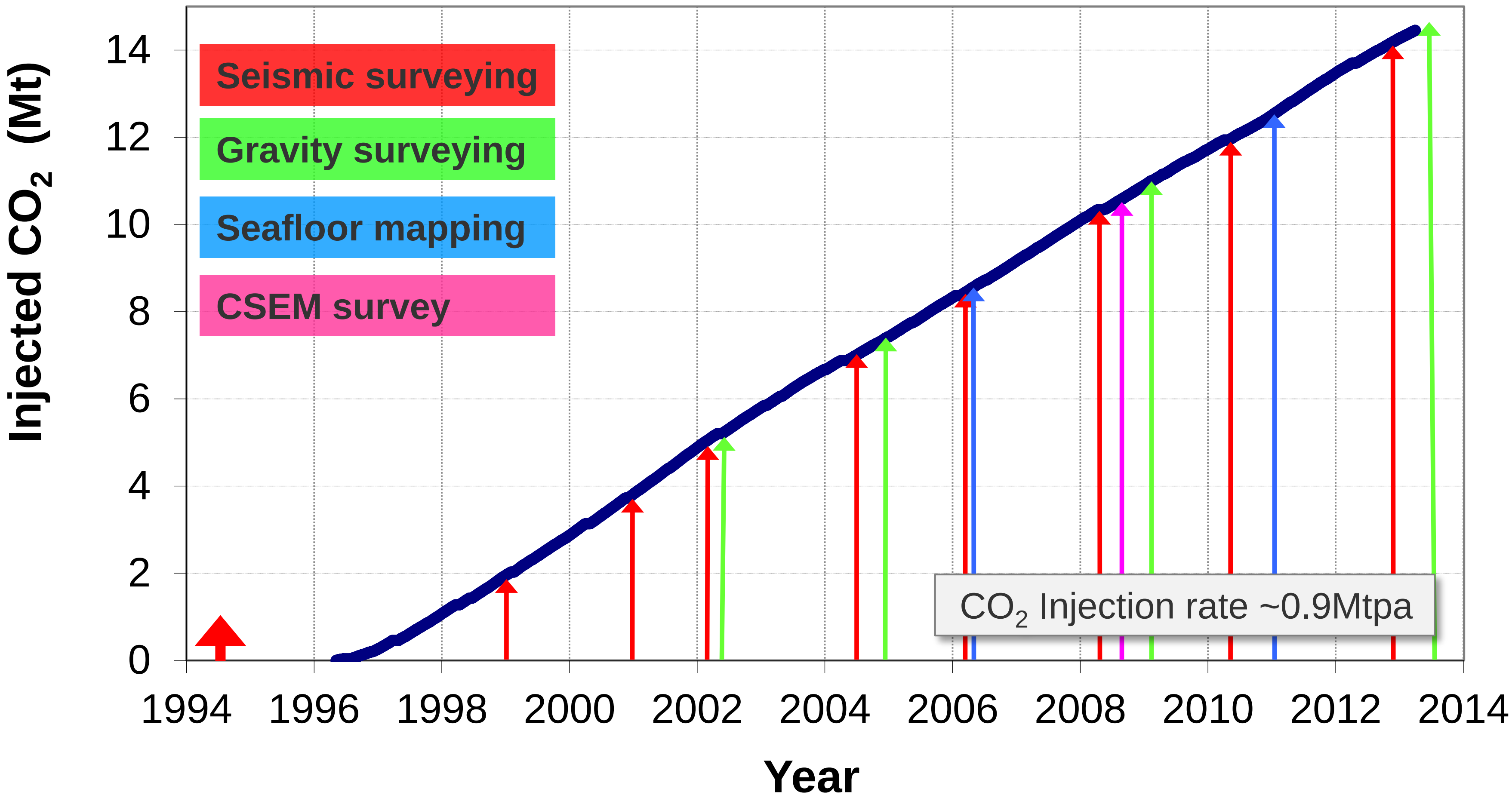
Sleipner injection and monitoring history

- Cost-effective monitoring and geophysical portfolio design



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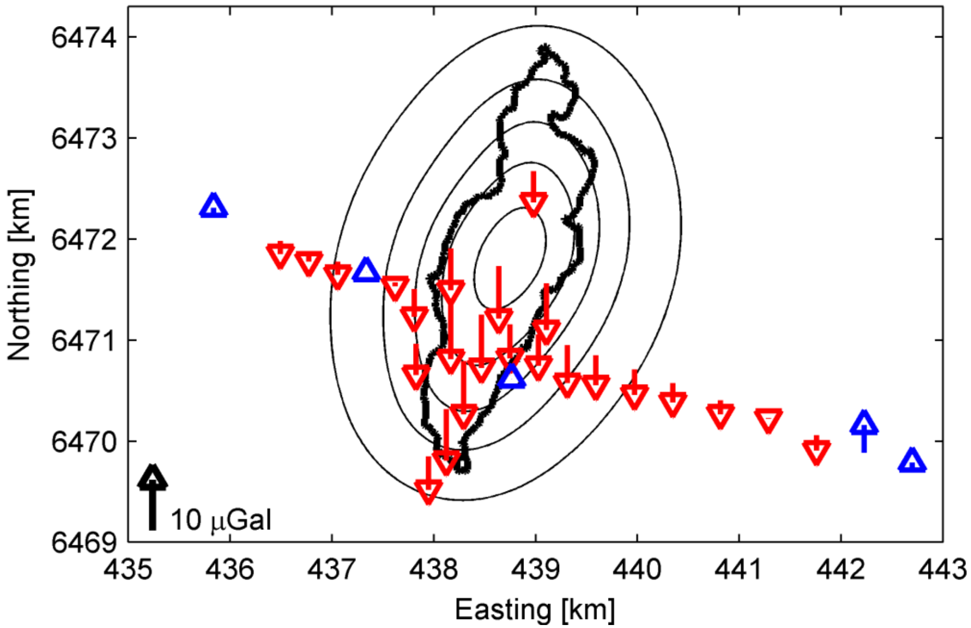
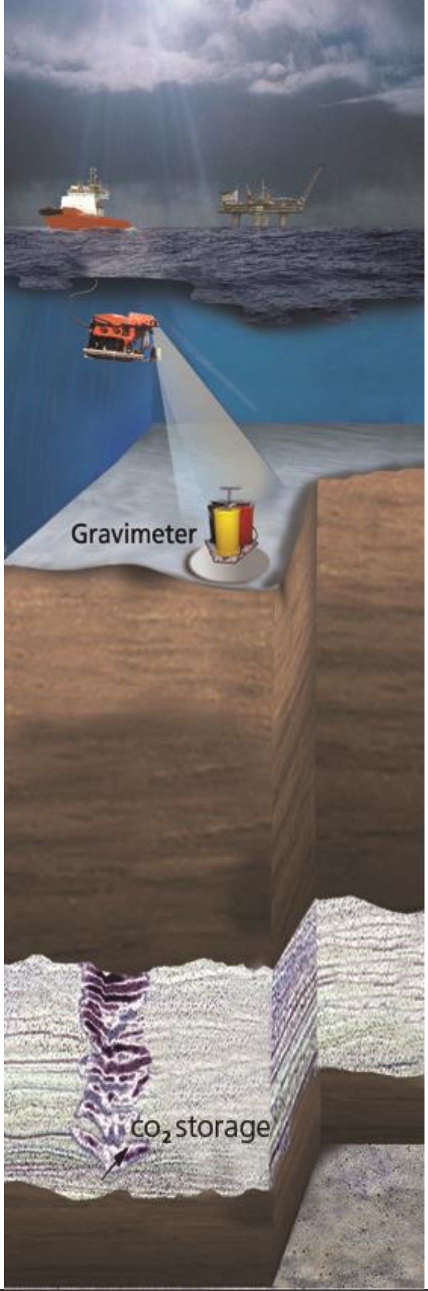
Sleipner gravimetric monitoring

- Developed accurate offshore gravity monitoring technology
  - Precision of ~2-3 μGal in time-lapse signal achieved
  - Valuable complement to 4D seismic
- Alnes et al. (2011; pers comm) use gravity data to estimate:
  - Average in-situ CO_2 density of 720 $\pm$ 80 kg/m^3
  - Upper bound on the dissolution rate of 2.7% per year





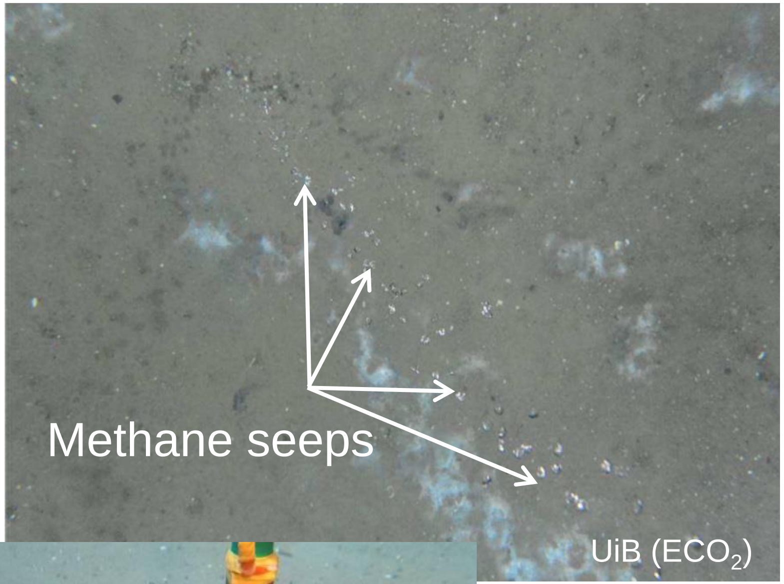
Alnes et al, 2011

Sleipner seabed/marine monitoring summary

- Initial site survey and yearly scanning near pipelines
- 2006: Sleipner dedicated echo beam and sidescan sonar surveys
- 2011, 2012, 2013 – ECO_2 Research programme surveys:
  - Sidescan sonar
  - Bathymetry
  - Water column surveillance
  - Water and sediment sampling

Current technology status is about developing best practice and understanding potential impacts (e.g. Jones et al., 2015)

HD photo mosaic around abandoned exploration well 15/9-11



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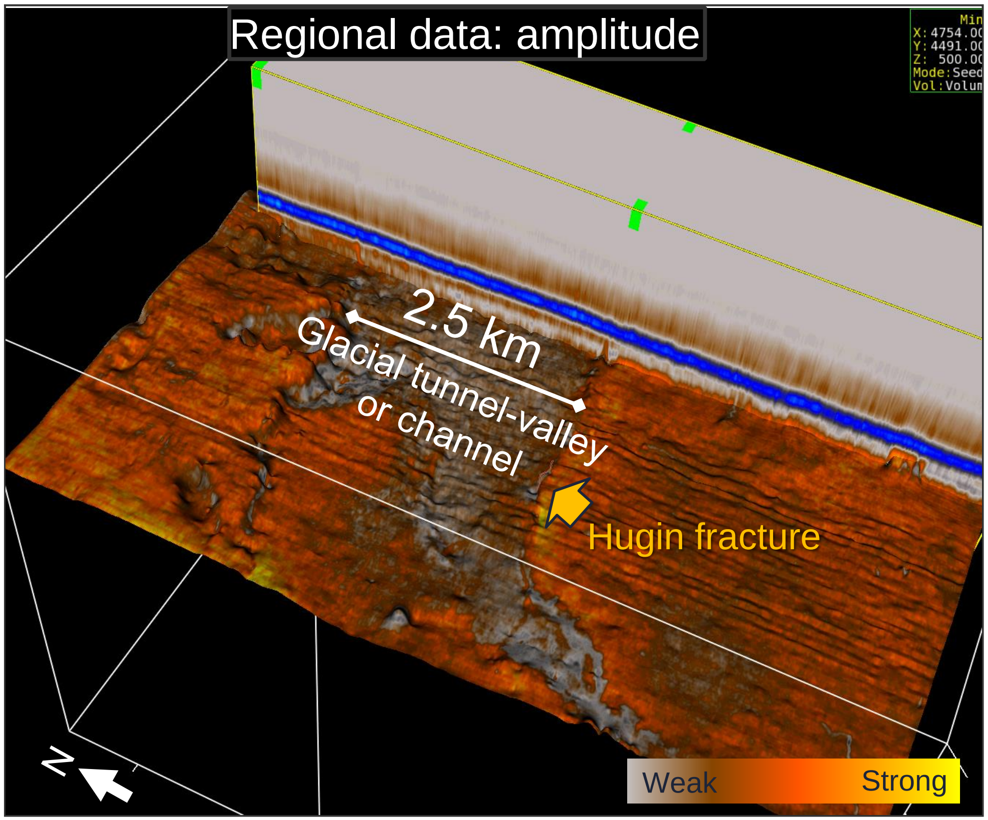
Regional mapping of shallow seismic features

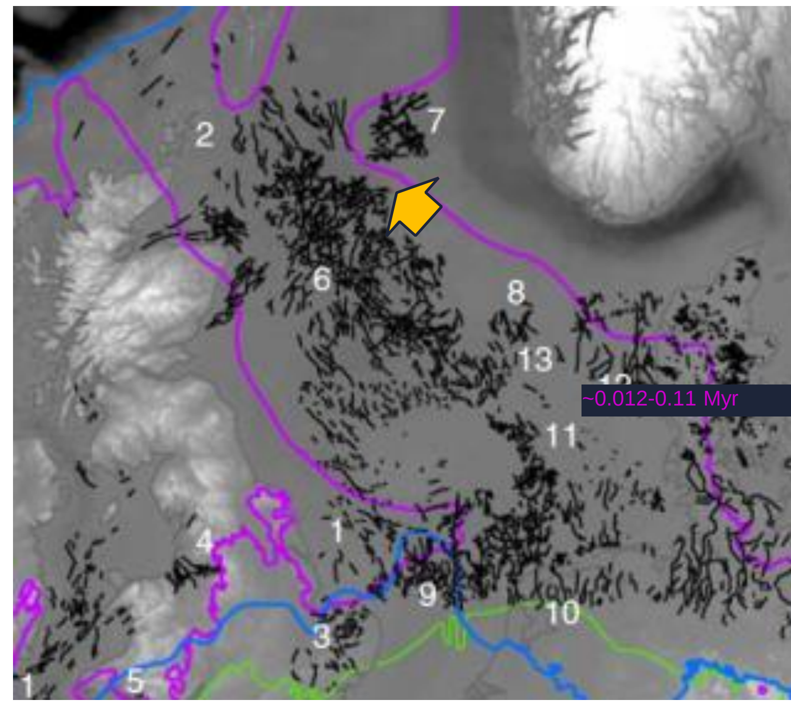
Public interest in seabed feature (Hugin fracture) 25km north of Sleipner (2013):

- Storage integrity assurance will need regional mapping and analysis to better understand glacial processes and their impact on the shallow rock system

Analysis of shallow seismic data (Furre et al., 2014)

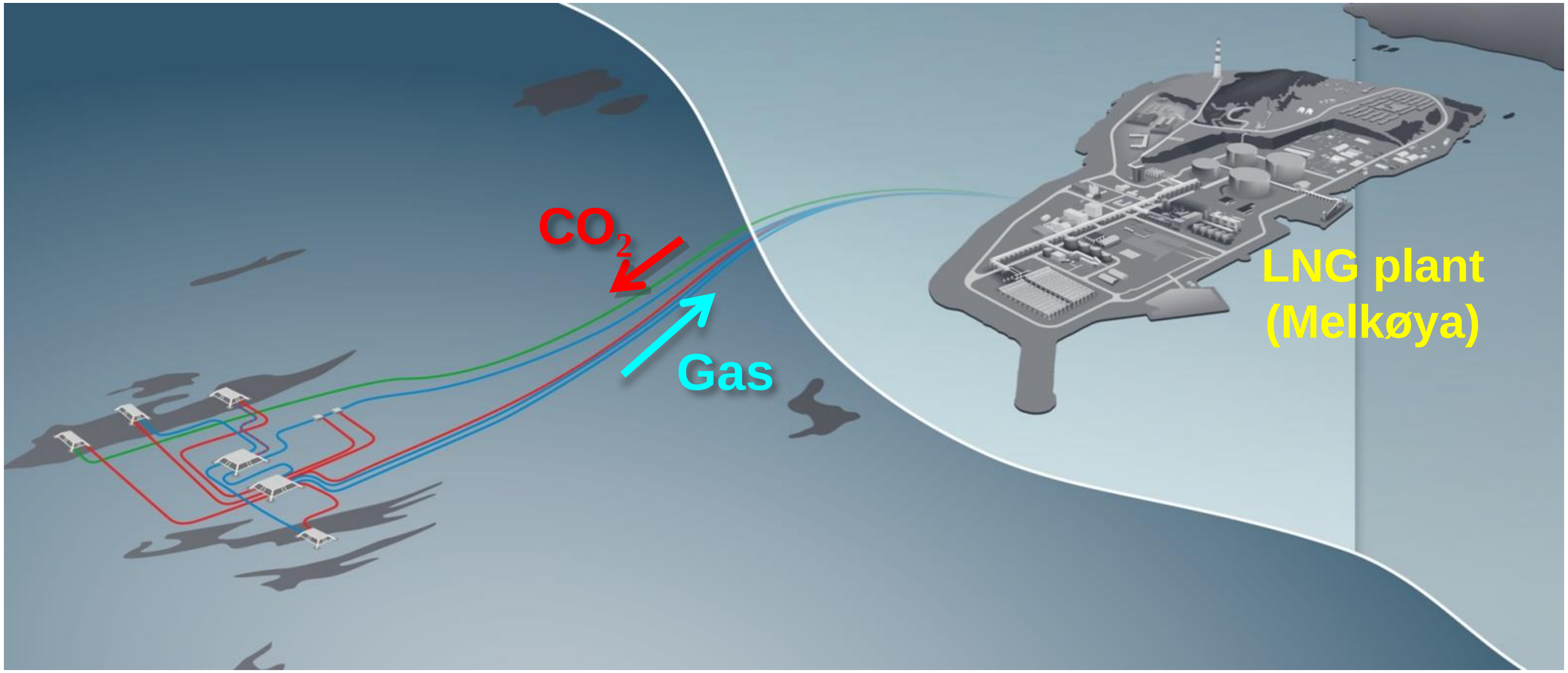


Regional observations on glacial valleys and channels (van der Vegt et al., 2012)



Snøhvit CO_2 capture and storage

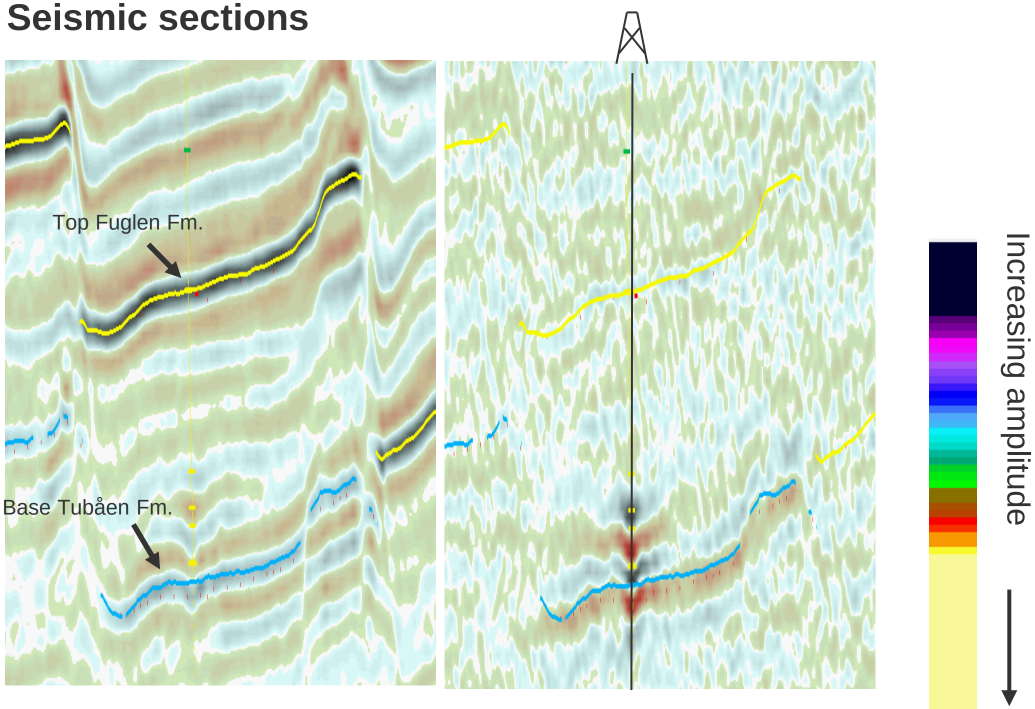
- *First onshore capture - offshore storage project (combined with LNG)*
  - 150km seabed CO_2 transport pipeline
  - Saline aquifers c. 2.5km deep adjacent to gas field
  - CO_2 stored initially in the Tubåen Fm. (2008-11) and then in the Stø Fm. (2011-)



Snøhvit well intervention in 2011

- Gradual rise in reservoir pressure indicated limited injection rate/capacity
- Repeat seismic survey (2009) showed CO_2 injection mainly confined to lower unit – reservoir permeability lower than expected
- Well Intervention operation successfully completed in May 2011

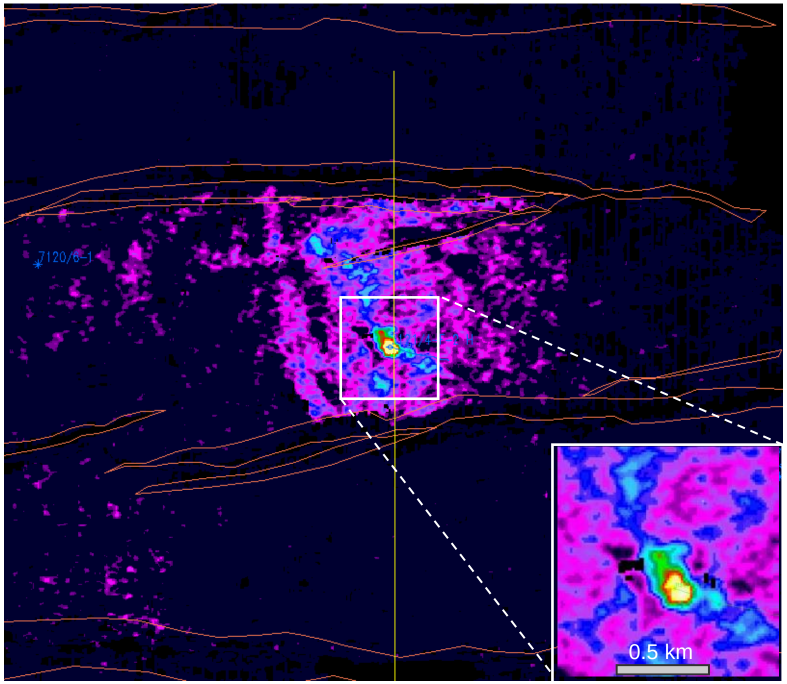
Seismic sections



2009 Seismic Survey

4D (Amplitude difference)

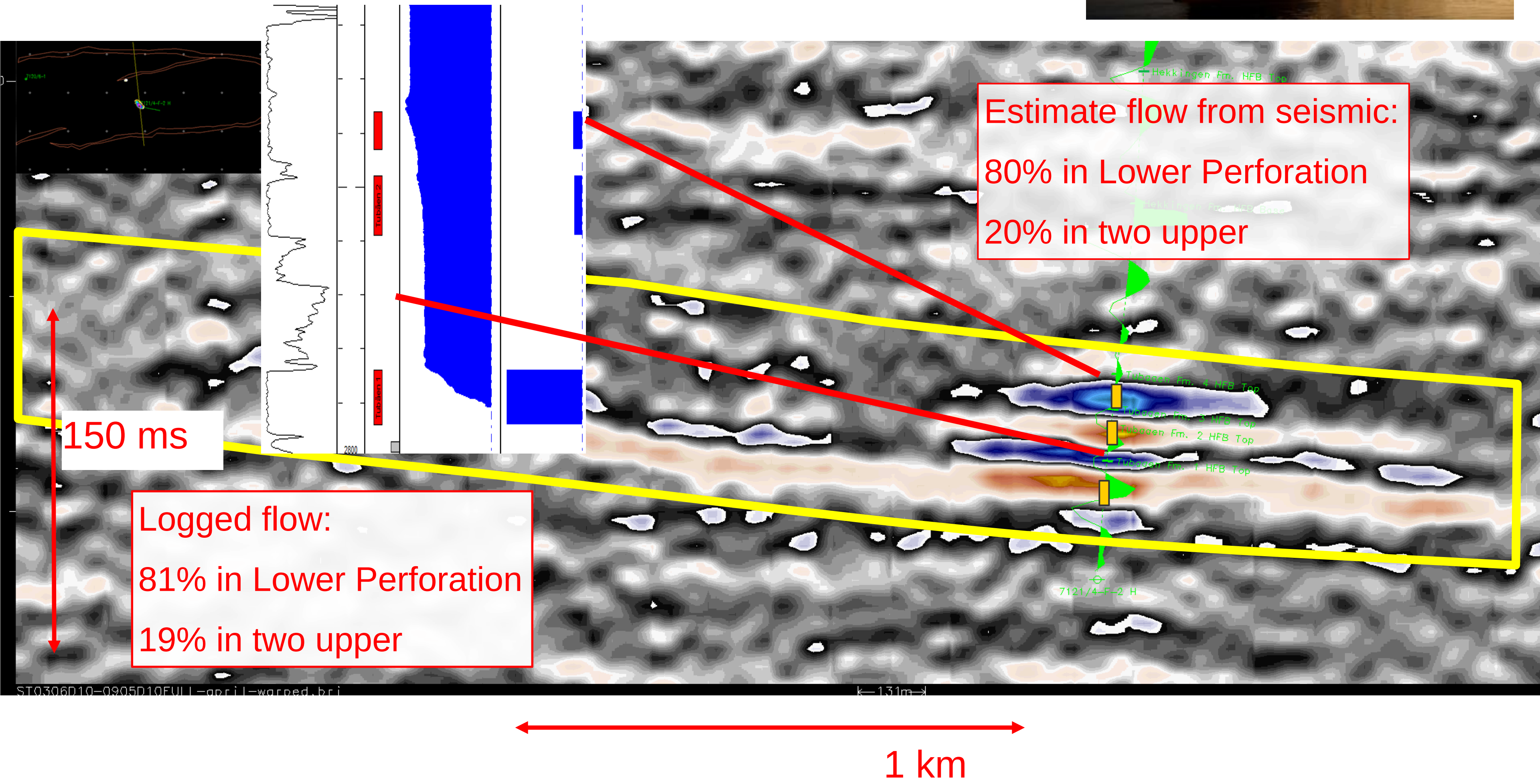
Amplitude change map



Hansen et al., 2013

Tubåen Reservoir Zone Monitoring

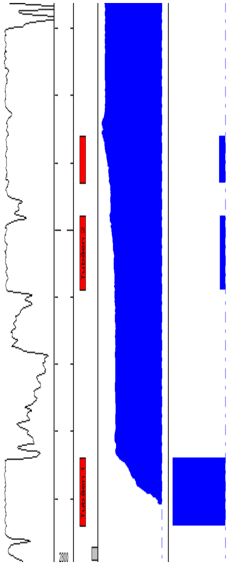
INFLOW LOG



Hansen et al., 2013

Monitoring techniques applied at Snøhvit

Down-hole data:
P, T, Q



- Seismic
  - 3D/4D repeats (so far 3 repeats)
  - 2D repeats (so far 1 repeat)
- Temperature / pressure monitoring
  - Continuous guage measurement
  - Weekly shut-in measurements
  - Long fall-off when feasible
- Downhole flow measurement
  - In-flow logging
- Gravimetry
  - 86 bases positioned (1 repeat)

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Main lessons learned – monitoring

1. Geophysical monitoring has proven essential for site management
   - Safe CO_2 storage containment confirmed
2. Monitoring of pressure is as important as saturation:
   - Down-hole gauges are highly desirable
3. Practical learnings about capacity and injectivity from well operation
   - Reservoir geology always has unpredictable elements
4. Monitoring the overburden is as important as the reservoir:
   - May require analysis of regional and near-surface datasets
5. Time-lapse seismic imaging of CO_2 plume development gives much improved understanding of flow processes:
   - Builds confidence in model forecasts
6. Sharing experience is important for building confidence in CCS
   - Different stakeholders have different interests in monitoring data

There's never been a better time for good ideas

Presented by Philip Ringrose

With thanks to many colleagues for discussions and insights

Acknowledgements to Statoil and project partners for permissions and use of data

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