Next generation cost-effective monitoring for offshore CO_2 storage

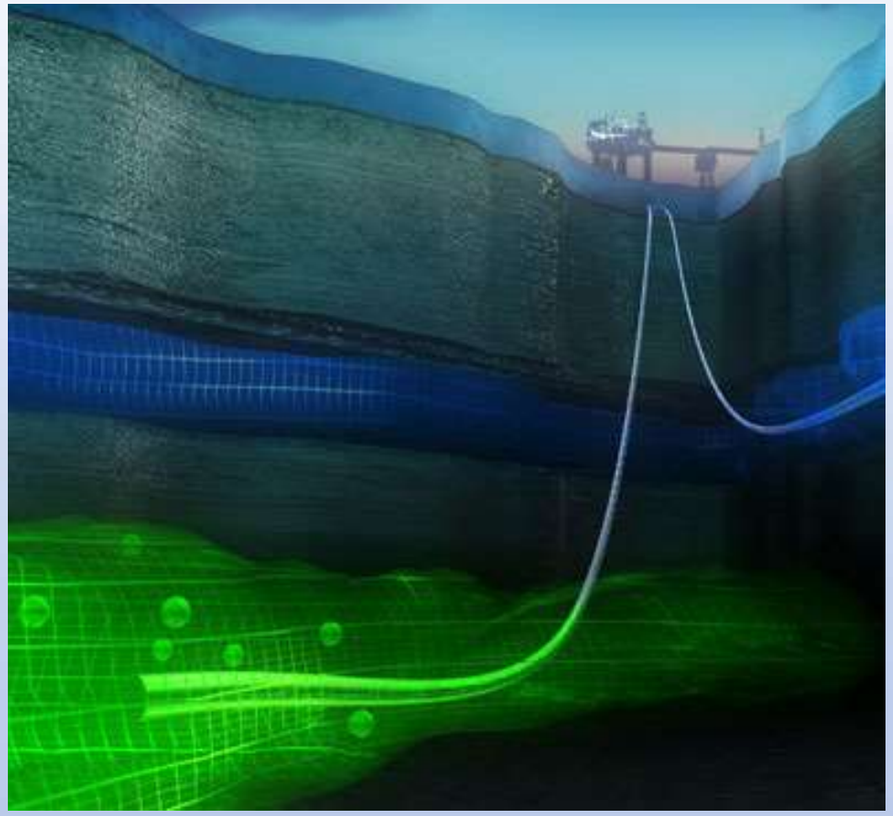
Philip Ringrose
NTNU, Trondheim, Norway

SFI Centre for Geophysical Forecasting

smile European Doctoral Network on Geo-energy

SHARP Storage

CO_2GeoNet Open Forum, 21-22 May 2024,
San Servolo Island, Venice



27½ years of storage and monitoring at Sleipner

Norwegian University of Science and Technology

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What's the problem?

- Operators can point to a long and successful track record of monitoring CO_2 stores …
- But these technical achievements do not always 'connect' with public concerns about safety.

➢ How can we monitor in a way that:

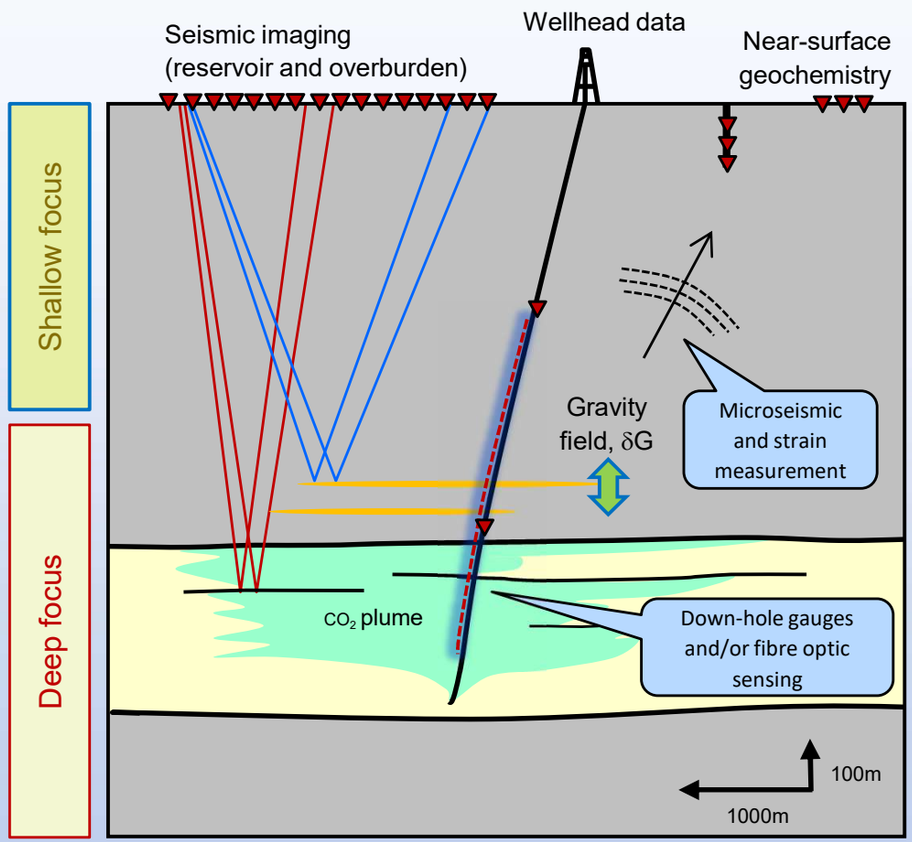
  ➢ Builds confidence in CCS

  ➢ Assures stakeholders with concerns about CO_2 storage safety

Monitoring methods applied at 5 CO_2 storage projects

Monitoring Technology	Sleipner (Offshore)	In Salah (Onshore)	Snøhvit (Offshore)	Decatur (Onshore)	Quest (onshore)
Wellhead monitoring	✓	✓	✓	✓	✓
Down-hole fluids	✓	✓	✓	✓	✓
4D surface seismic	✓	✓	✓	✓	✓
4D VSP seismic (DAS)				✓	✓(*)
4D gravity	✓		✓		
Microseismic		✓		✓	✓
Down-hole gauges			✓		✓
Seabed surveys	✓		✓		
Satellite (InSAR)		✓			
Surface/shallow gas	✓	✓		✓	✓
Groundwater sampling		✓		✓	✓

NB. Summary of main technologies applied – not everything done



Idealised storage site monitoring programme

Modified from Ringrose (2023)

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Proposed monitoring solutions and strategies

The ‘could it leak’ scenarios:

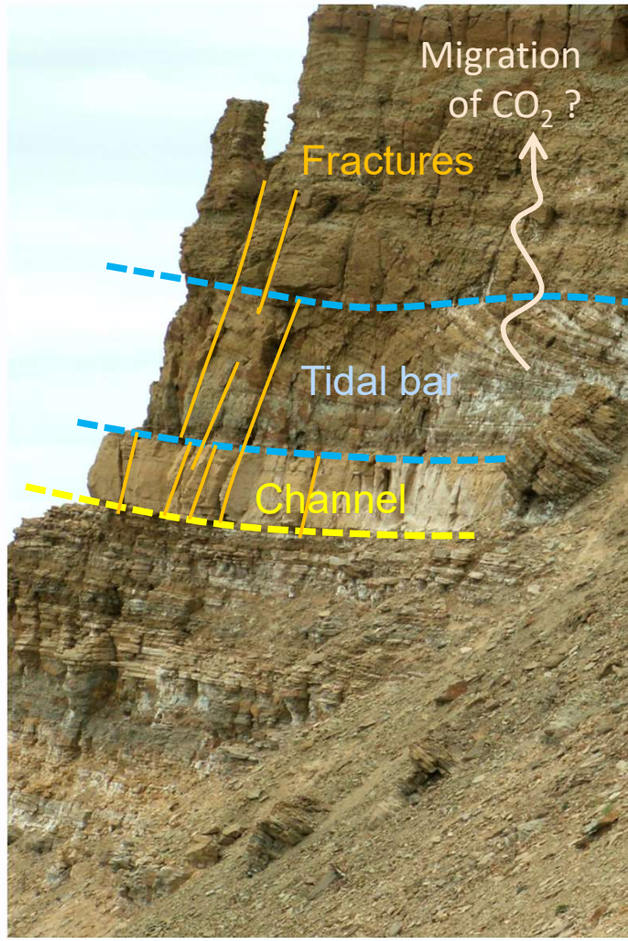
- Latest 4D seismic detection methods combined with knowledge of flow physics, can be used to quantify the probability of migration beyond the detection limit.

The ‘could it break’ scenarios:

- Use pressure and strain monitoring to show that injection stays well away from fracturing thresholds.
- Proactive seismicity monitoring is a key component of this strategy.

The cost and stakeholder assurance questions:

- Next generation CO_2 storage site monitoring can be both high-tech and affordable:
  - Especially by using fibre-optic detection technologies
  - Also, by monitoring ‘at the right time’ and ‘in the right place’

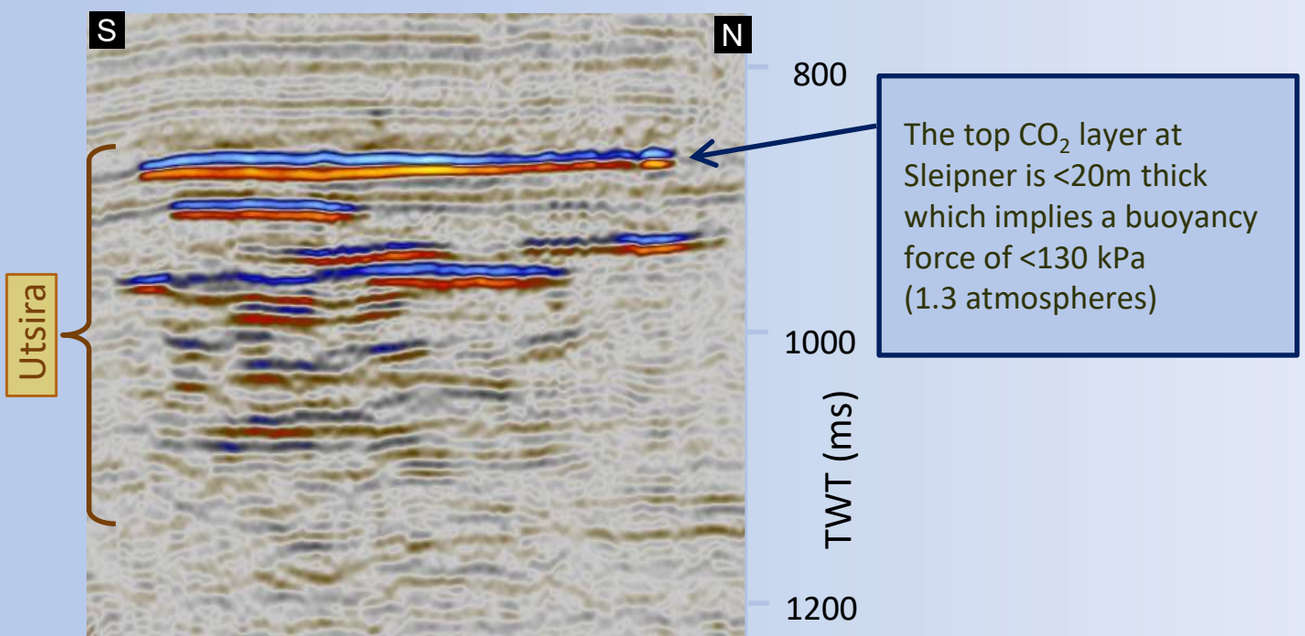


Tidal Delta Sedimentary Architecture
(Niell Klinter Formation, Greenland)

Understanding capillary seals and geological traps

- Molecular-scale capillary forces provides the essential seal for any non-wetting buoyant fluid (such as CO_2)
- The giant Troll gas/oil field (230m gas column & 26m oil column) was filled around 60 Million years ago …
  … and then 'survived' a tectonic tilting event 20 Million years ago, with some re-migration of oil and gas.
- However, a CO_2 store is quite different from a gas field: It is less buoyant and has a much lower column height

Seismic section through the Sleipner CO_2 plume showing observed reflection amplitudes.



2010 survey (IL875)

Laboratory demonstration of a capillary seal
(using an aquarium tank, air and a food sieve)
https://www.youtube.com/watch?v=8-dXwakvmsI

CO2 storage explained

Seismic data used with permission of the Sleipner Group of companies (Equinor Energy AS (operator), ExxonMobil Exploration and Production Norway AS, LOTOS Exploration and Production Norge AS and KUFPEC Norway AS).

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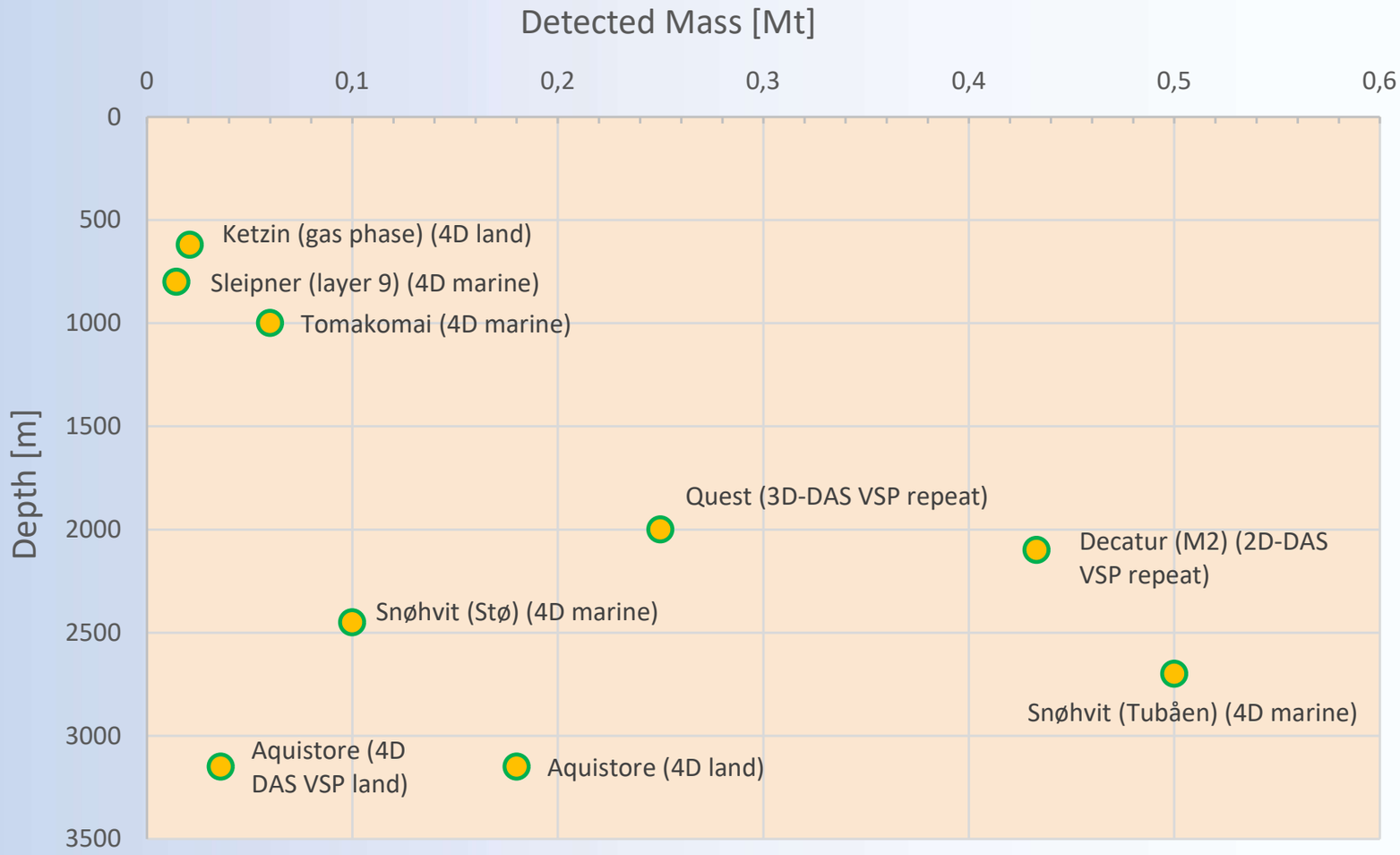
General experience on CO_2 detection limits using 4D seismic

(selected projects – published data gleaned by Anne-Kari Furre, Equinor)

Actual detection limit depends on many factors:

- Seismic acquisition plan
- Depth & Porosity
- Geological architecture
- Overburden

At around 1 km depth detection down to 20-50 kt of CO_2 seems realistic/possible



Modified from Ringrose (2023)

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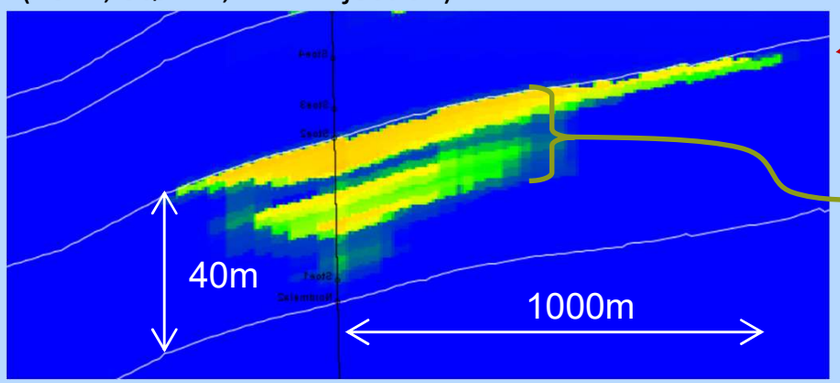
What about the parts of the CO_2 plume we cannot detect?

Problem statement – illustrated by Snøhvit example

CO_2 saturation simulation
(2012, Stø Fm, F-2H injection)

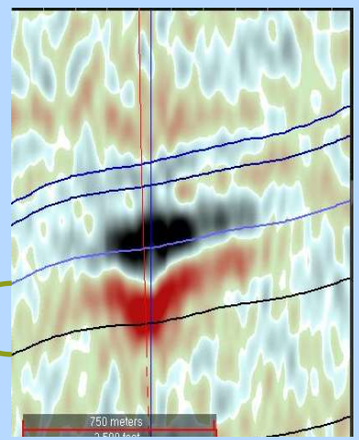


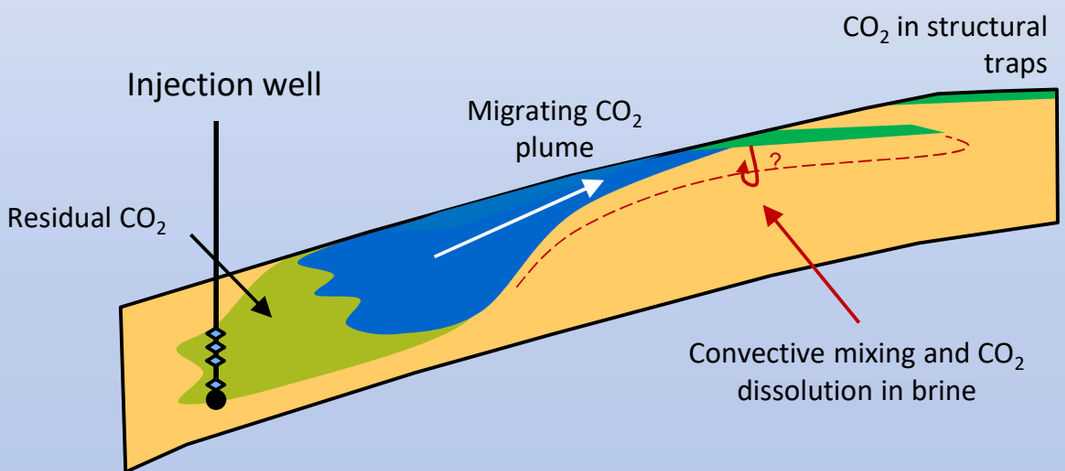
Osdal et al., 2014

What about the part we cannot detect?

Say we can detect this part from seismic 4D data?

Monitoring using 4D seismic
Base-2012





Flow processes involved are well known:

- Mobile CO_2 plume migration (mobility)
- Effects of fluid density (buoyancy)
- Residual trapping
- Structural trapping
- CO_2 dissolution in brine
- CO_2 mineralization

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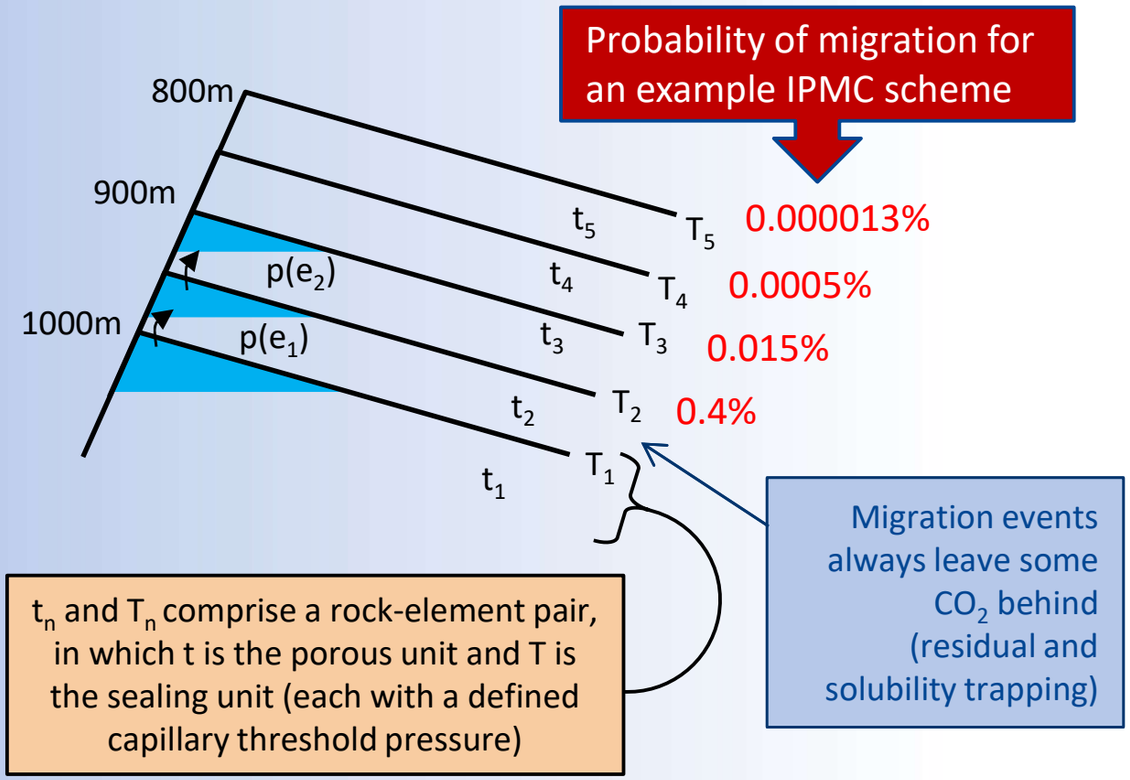
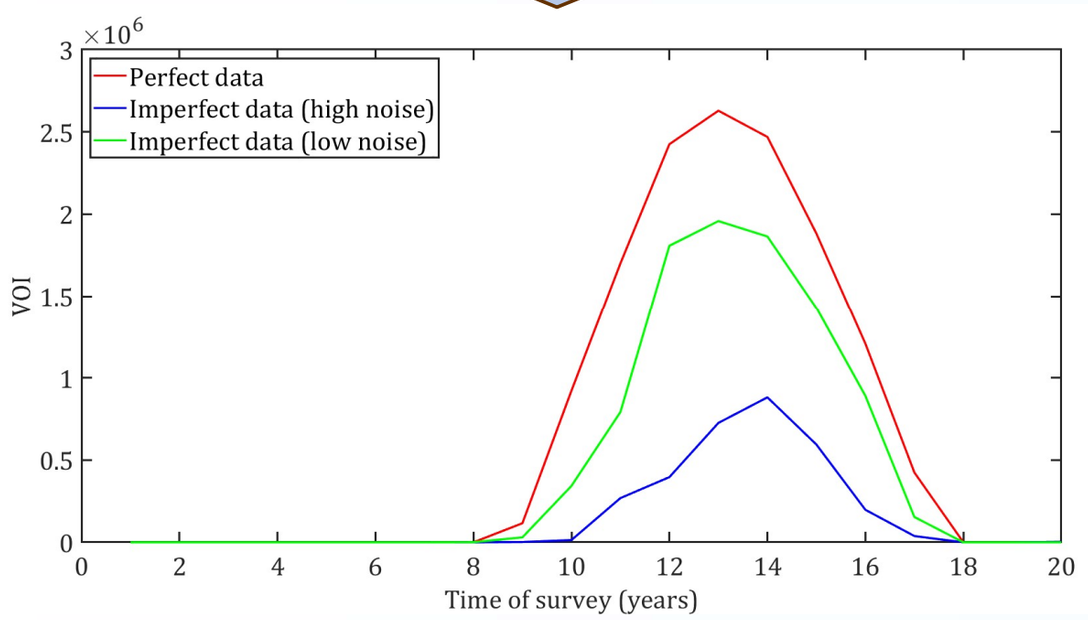
Invasion Percolation Markov chain (IPMC) concept for assessing CO_2 storage containment risks (Callioli Santi et al. 2022)

Basic concept:
Simplified stack of storage units ($t_{1\text{-}5}$) separated by sealing layers ($T_{1\text{-}5}$) in a tilted fault block.



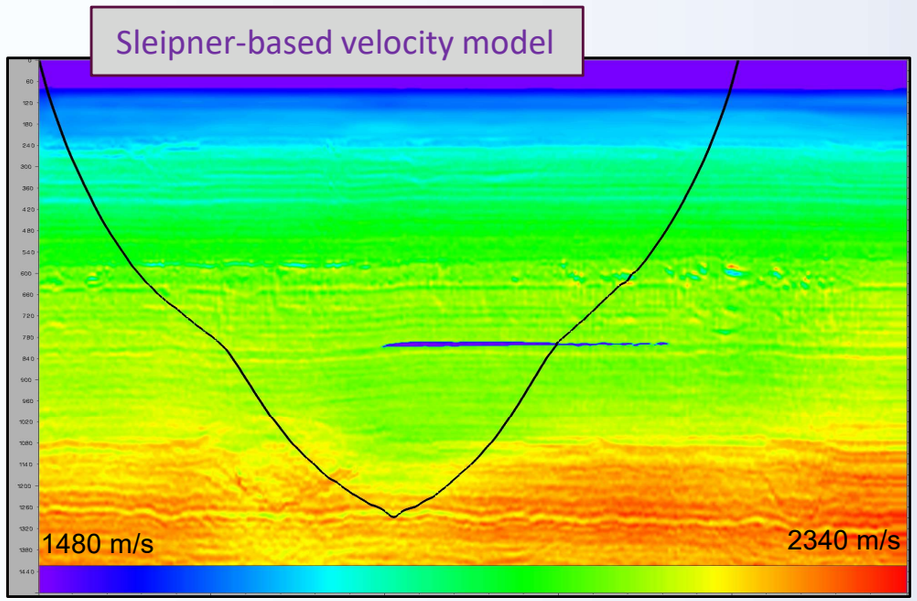
Dutta et al. (2023, 2024) developed this IPMC approach into a VOI for monitoring framework (using a simplified model based on Sleipner):

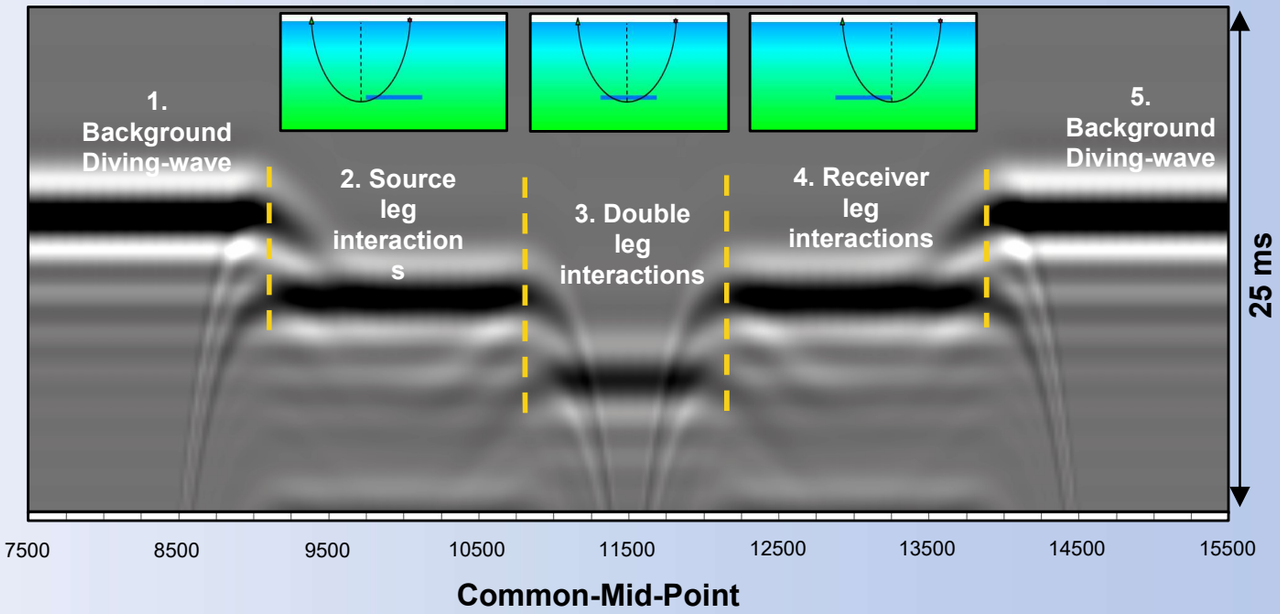
- E.g. when would you need to shoot a seismic survey to detect migration into layer t_2



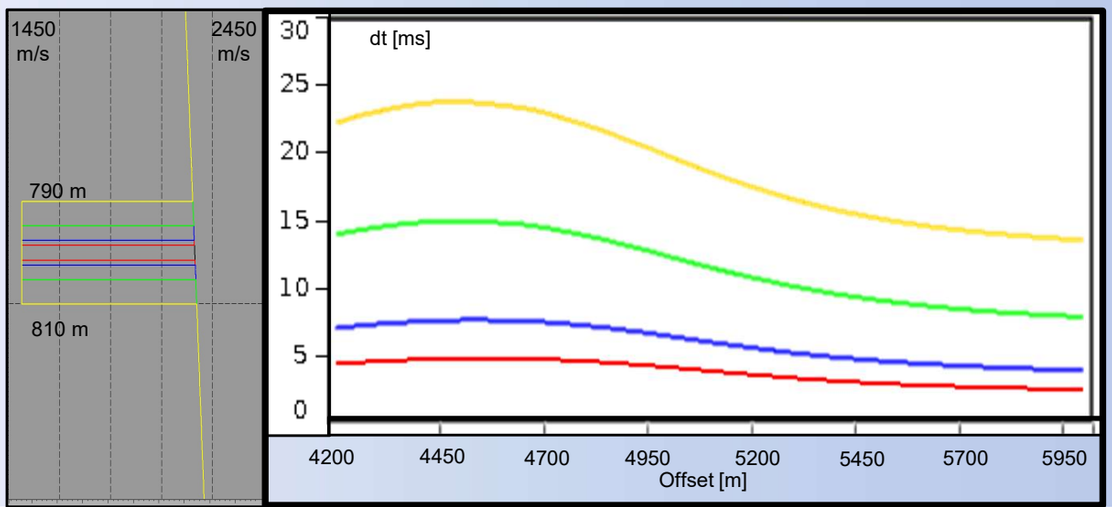
Improving detection: 4D analysis of diving waves for CO_2 thin layer detection

Ricardo Martinez et al. (2024)





We can quantifiably detect thin layers of CO_2 down to a few metres of thickness



Martinez et al. (2024) GJI. *Software Courtesy of CGG*

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Rock mechanics and CO_2 storage

Projects need to assess:

- Elastic response to pressure increase
- Likelihood of induced fractures or faults

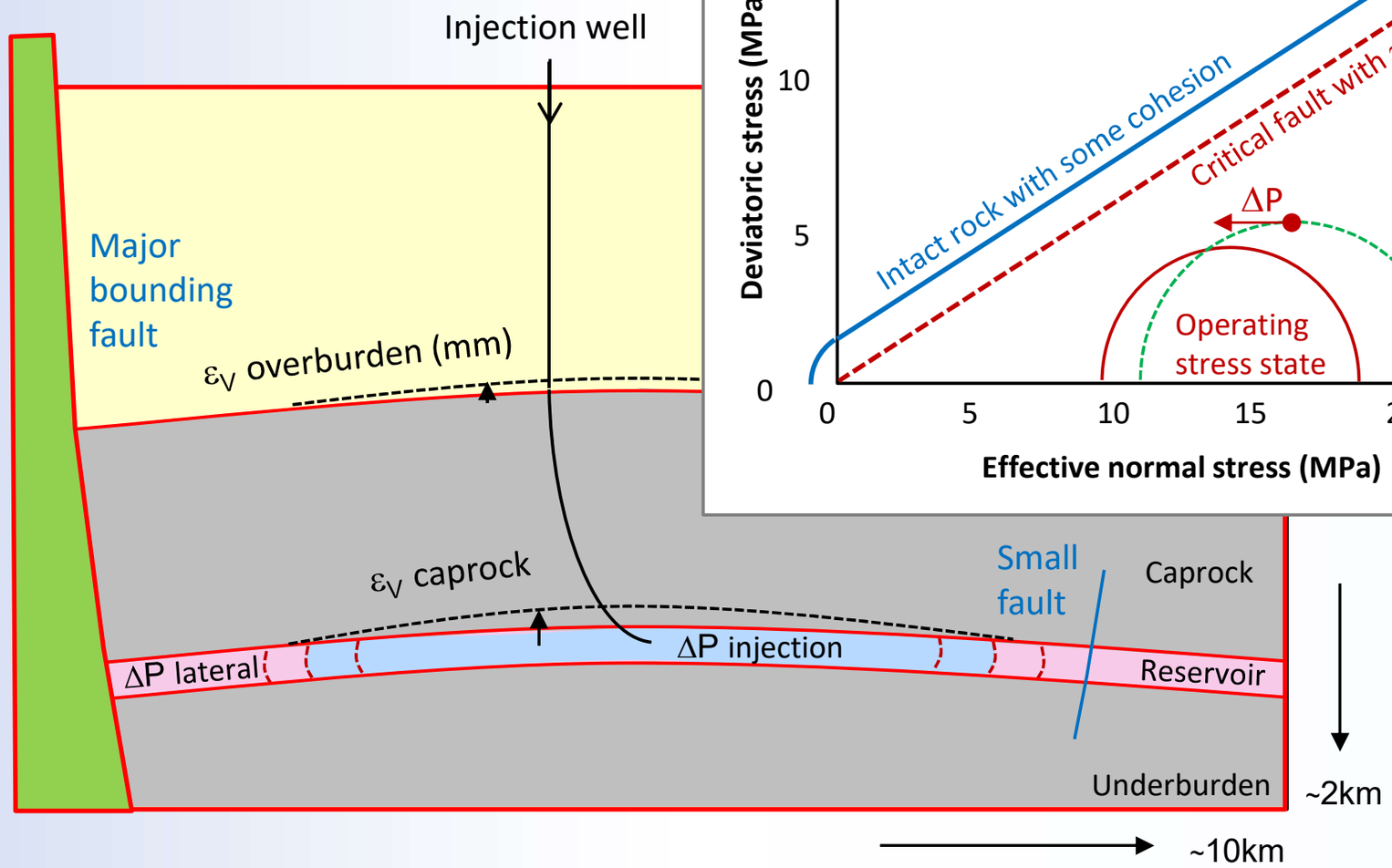
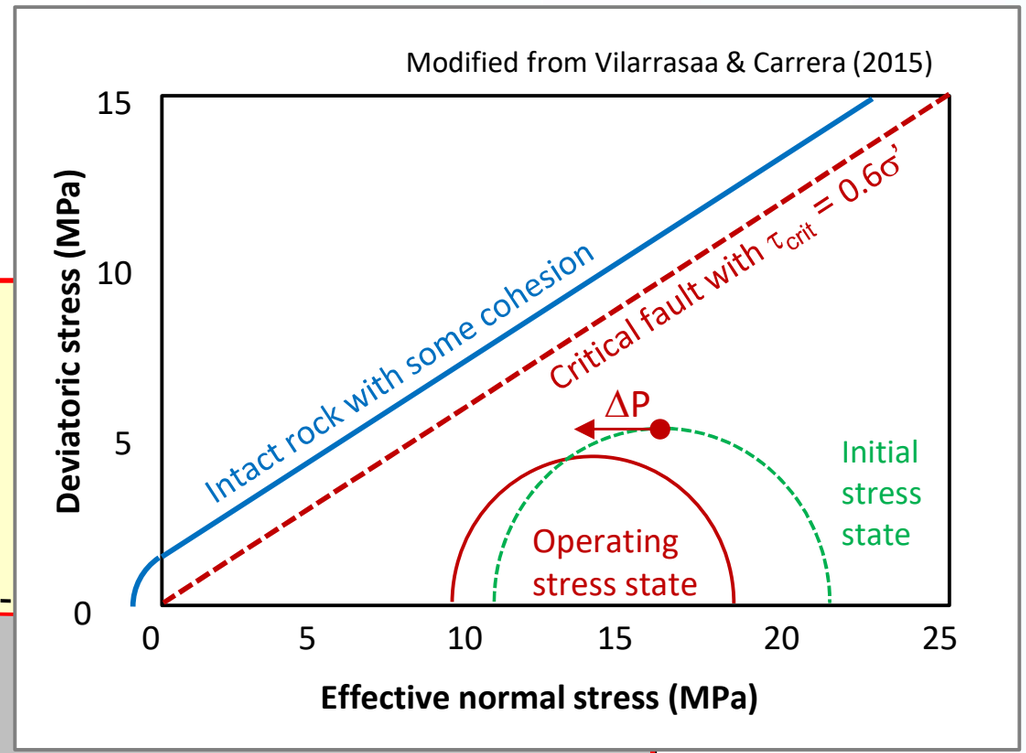


Illustration of rock strain response to elevated injection pressure in a reservoir unit. ΔP = change in fluid pressure; ε_V = vertical component of rock strain.

Pressure and stress-state management



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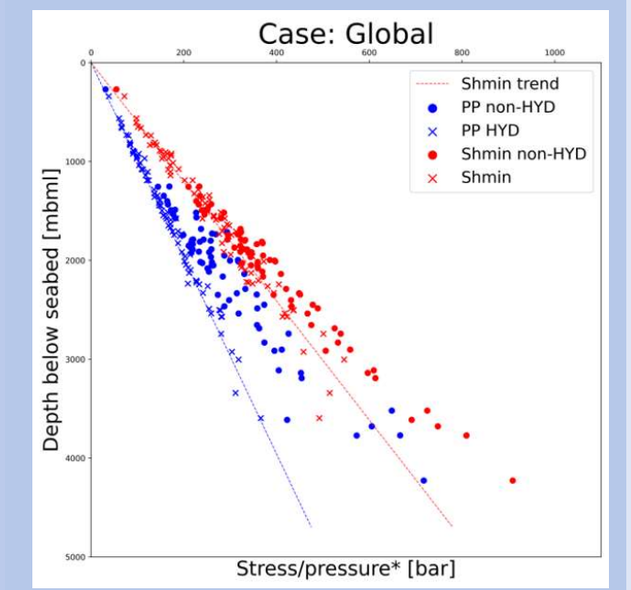
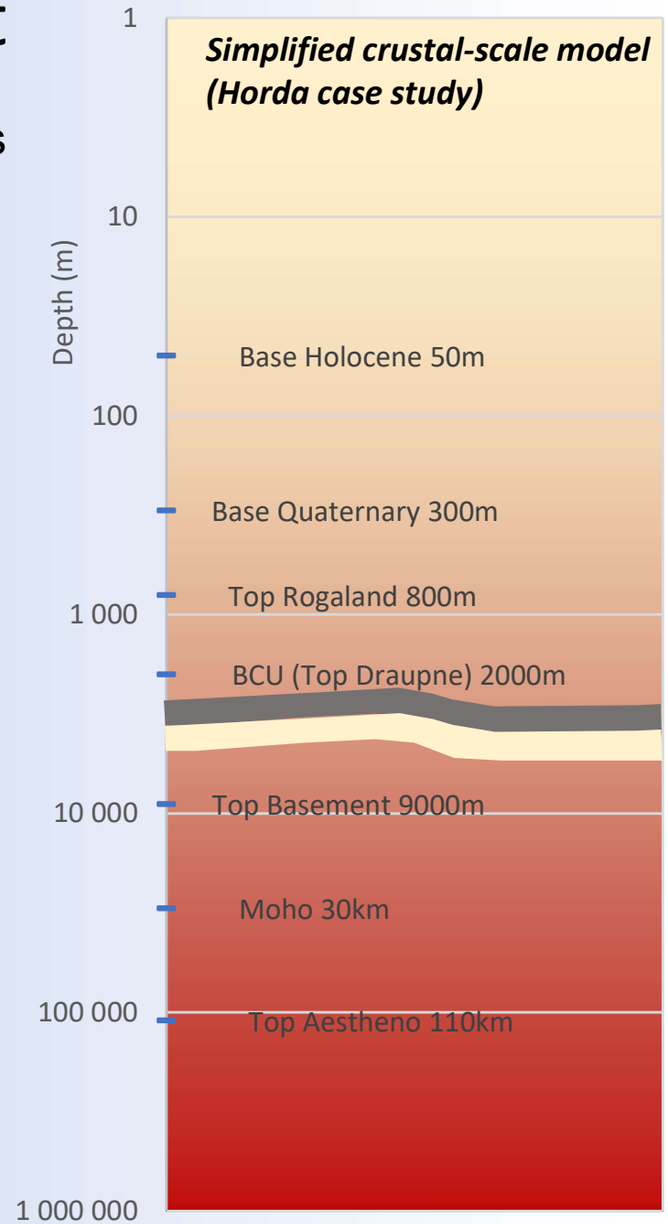
On improved quantification of CO_2 storage containment risks

Developing a 'right-time and right-place' monitoring scheme for stress & strain

Depth trend datasets (example)



Thompson et al. (2022)



Geomechanical parameters	Site characterisation data	
K_o = 0.5 μ < 0.1 V_p = c.1000m/s	Maps, surface measurements	Overburden
K_o = 0.2 μ = 0.2 V_p = c.2000m/s ν = 0.4	Cores, logs, geotechnical tests	
K_o = 0.2 μ = 0.5 V_p = c.3000m/s	Cores, logs Geomechanical tests Formation tests (FIT)	
e.g., Draupne: K_o = 0.6 μ = 0.4-0.6 E = 1.25GPa ν = 0.4	Cores, logs, etc 3D seismic surveys	Aquifer-Caprock
K_o = c.0.4 μ = c.0.8 V_p = c.6000m/s	Some regional well data 2D/3D seismic surveys Regional modelling	Underburden

What about the overburden?

Main rock mechanical focus depth

What about the underburden?

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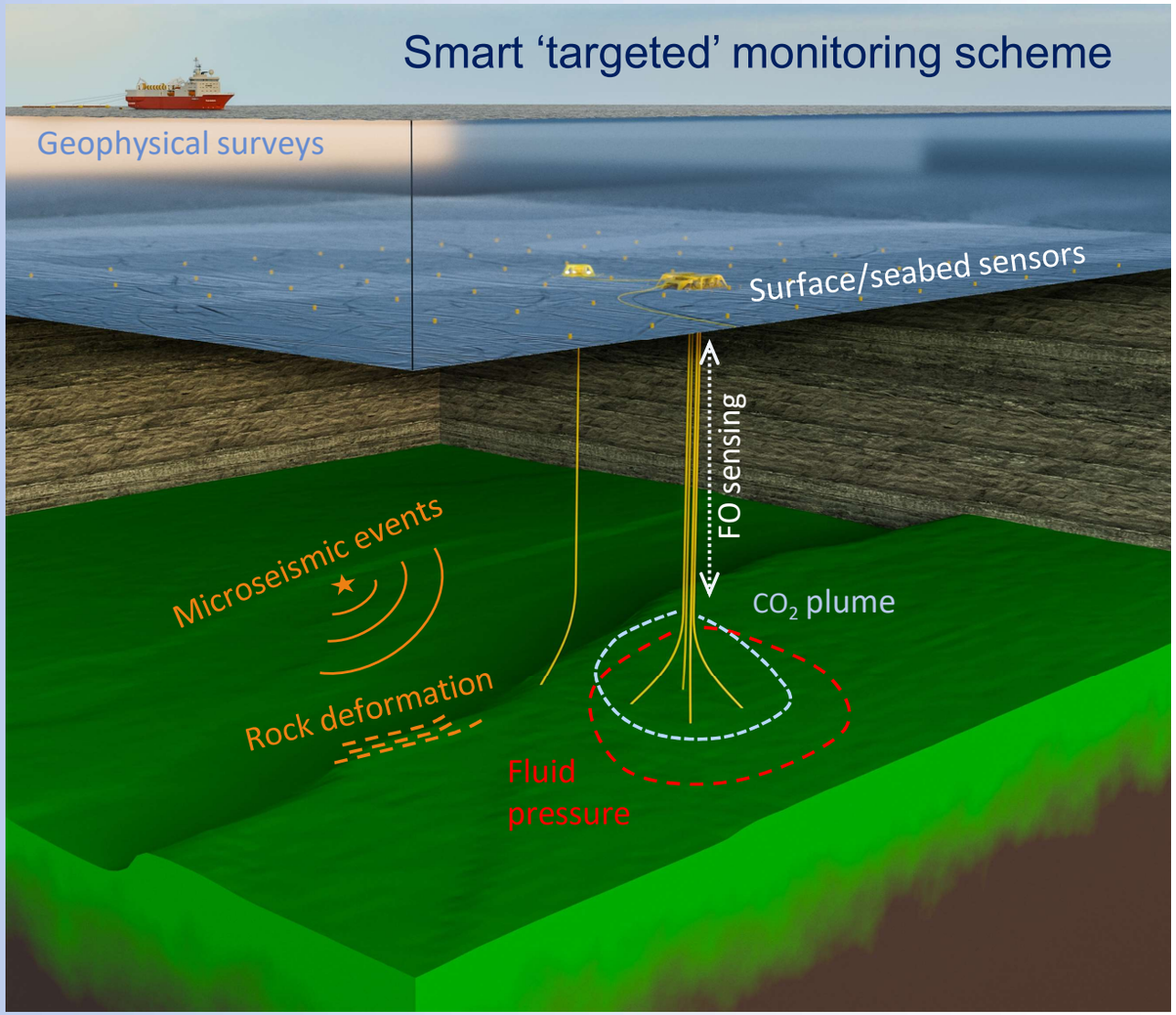

SHARP-Storage - SHARP-Storage (sharp-storage-act.eu)

Geomechanical parameters	Site characterisation data	Monitoring options (example only)	
K_o = 0.5 μ < 0.1 V_p = c.1000m/s	Maps, surface measurements	**Surface deformation (InSAR, marine geodetics)**	Overburden
K_o = 0.2 μ = 0.2 V_p = c.2000m/s ν = 0.4	Cores, logs, geotechnical tests	**None (N/A)**	
K_o = 0.2 μ = 0.5 V_p = c.3000m/s	Cores, logs Geomechanical tests Formation tests (FIT)	**Overburden gauges (P, T)** **Regional and local seismic network** **Surface DAS sensing**	
e.g., Draupne: K_o = 0.6 μ = 0.4-0.6 E = 1.25GPa ν = 0.4	Cores, logs, etc 3D seismic surveys	**4D seismic** **P/T gauges** **Regional and local seismic network** **FO sensing (Downhole and surface)**	Aquifer-Caprock
K_o = c.0.4 μ = c.0.8 V_p = c.6000m/s	Some regional well data 2D/3D seismic surveys Regional modelling	**Regional seismic network**	Underburden
		Global seismology	

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Seismicity monitoring in preparation for large-scale CO_2 storage offshore Norway

(HNET, Climit Demo)

Project goal: Baseline seismicity assessment for CO_2 storage the Horda Platform region

Why?

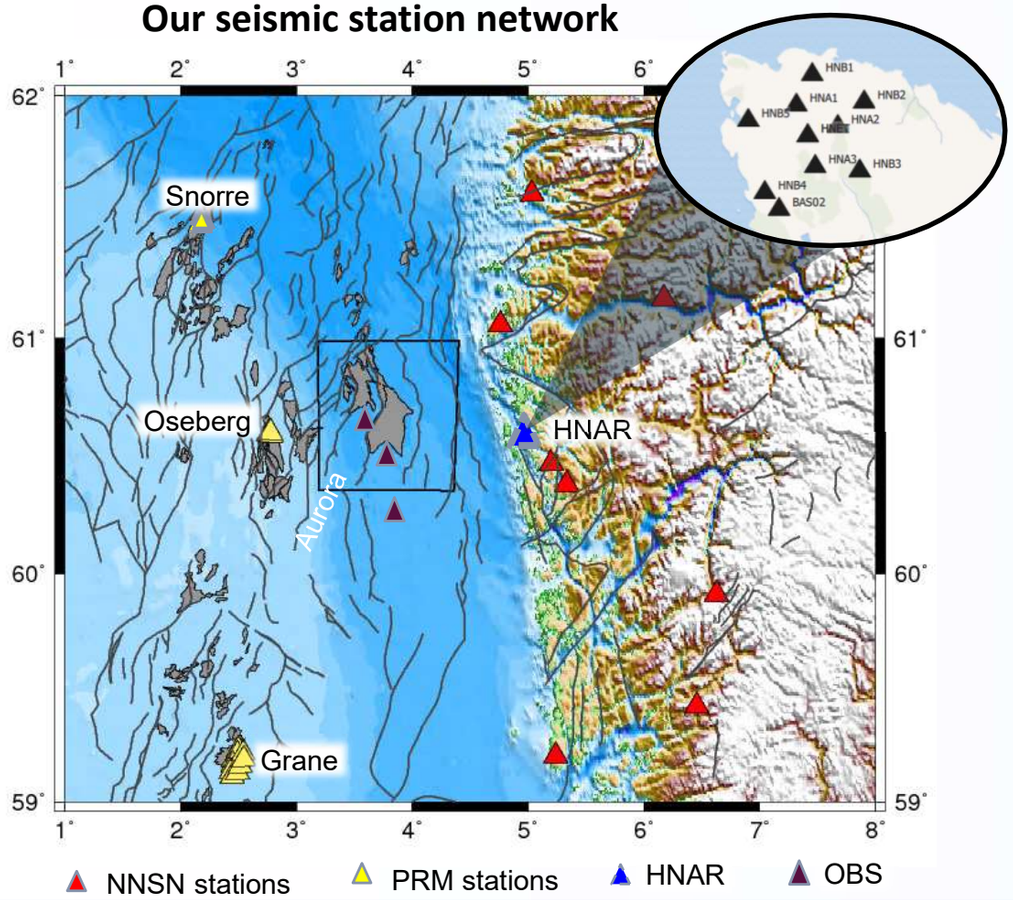
Seismic risk assessment is an important part of site selection and safety assessments

Understanding induced seismicity is important for storage operations and long-term storage integrity

Actual risk of induced earthquakes is very low and manageable, however false association with nearby tectonic events is a concern

HNET project (hordanet.no)

Our seismic station network

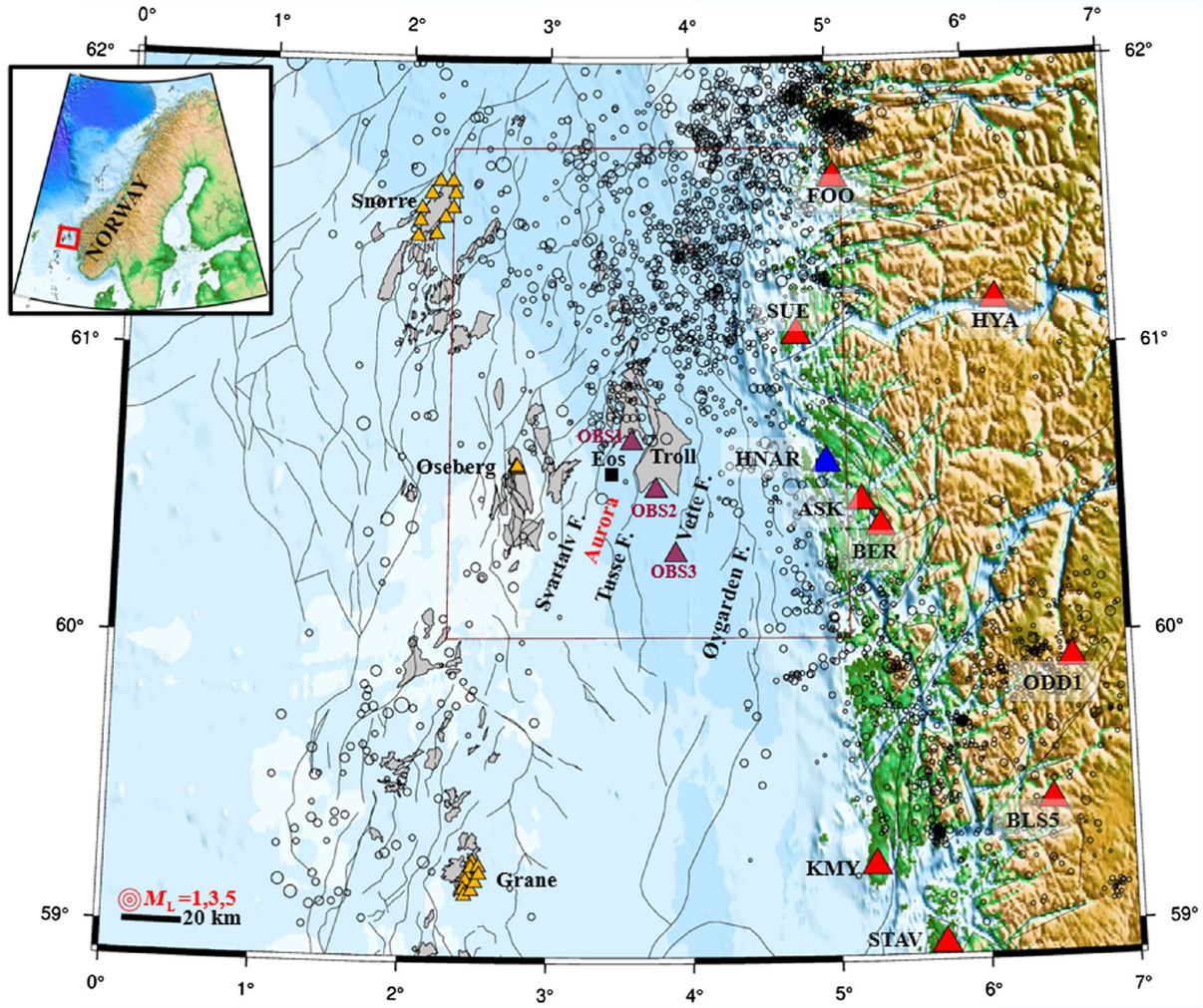


HNET: Project findings so far

1. Normal tectonic activity observed:
   - Gutenberg-Richter b-value of close to 1
2. Integration of the offshore geophones with the onshore & offshore (BB) seismometers gives:
   - Better azimuthal coverage
     ⇒ improved location
   - Improved detection
     ⇒ array processing and ML methods
4. Improved understanding of stress sate:
   - Indications of stress relaxation in/below the sedimentary basin package

(Zarifi et al. 2023, *Seismological Research Letters*)

Seismicity in the Horda platform and surrounding areas



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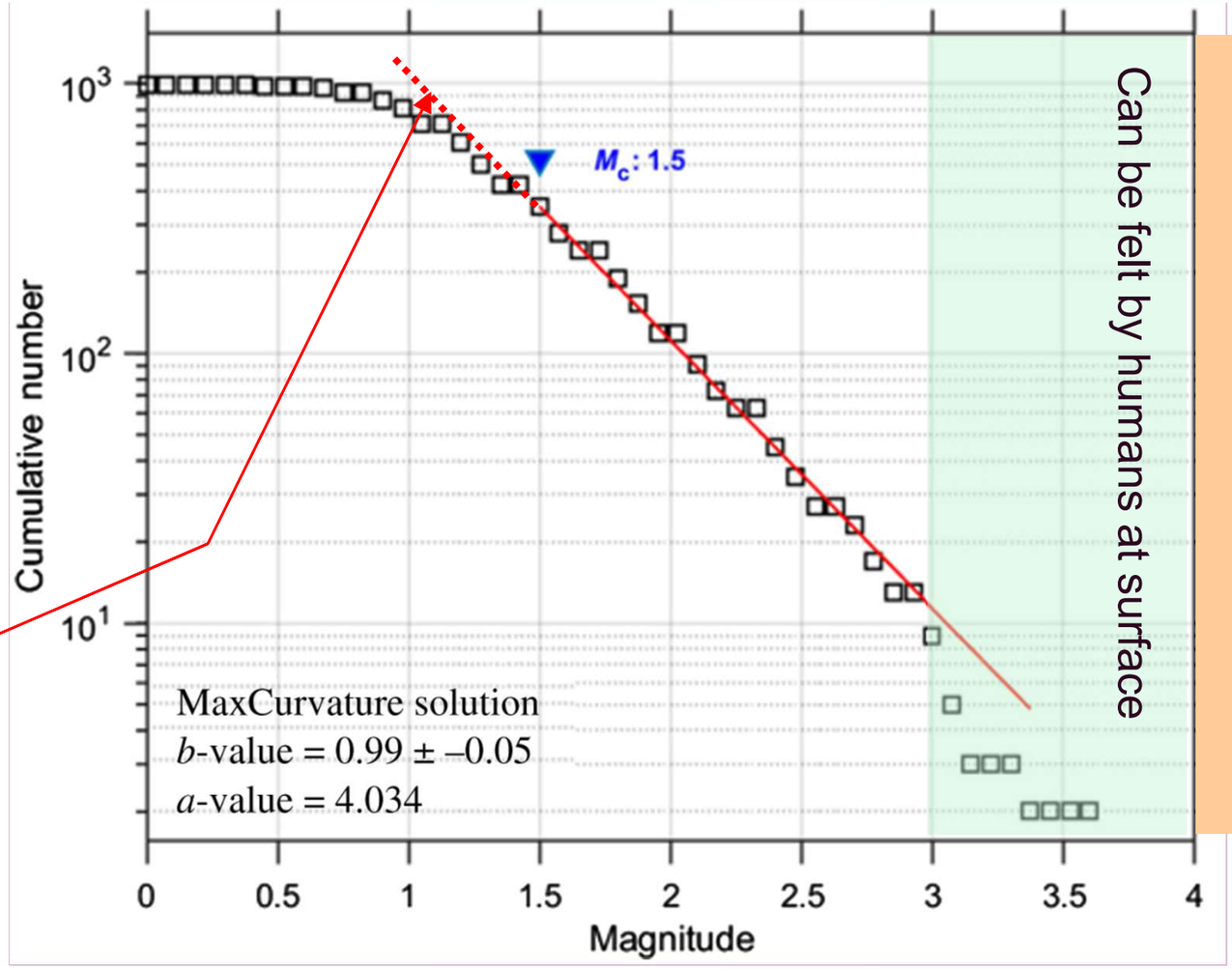
How often do earthquakes occur in this region?

Statistical analysis of seismicity in the Horda Platform area (Zarifi et al. 2023):

- Data since 1990 (NNSN catalog)

Now using/testing offshore seabed FO cables to improve local event detection



Moderate earthquakes (M_L 4-5) have occurred in wider region

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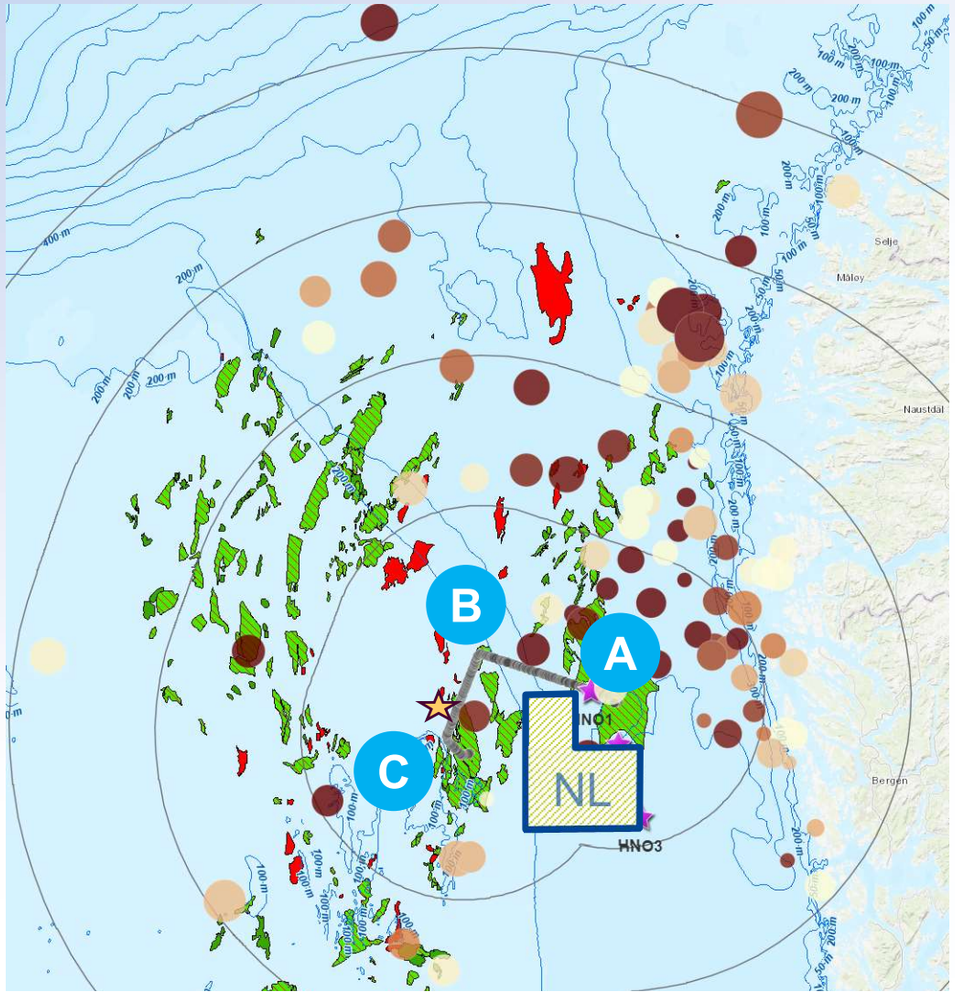
Using seabed DAS fiber for passive seismic monitoring

Small earthquake detection using 100km telecom fiber near Northern Lights project. Estelle Rebel et al. 2023 (TCCS-12)



Seismic activity during the 9-month test period (9/22-5/23)

(Events detected by seabed DAS – but QC with OBN and onshore BB)

Magnitude 1.3 Earthquake detection example

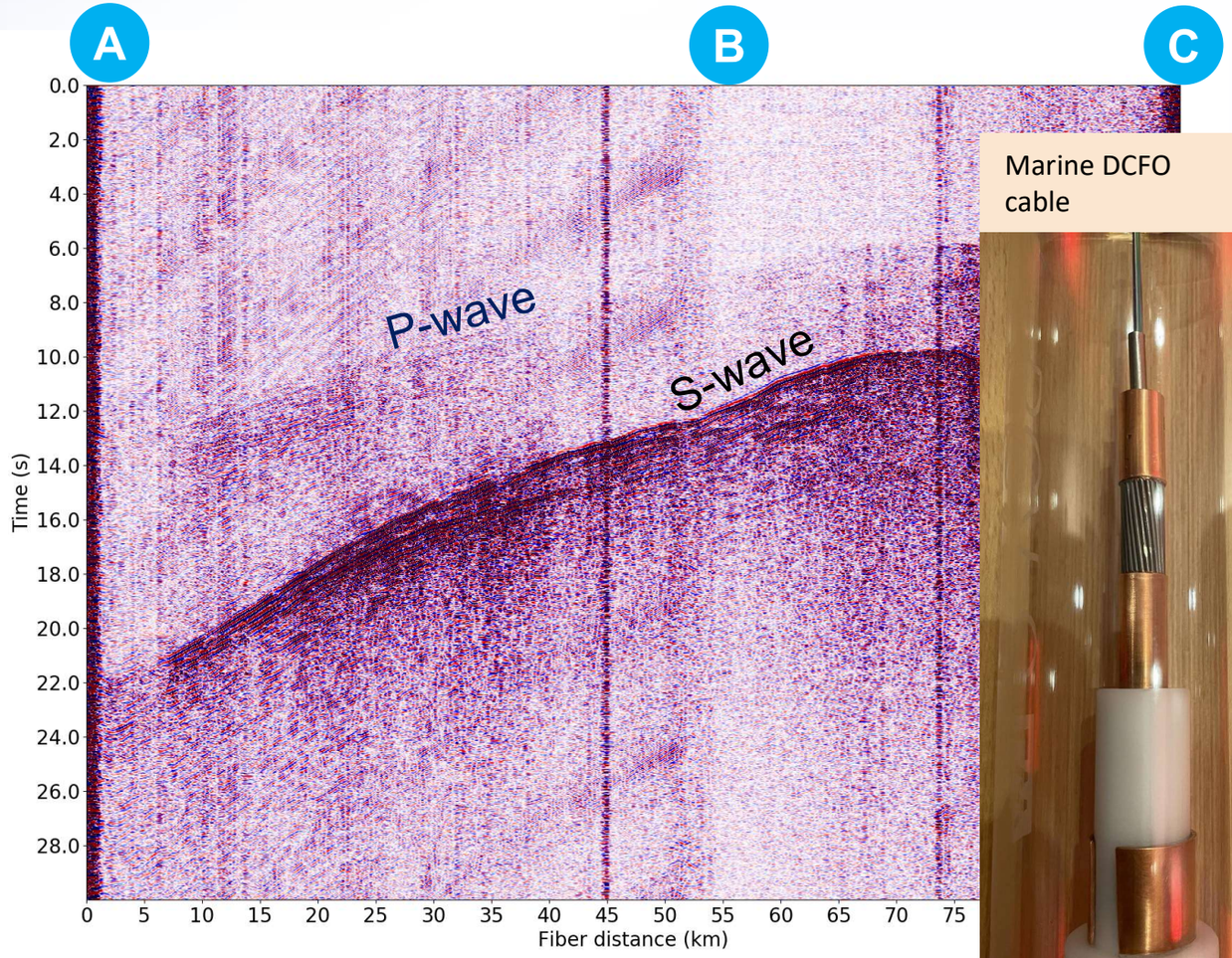
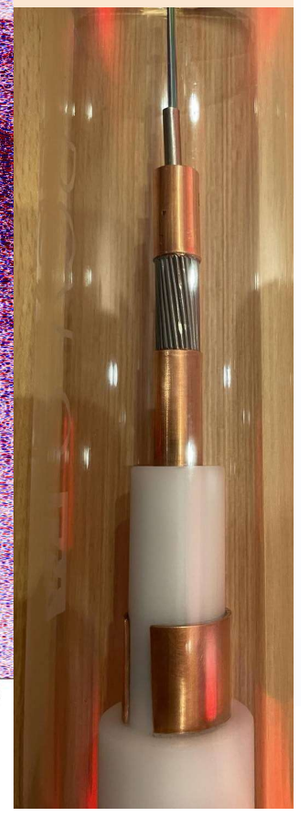


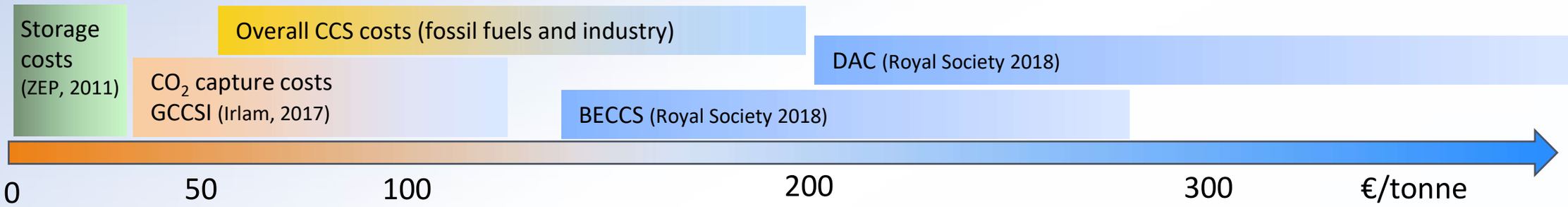
Image courtesy TotalEnergies

Marine DCFO cable



Costs and benefits of monitoring

CCS cost estimates:



Monitoring costs are comparatively very cheap within this framework:

- **Overall storage monitoring costs are** in the range of 0.6 to 1.7 €/tonne (Zero Emissions Platform, 2011)
  - 10% of storage costs, or as little as 1% of total CCS project costs.
- **Offshore monitoring Norway reference case** was €2/tonne (for a 2015 reference; Ringrose et al. 2018)
  - Should get to around €1/tonne

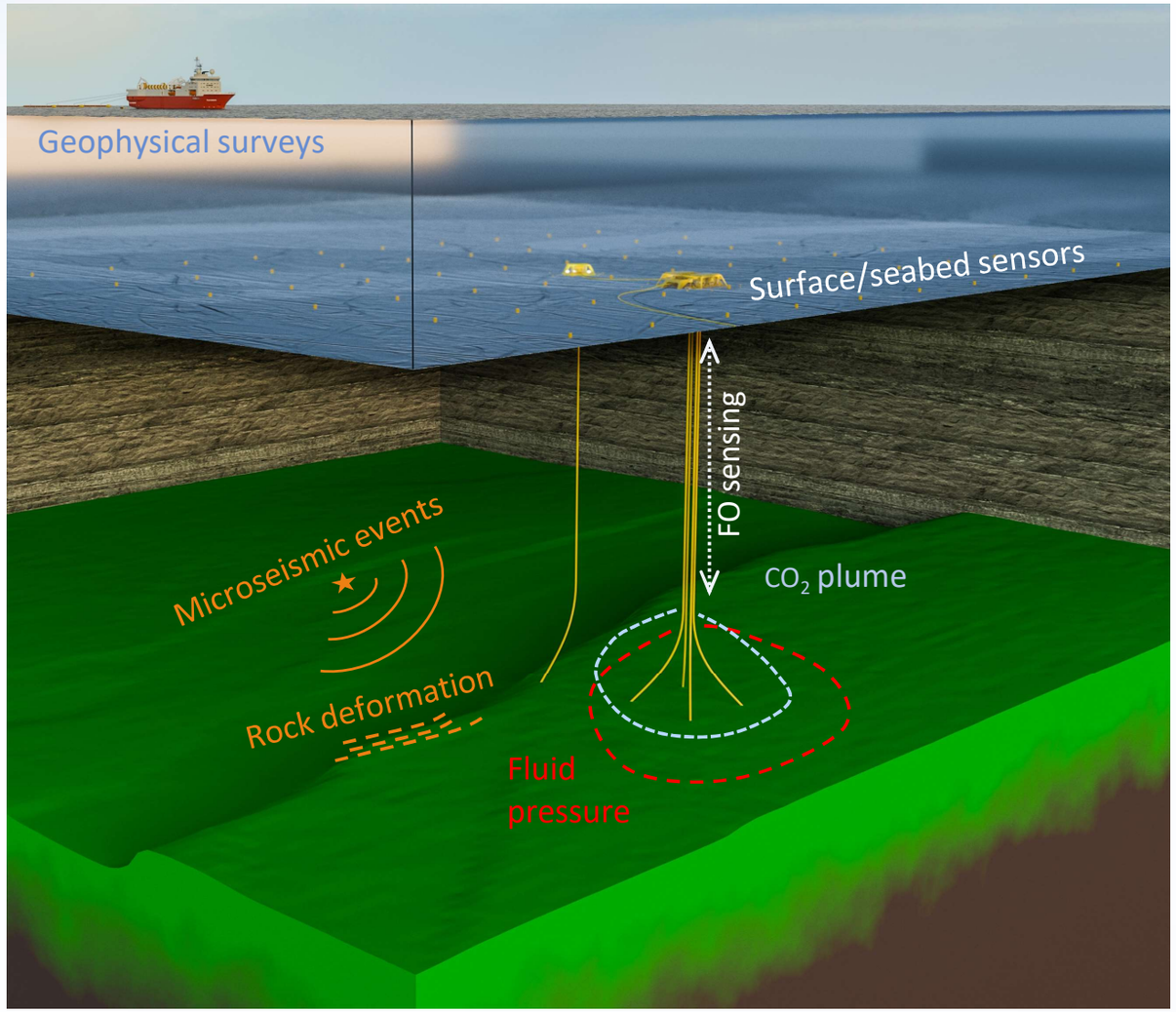
The positive value of monitoring can be quantified in terms of reduced operational costs:

1. Enabling improved injection well regularity
2. Avoidance of additional operational costs (unplanned well interventions)
3. Avoidance of major CCS project costs (additional wells, suspended injection, loss of revenue).

For sources see Ringrose (2023)

Summary and Conclusions

1. We <u>can</u> monitor in a way that:
   - ➢ Builds confidence in CCS
   - ➢ Assures stakeholders with concerns about CO_2 storage safety
2. But we do need to be <u>proactive</u>:
   - ➢ Prevention is better than a cure
   - ➢ Anticipation is better than 'whoops' 🙈



Thank you!

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- Sleipner data was provided by the Sleipner Group of companies (Equinor Energy AS, ExxonMobil AS, LOTOS AS and KUFPEC Norway AS).
- HNET project is funded by Gassnova, Northern Lights JV, Equinor, Shell, TotalEnergies & CGG
- ACT SHARP is an international collaboration with many partners under the ACT programme
- Many colleagues for ideas and inputs

CGF SFI Centre for Geophysical Forecasting

smile European Doctoral Network on Geo-energy

Accelerating CCS Technologies

SHARP Storage

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