CLIMIT

Presentations 9 February – Technical session - Storage

- Jonas Solbakken, NORCE
- Tone Holm-Trudeng, TGS
- Philip Ringrose, Equinor
- Elin Skurtveit, NGI

Jonas Solbakken

SENIOR RESEARCHER

How fast can we get CO_2 into geological formations – without getting operational problems?

Jonas Solbakken is a senior researcher in NORCE (Norwegian Research Centre). He holds a PhD in petroleum technology and has mostly been working on challenges involving fluid flow in porous media, including CO_2 Injectivity and CO_2 for Enhanced Oil Recovery (EOR).

CLIMIT SUMMIT

#CLIMITSUMMIT2023
7–9 February

The Research Council of Norway

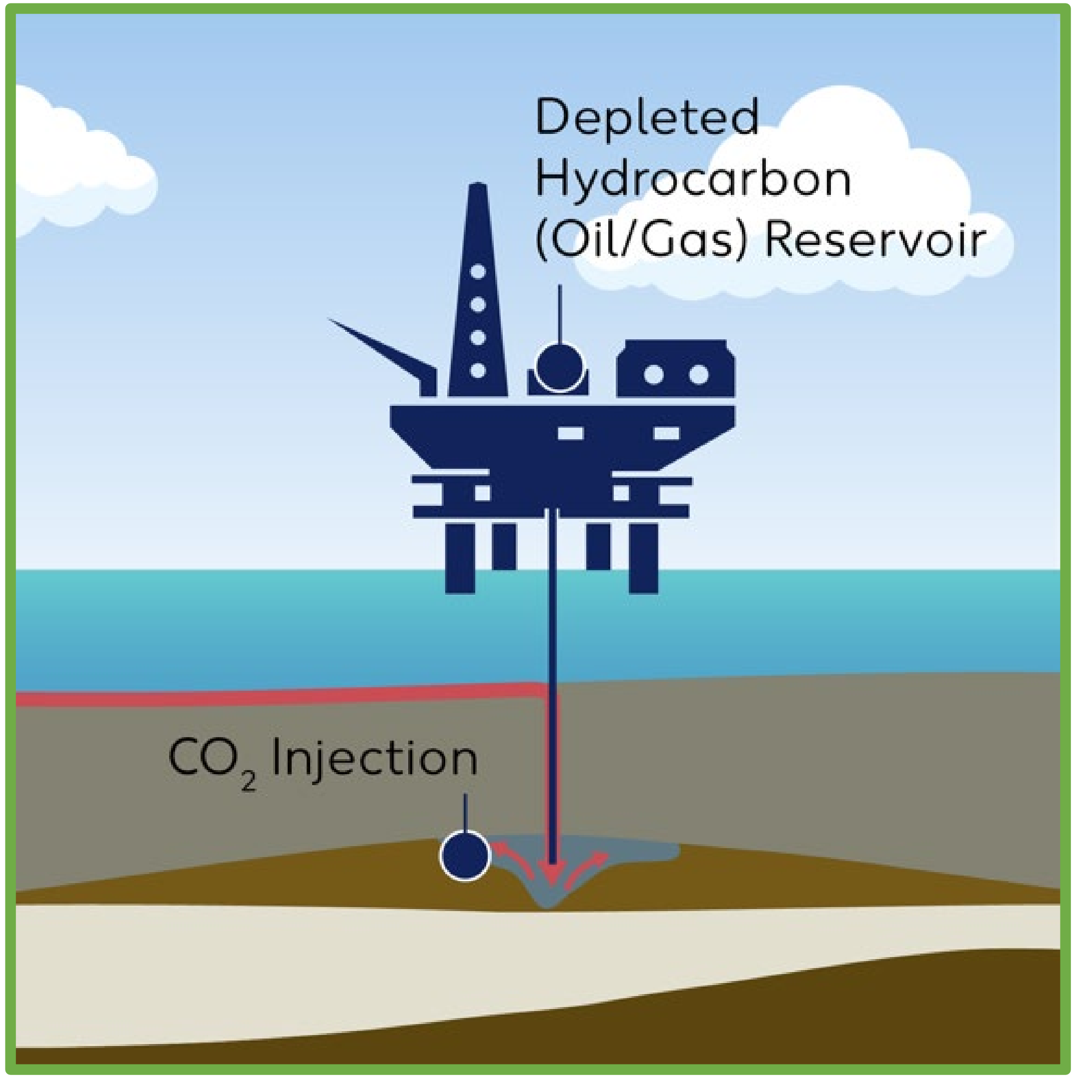
GASSNOVA

InjectWell - Experimental and Numerical Assessments of CO_2 Injectivity and Flow Assurance during Storage in Depleted Hydrocarbon Reservoirs

CLIMIT Demo – grant no. 621097

14 MNOK

2021-2023

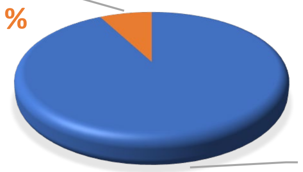


(Re)-using Hydrocarbon Reservoirs for CO_2 Storage

Motivation

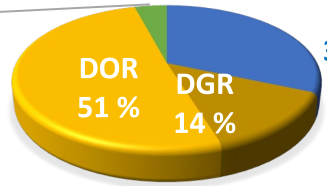
- Accelerate decarbonisation
- Less geological surprises
- More data
- Infrastructure (wells/platforms)?
- Potential for EOR/EGR combined with storage
- **Cost/Risk/Reward**

Total storage capacity

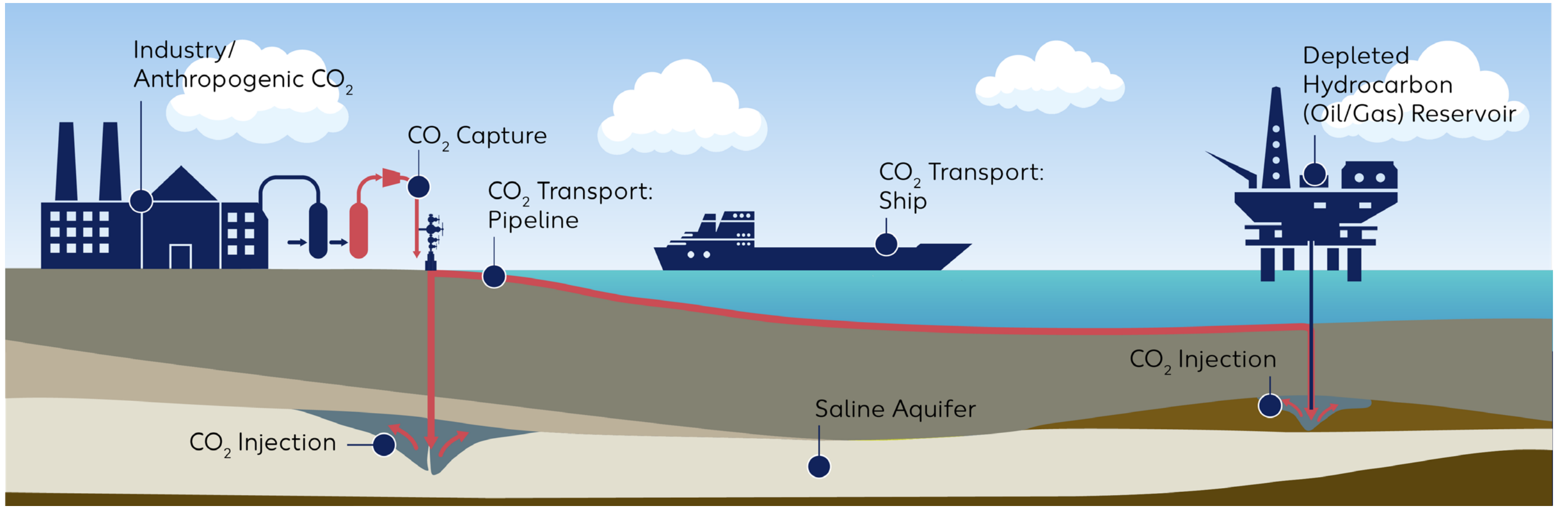


SAs dominate the GCS resource inventory; however, SAs are high level volumetric estimations whereas DHRs are based on reserve calculations (higher confidence)
Source: Global CCS Institute, Resource Assessment Report 2019

Actual projects



On-going and planned GCS projects
(DOR also includes CO_2-EOR projects)
Source: CO2Re 2020



INJECTWELL

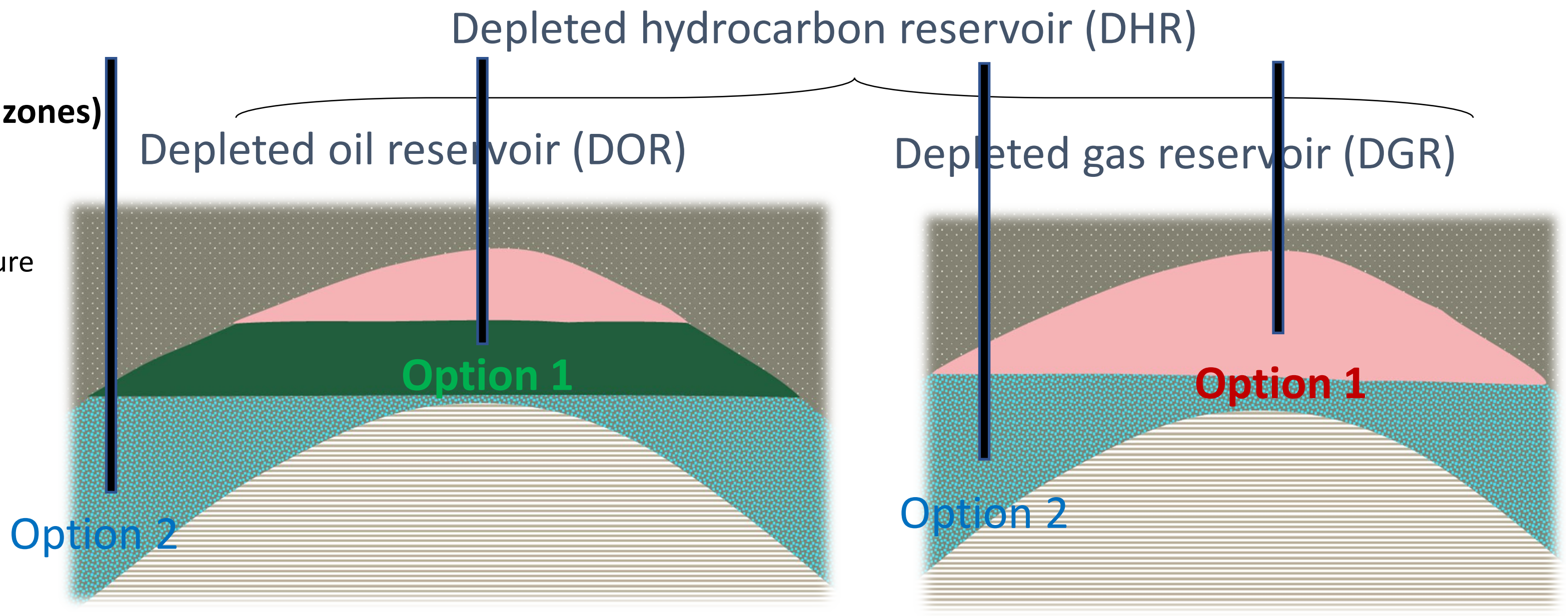
Strategies for CO_2 injection into Depleted Hydrocarbon Reservoirs (DHR)

Option 1

- **Injection into reservoir top (oil- & gas-bearing zones)**
- Stable dry-out zone around the injector (low risk for inj. problems by salting-out)
- Higher wellhead pressure compared to reservoir pressure (higher risk of thermal effects due to JT-cooling)
- Bigger portion of "mobile" CO_2

Option 2

- **Injection into aquifer bottom**
- Unstable dry-out zone around the injector (high risk for inj. problems by salting-out, brine backflow)
- Large CO_2-water contact area (faster mixing, higher contribution of diss. CO_2 to capacity)
- Bigger portion of capillary trapped CO_2

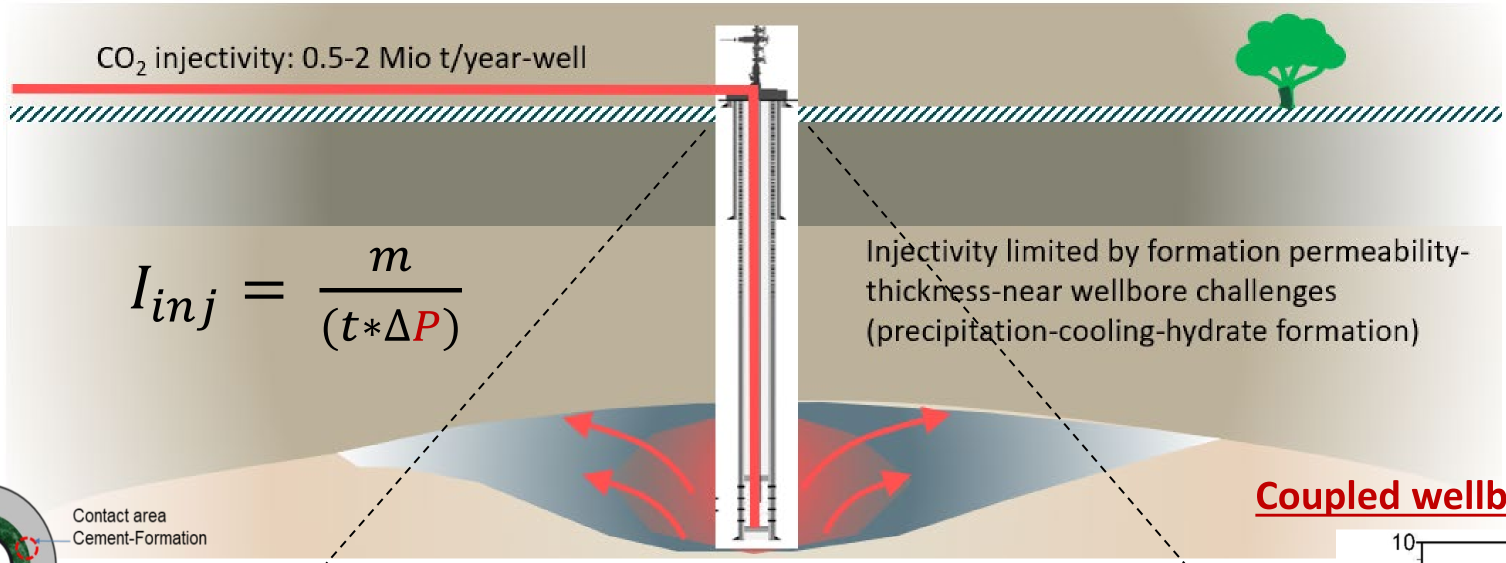


- Reservoir pores filled with **saline water, remaining oil** and **gas**
- Actual pressure ≈ 50 % of initial pressure

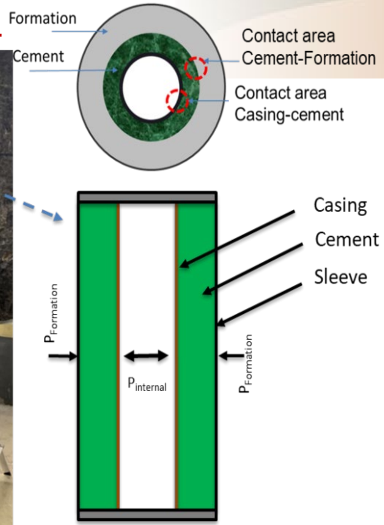
- Reservoir pores filled with **saline water** and **remaining gas**
- Actual pressure ≈ 10 % of initial pressure

INJECTWELL

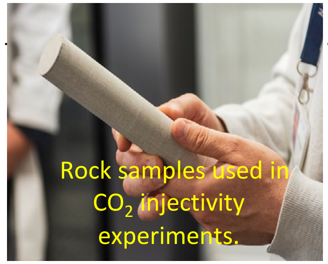
How fast can we get CO_2 into the geological formation – without getting operational problems?

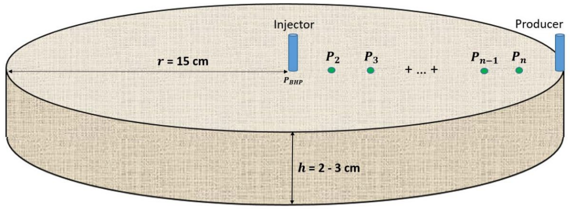


Well Integrity:

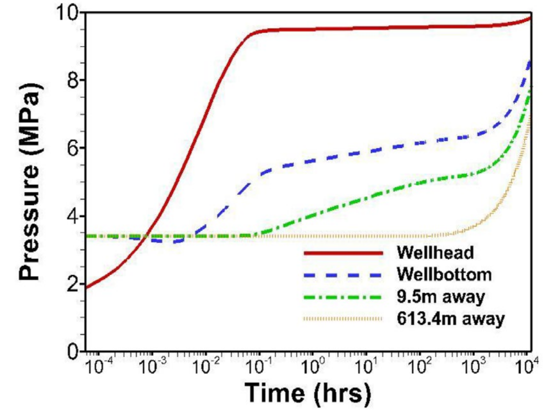


Near-wellbore effects and phenomena:





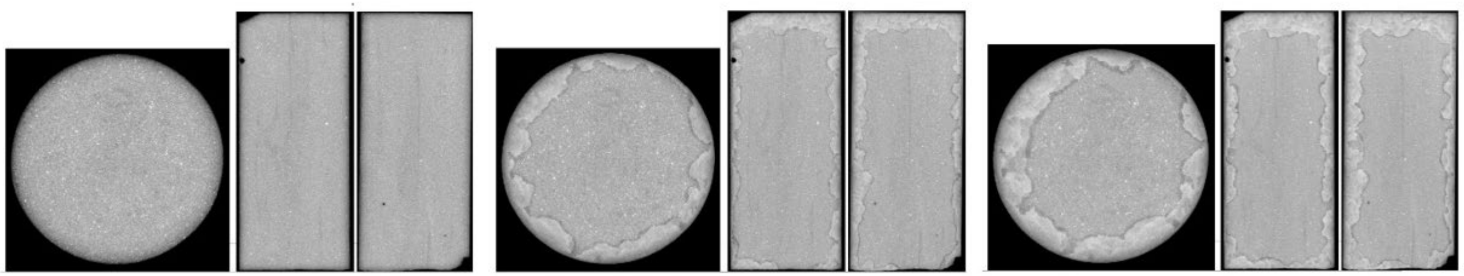
Coupled wellbore-reservoir flow aspects:



INJECTWELL

Experiments #1: Wellbore Integrity (casing/cement/formation rock + their contact areas)

- Mimic exposure of cement types to CO_2-acidic environment – «worst case scenarios»
- Evaluate effect of cyclic pressure and temperature conditions on bond-strength and cement integrity



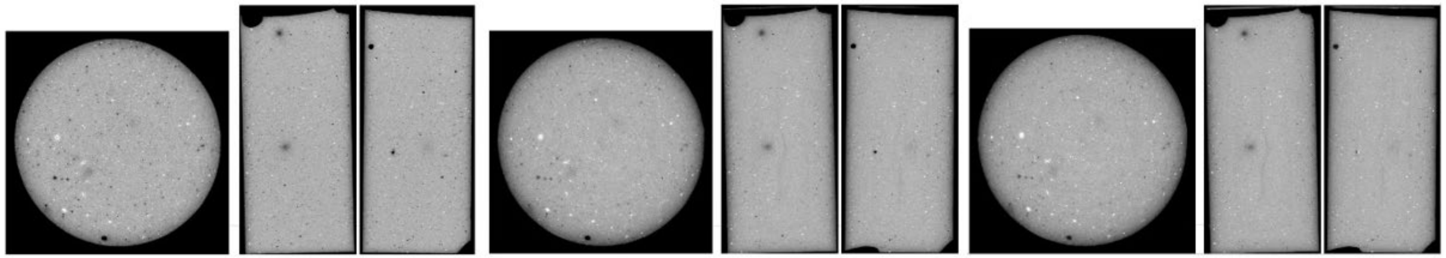
Plug no.10 reference

Plug no.10 after 3 months in CO2 autoclave

Plug no. 10 after 6 months in CO2 autoclave

Cement - Type 1

Compressive strength **not** reduced particularly: ↑

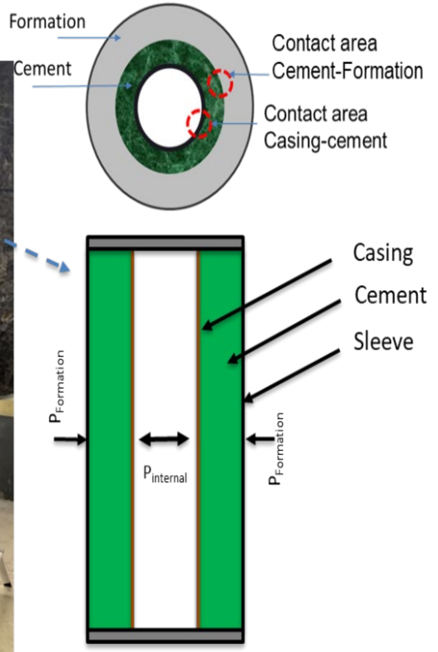


Plug no.6 reference

Plug no.6 after 3 months in CO2 autoclave

Plug no. 6 after 6 months in CO2 autoclave

Cement - Type 2

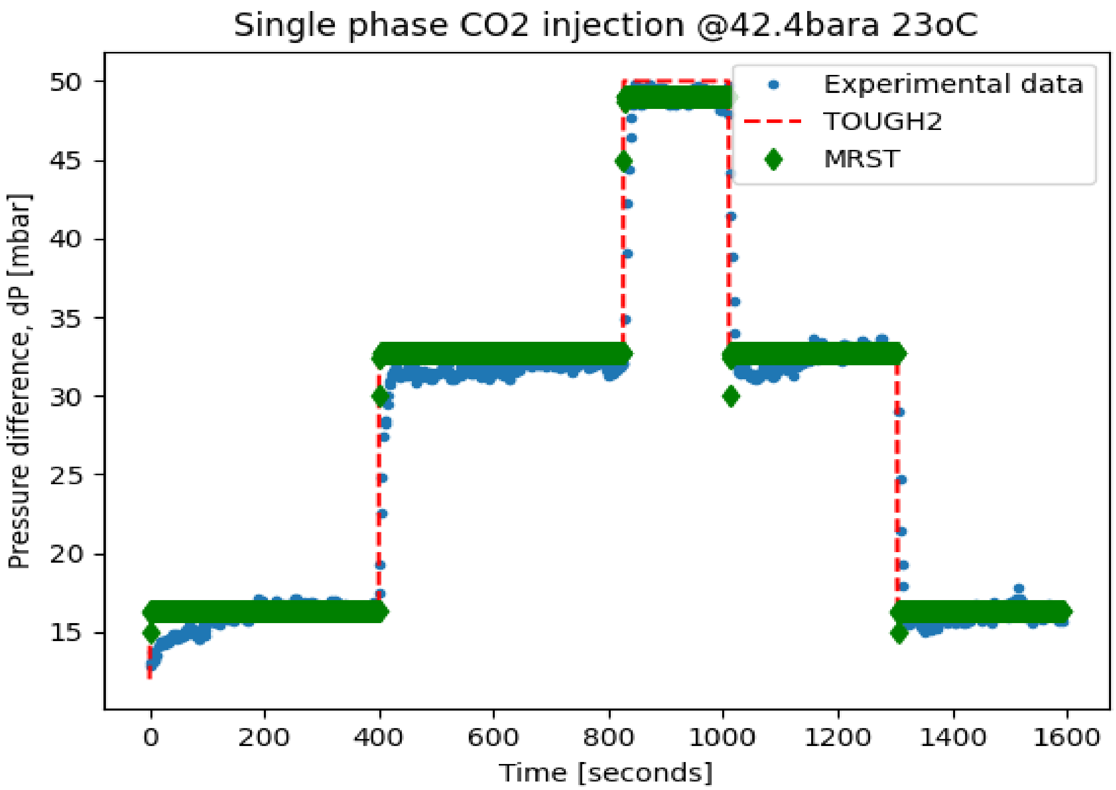


- **Cyclic pressure/temperature:** Both P&T plays a role
- **Effective pressure most important:** Low P_{eff} – channel flow (contact area cement-formation/cement-casing
- **Extreme case:** cement-cracking due to cold CO_2 injection (water expansion)

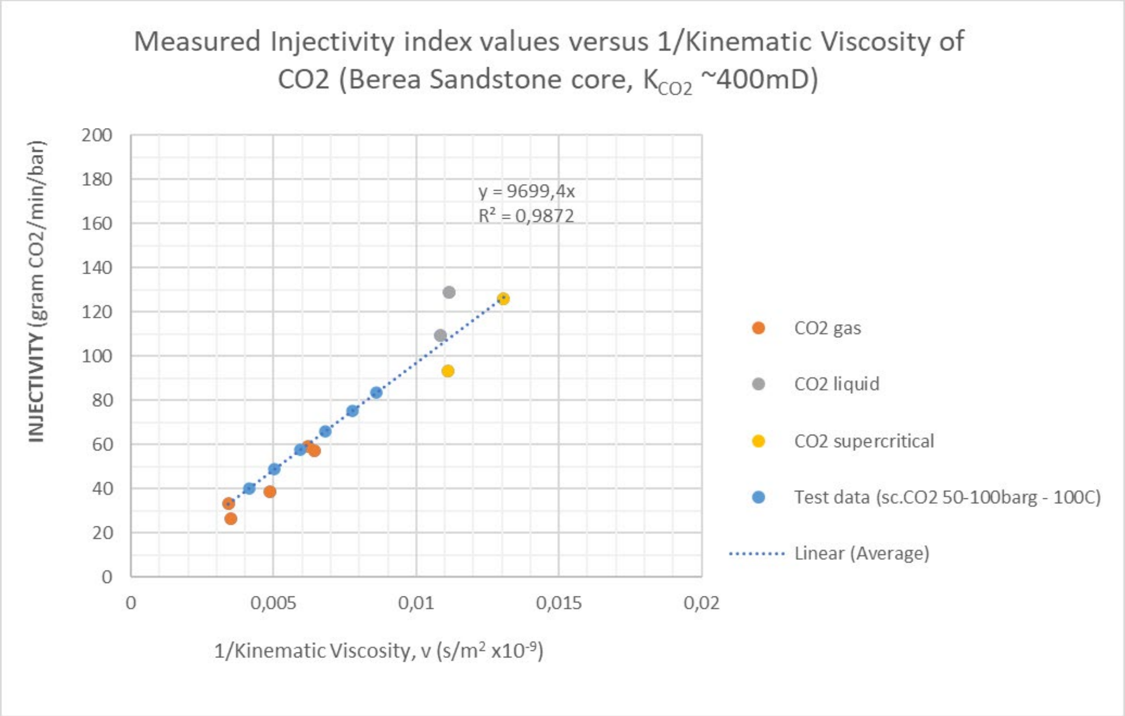
INJECTWELL

Experiments #2: Single phase CO_2 flow – Porous Media

- Better understand the influence of CO_2 phase behavior on injectivity (lab-to-field)
- Compare CO_2 experimental data with simulation predictions



Good match between experimental data and simulation results

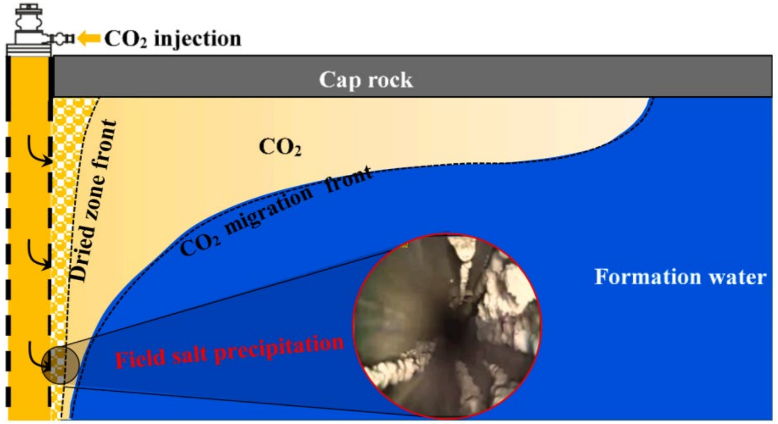


Injectivity index for pure CO_2 is a function of CO_2 kinematic viscosity (μ/ρ)

Experiment #3: Near-wellbore phenomena – aquifer bottom

- **Salt precipitation** – Onset conditions, injectivity impact, mitigation options
- **De-couple impact from other effects**: two-phase flow, geo-chemical, thermal…

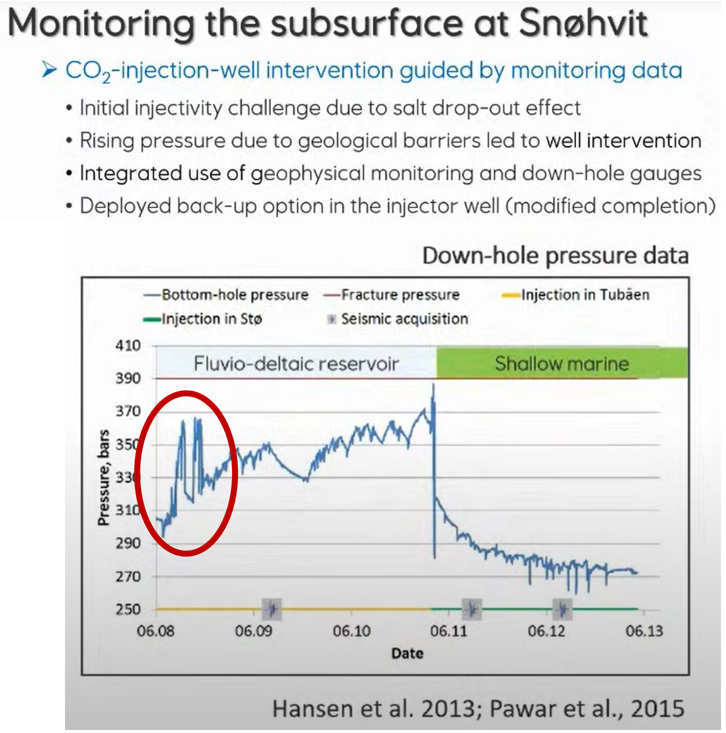
Many field-observations of this phenomena:



Cui et al., (2023) – Aquistore CCS-project - Canada

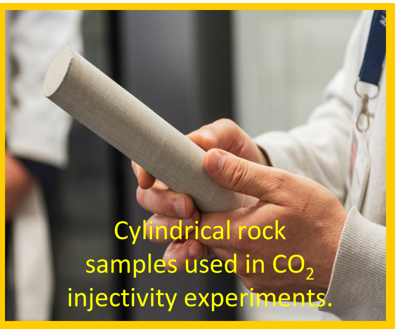
Fig. 3. Partially plugged perforation from Quest CO_2 injection well IW 7–11 April 2018 Downhole Video Log.

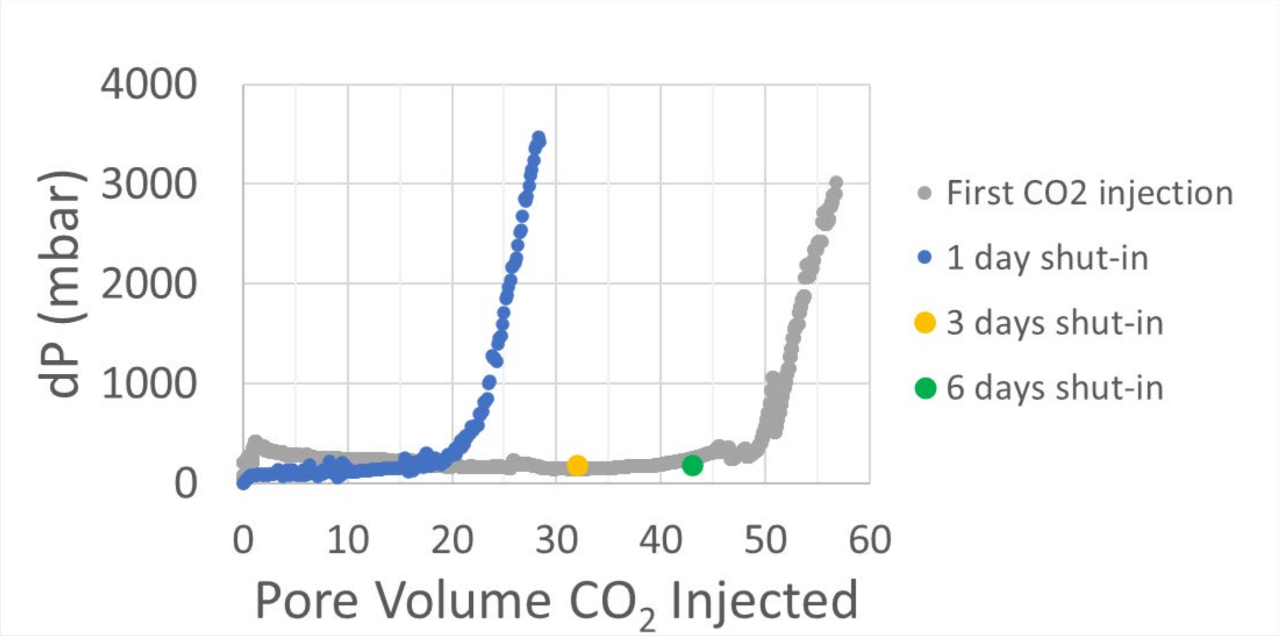
Smith et al., (2022) – Quest CCS-project - Canada



Salt Precipitation Experiments

CO_2 injection into core plug saturated with salt water (core scale observations)





Sandstone core plug
K_w = 400mD

Core inlet

Core oulet

- **Significant injectivity impairment due to salt precipitation**
- Occurs both at supercritcal and gaseous CO_2 conditions.
- Onset of saltblocking are rate, salt, permeability dependent.
- Shut-in time may be a «first-option» to regain injectivity.
- Treatment options/tools needs to be optimized to sustain injectivity.

INJECTWELL

Before exposure

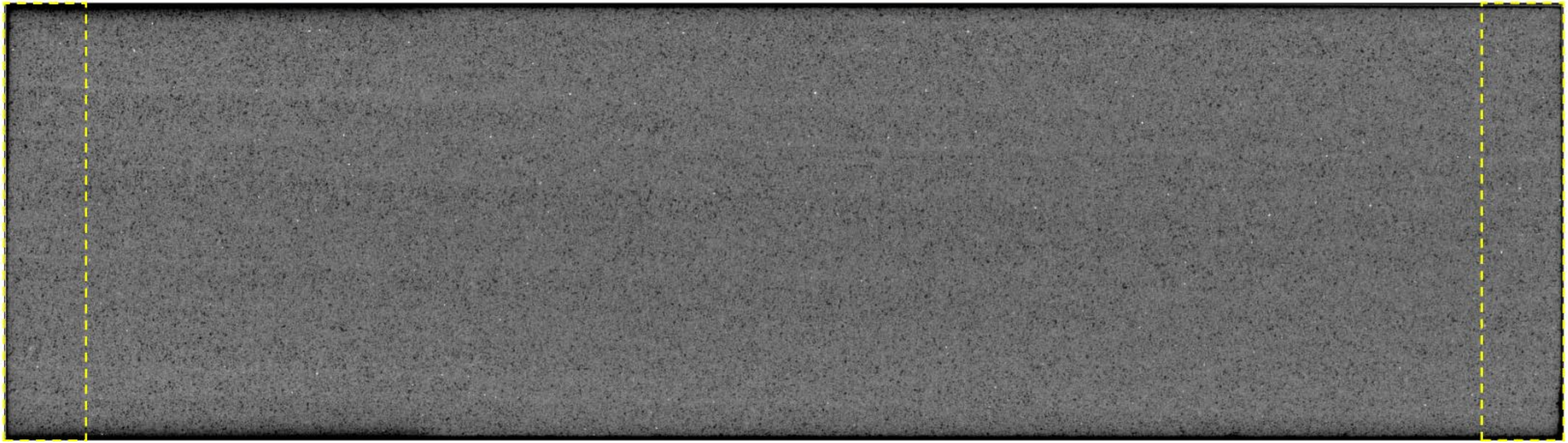
After exposure

Carbonate minerals dissolving in CO_2-brine are mainly; **ankerite and dolomite, with some siderite and calcite**

Central orthogonal longitudinal slices (X & Y) of 3D image: width 38.9 mm and voxel size 17.1 µm

INLET

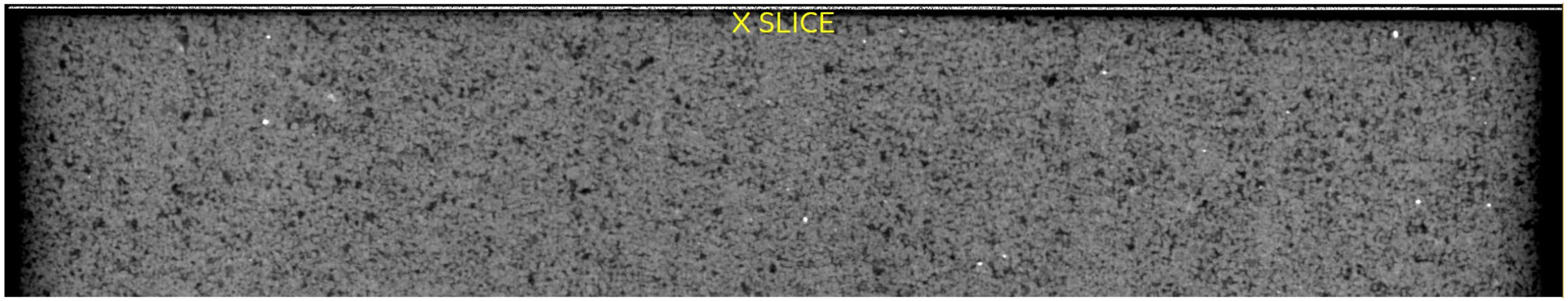
X SLICE



OUTLET

X SLICE

After exposure

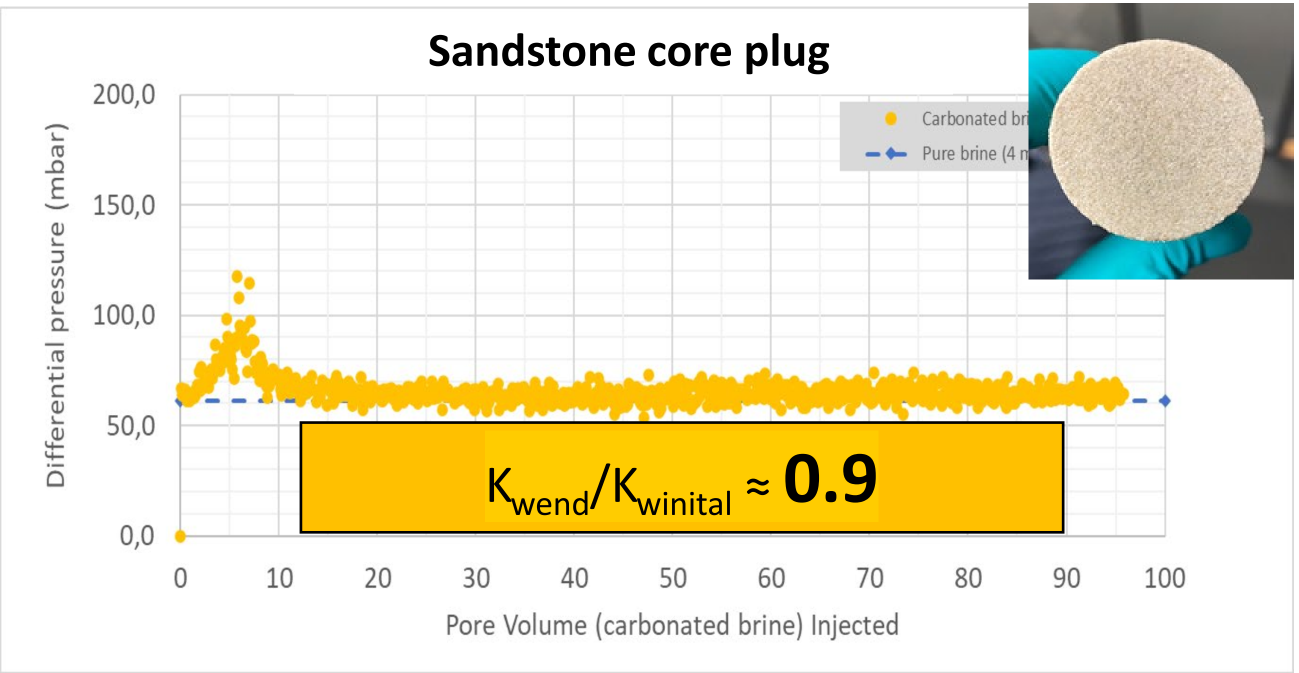


After exposure

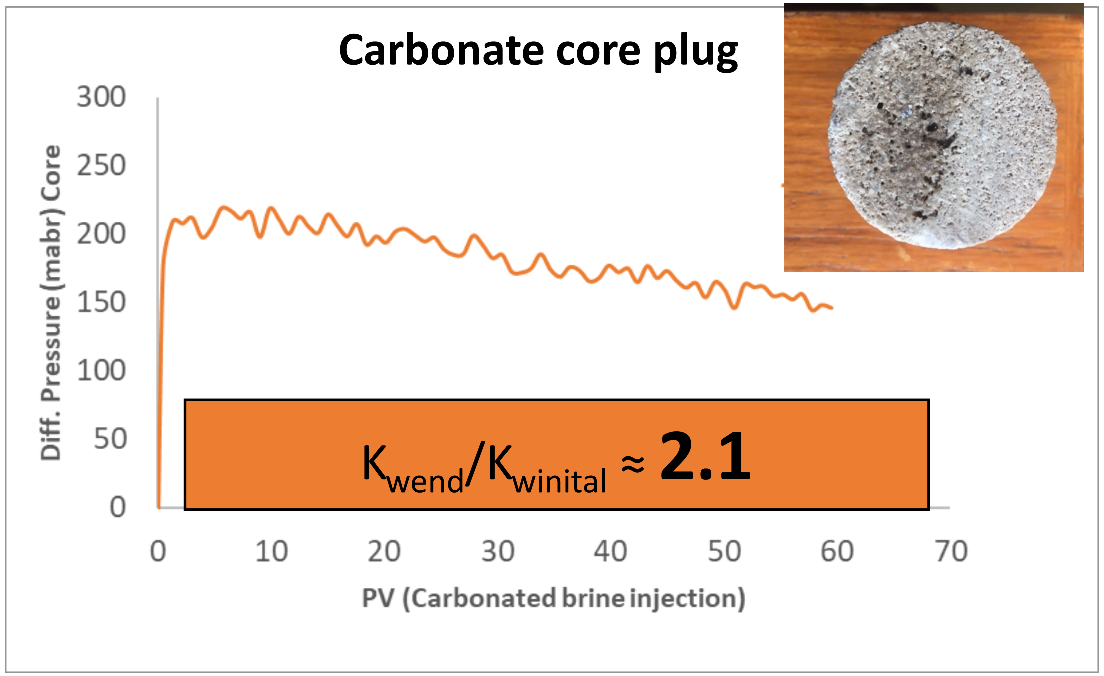
Geo-chemical Experiments

Carbonated water injection into core plug saturated with low salinity water
(core scale observations)

Core inlet



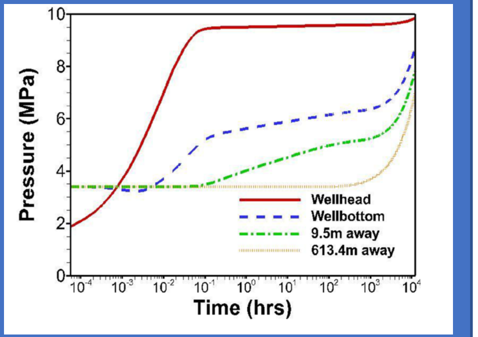
Core inlet



- **Rock specific effect →** experiments/evaluations need to be performed on reservoir spesific rock material.

Numerical Simulation Tools: Advantages & Disadvantages

- **T2WELL:** Philosophy, functionalities, reliability, sensitivity, practical applicability….
- **Case-runs:** Comparison with other tools



ADVANTAGES

- Coupling wellbore and reservoir
- Thermal flow
- Handling phase transition
- Flexibility
- More scientific than industrial

Decision Making

- How flexible and accurate
- Practical applicability
- Handling impurities
- Handling near-wellbore phenomena
- Commercial requirements

DISADVANTAGES

- Flexibility
- No pre- and post- processing
- Difficult in generating input file
- Difficult in handling mesh
- Difficult in handling well-deviation
- Inconsistency in output results (GOFT, TIME, variable injection rate)

INJECTWELL

Summary

The InjectWell project delivers:

- **New experimental efforts on i) wellbore integrity and ii) near-wellbore reservoir effects.**
- **Validation of commercial simulators (T2WELL and others) for coupled wellbore-reservoir flow aspects.**

- **Goal: provide improvement-suggestions to reduce uncertainties and risks of unsustainable injection rates for generic and specific storage projects.**

- **Most of the results from this project will be published in 2023.**

Thank You!

CLIMIT SUMMIT- 09.02.2023

Jonas Solbakken
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INJECTWELL

Tone Holm-Trudeng

RENEWABLES DIRECTOR

CLIMIT SUMMIT

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7–9 February

Extended High Resolution (XHR) Seismic for Mapping and Monitoring of CO_2 reservoirs

Tone Holm-Trudeng joined Magseis Fairfield in 2018 where she is currently serving as Director of Renewables. Prior to joining Magseis Fairfield, Tone worked for 10 years in Schlumberger and WesternGeco. Tone started her career at Schlumberger in Stavanger working with seismic reservoir characterization projects. She holds a MSc in Petroleum Geophysics from Norwegian University of Technology and Science.

The Research Council of Norway

GASSNOVA

Extended High Resolution (XHR) Seismic Mapping and Monitoring of CO_2 reservoirs

Speaker : Tone Holm-Trudeng[1]
Authors: Roya Dehghan Niri[2], Åsmund Sjøen Pedersen[2], Sandrine David[1] and Paul West[1]
1: TGS, 2: Equinor

9th February 2023

Outline

- Background and objectives

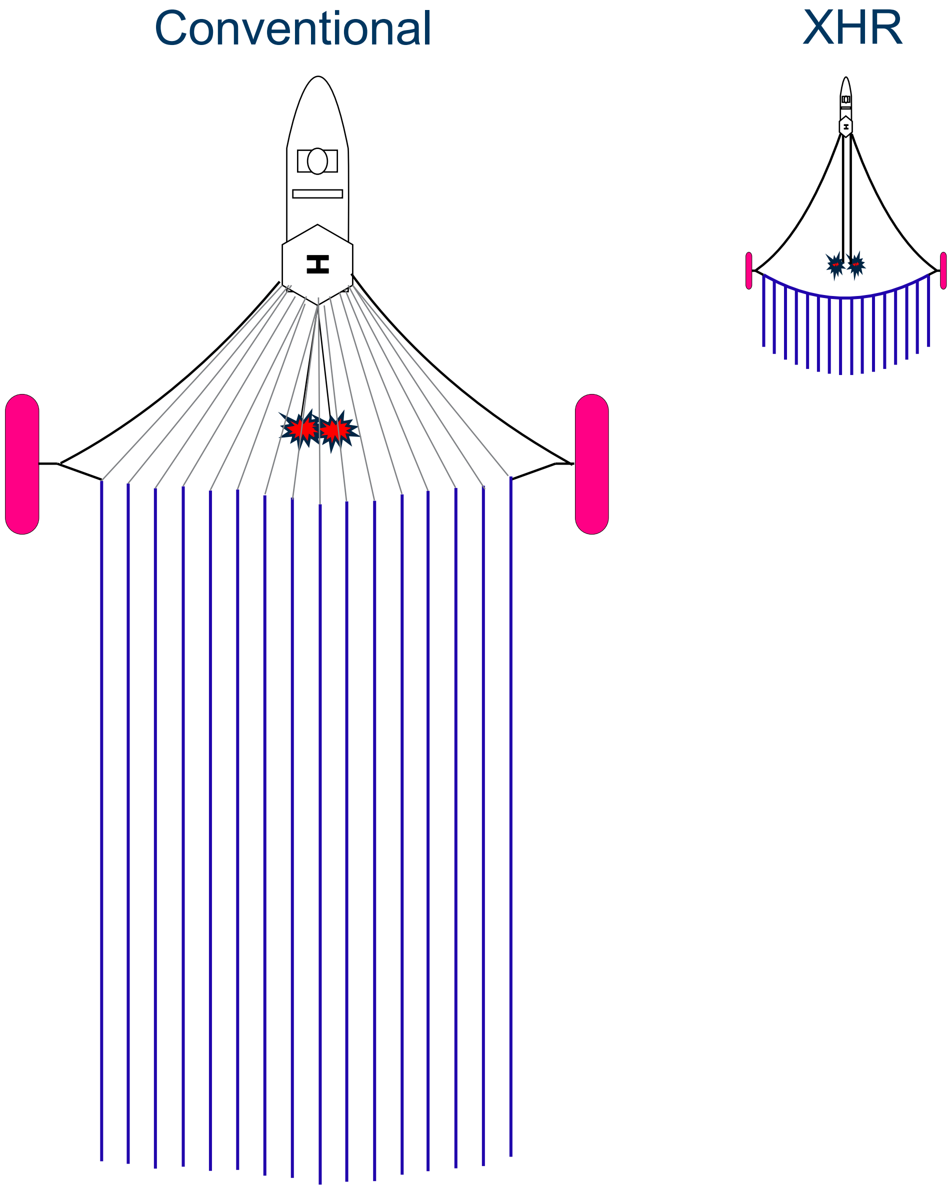
- Acquisition and results
  - Very encouraging

- How does this help to reduce cost and risk related to CCS
  - More detailed monitoring of the overburden and CO_2 plume at reduced cost

- Contribution to Longship/commercialization of CCS
  - Proof of concept of cost effective monitoring technology

Background & Objectives

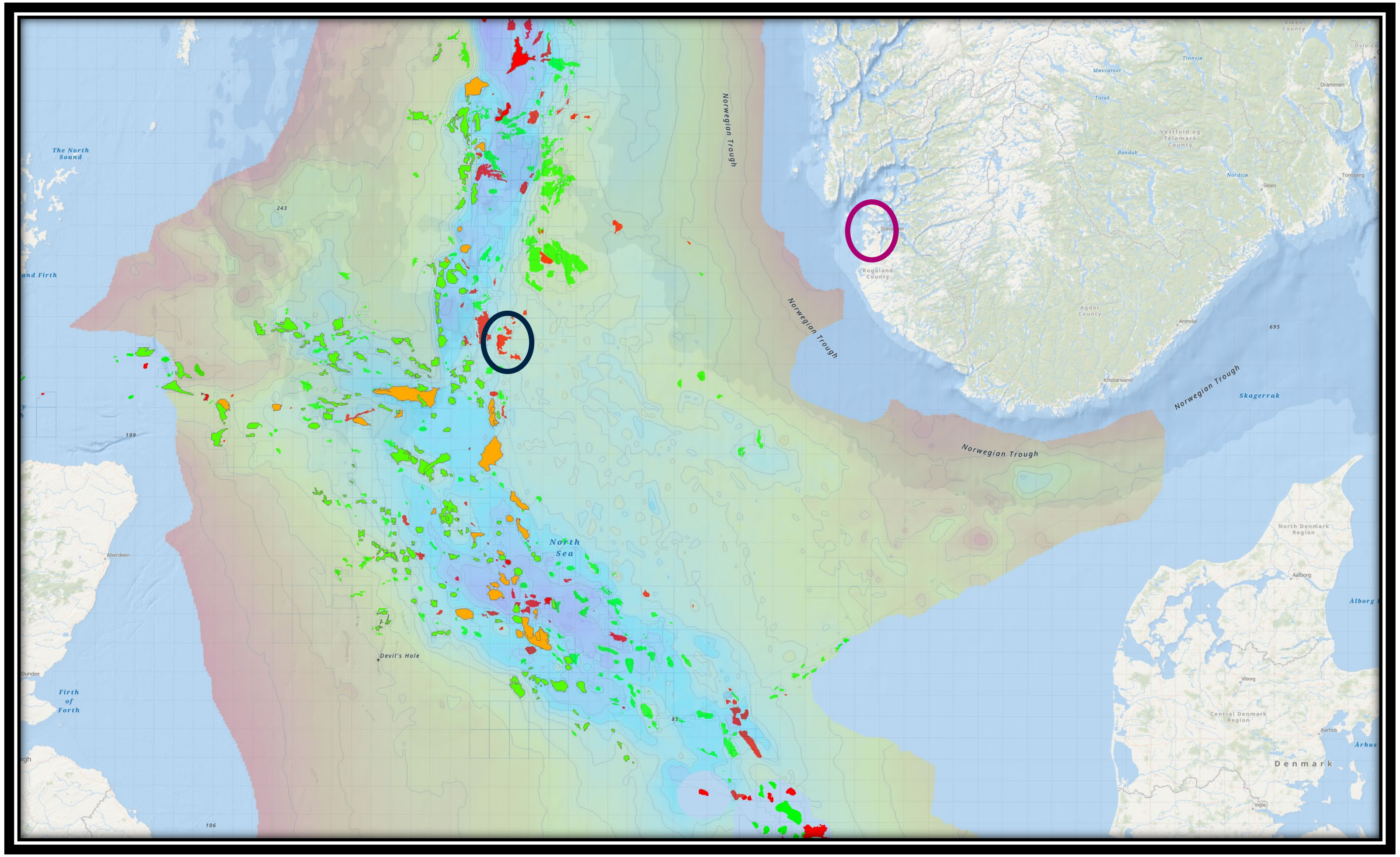
- Ensure conformance and containment of stored CO_2.
- Developed a technology for seismic mapping and monitoring of CO_2 reservoirs, called Extended High-Resolution (XHR)
  - Improved imaging/details in reservoir and overburden
  - Cost effective solution
- Reduced footprint – vessel of opportunity:
  - Reduced cost
  - More environmentally friendly
  - Flexibility – arrange quickly
  - Overburden monitoring (Northern Lights)



Collaboration

- Equinor has shown interest in the CCS application of the XHR technology.

- Collaboration on small scale concept test in 2020 and 2021 over Sleipner
  - Yield promising results
  - Collaborate on full scale test in 2022



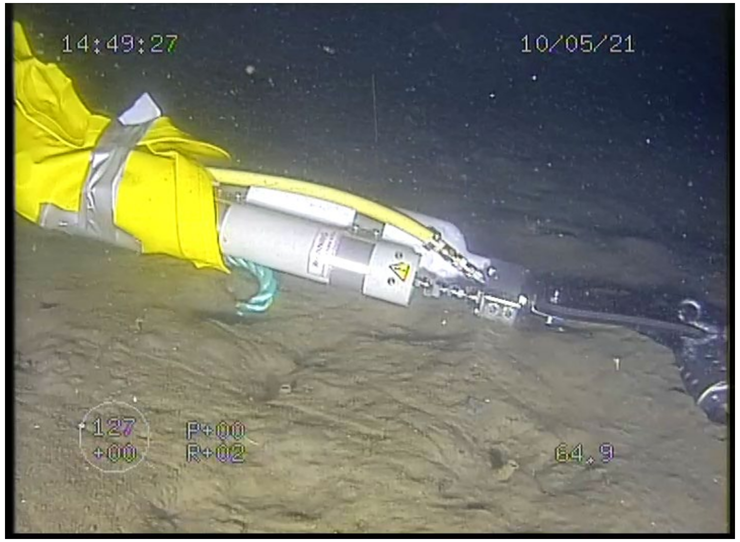
Mobilization port: Tananger

Field location: Sleipner

Office support from Oslo and Trondheim

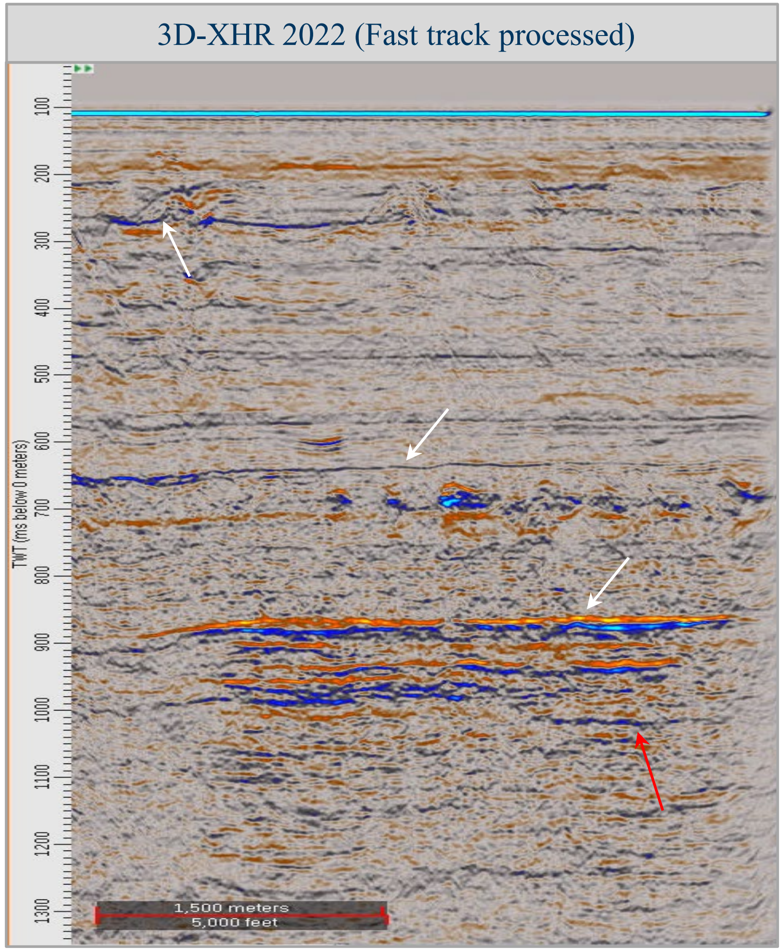
Sleipner 2022 Pilot - Combining XHR with OBN

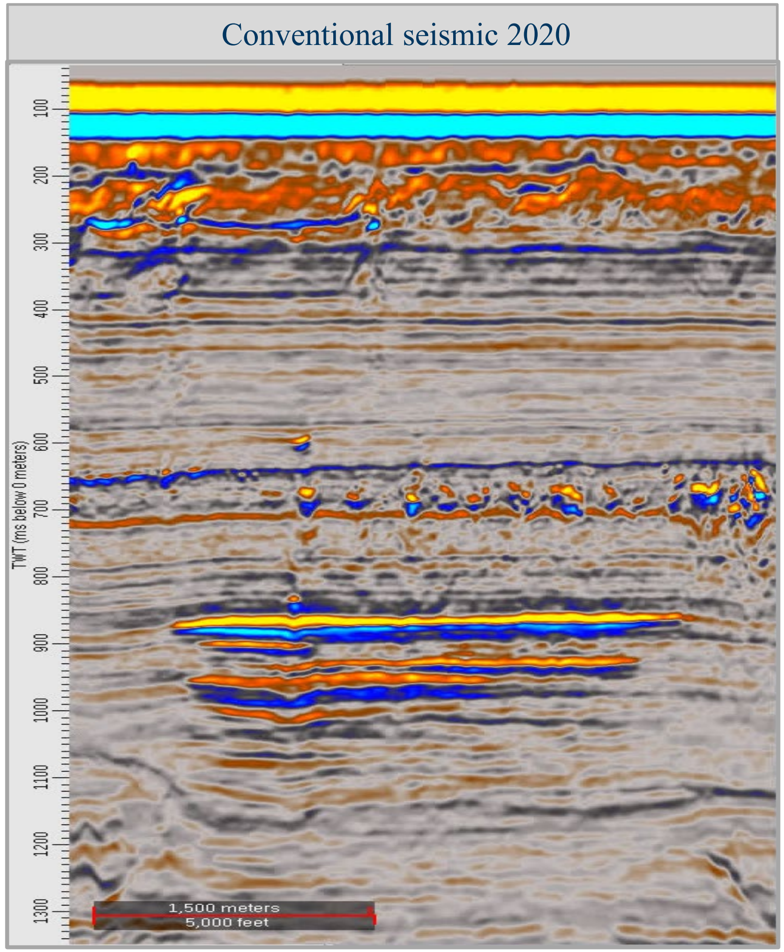
- Acquisition in August/September 2022.
- Nodes was deployed and retrieved cost-efficiently using TGS' proprietary node drop and self-recovery technique.
- The streamer data will provide a high-resolution reflection image.
- The nodal data will provide longer offsets, allowing for new ways of monitoring CCS based on refraction data, e.g., monitoring changes in velocity or attenuation in a 4D FWI scheme.



Results - Comparison of XHR and conventional seismic data

- The CO_2 plume is visible.
- Improved overburden imaging.
- Some reflections are sharper and crispier (white arrows).
- Red arrow indicate some remnant of multiples (not real events)
  - This shows the fast-tracked results, and we expect improvements after final processing.





Data courtesy of Equinor

Contribution to Longship/Commercialization of CCS

- Successful pilot showcasing innovative seismic monitoring technologies
  - Improved imaging/details in reservoir and overburden
  - Cost effective solution

- Reduced footprint – vessel of opportunity:
  - Reduced cost
  - More environmentally friendly
  - Flexibility – arrange quickly
  - Overburden monitoring (Northern Lights)

- Going forward
  - Exploit the data – publish results
  - Further develop efficiency and data quality

TGS

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Philip Ringrose

GEOSCIENCE SPECIALIST

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

Philip Ringrose is a specialist in CO_2 storage and reservoir geoscience at the Equinor Research Centre, Trondheim, Norway. He is also Adjunct Professor in CO_2 Storage at the Norwegian University of Science and Technology (NTNU) and a leader in the Centre for Geophysical Forecasting based at NTNU.

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

HNET project (hordanet.no)

Presented by: Phil Ringrose (Equinor)

HNET project team:

Volker Oye, Andreas Köhler, Annie Jerkins (NORSAR)
Lars Ottemöller, Mathilde Sorensen (Univ. Bergen)
Zoya Zarifi, Roya Dehghan Niri, Roger Bakke (Equinor)
Steve Oates (Shell)
Estelle REBEL (TotalEnergies)
Matthieu Vinchon, Anne-Kari Furre (Northern Lights JV)
Vetle Vinje, Marianne Lefdal (CGG)

Broadband seismometer at Holsnøy (HNAR)

What are we doing and why?

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

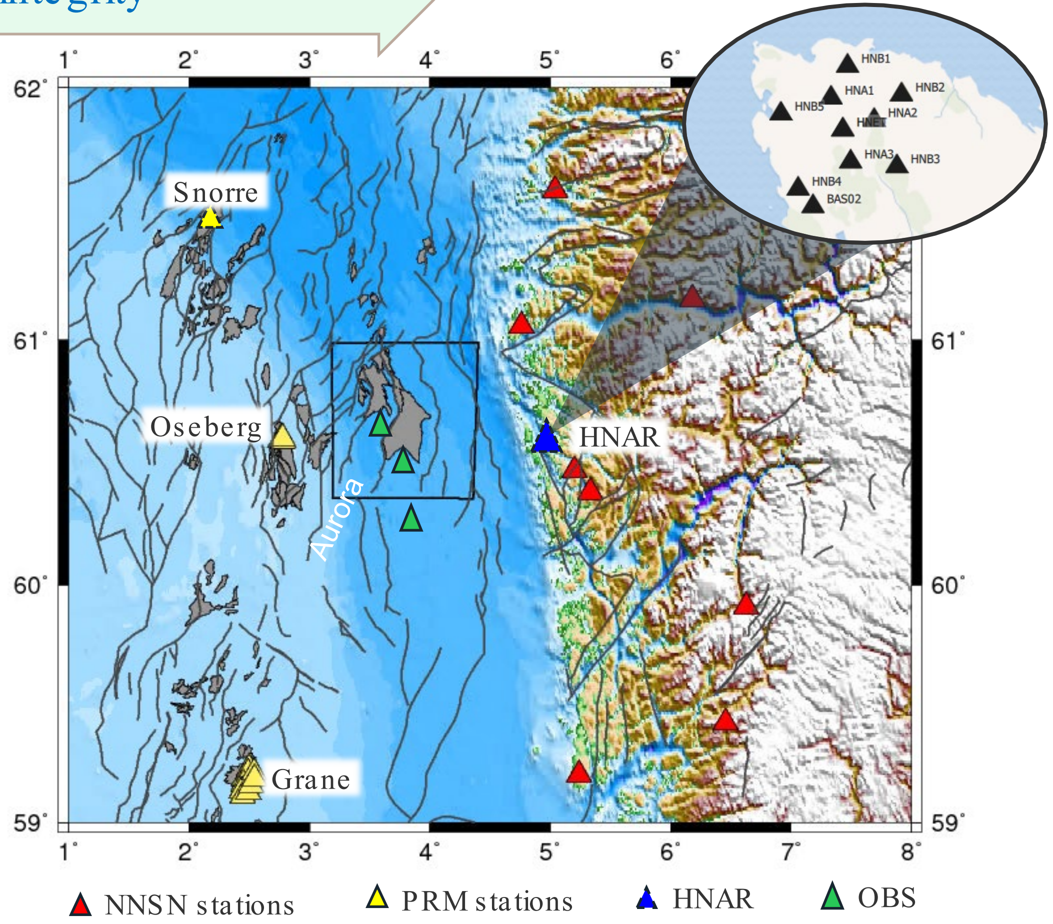
Summary HNET 3 CLIMIT DEMO Project:

- May 2021 to April 2024 - 10.5 MNOK

Main activities in HNET Phase 3 Project:

- **A1:** Routine operation of the HNAR seismic array (Holsnøy)
- **A2:** Testing of offshore deployment of ocean bottom seismometers (in the Aurora region).
- **A3:** Advanced data analysis and interpretation research
    - Automatic routines for joint processing of offshore nodes and onshore data.
    - Improvement of the regional velocity model.
    - Routine use of waveform correlation methods.
- **A4:** Risk assessment and data integration.

Our seismic station network



Project time line (HNET)

2018 — 2020 — 2022 — 2024

Phase 1 | Phase 2 | Phase 3 | Injection start at NL

Project start

Feasibility studies

HNAR array deployment

OBS deployment

OBS retrieval

Concepts for future deployments

Demonstrate array processing

Test use of FO sensing

Risk communication

Challenges of offshore sensing

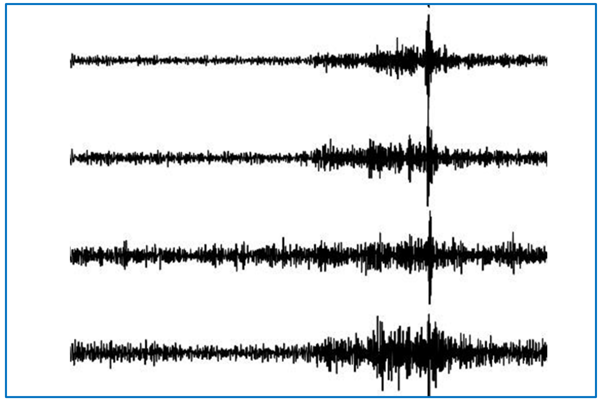
Integration of oilfield PRM nodes

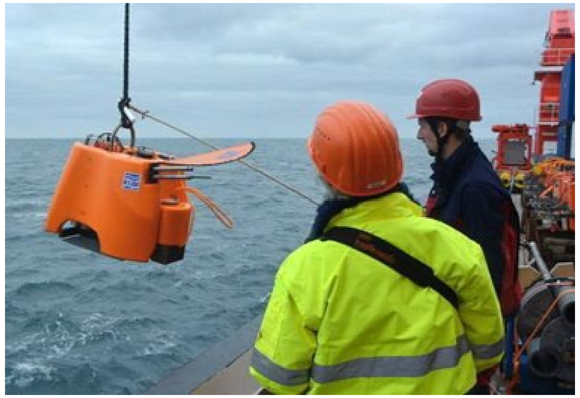
Automatic routines

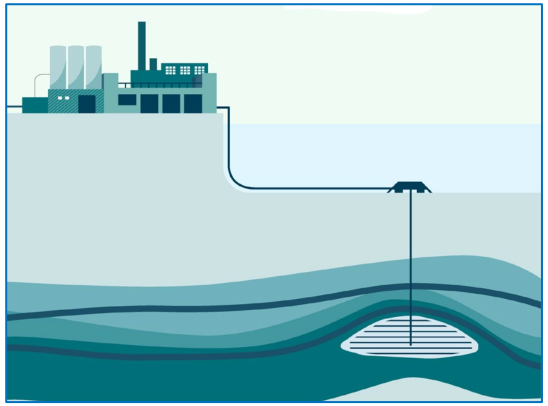
Develop seismicity dashboard

HNAR made open data

Improve velocity model







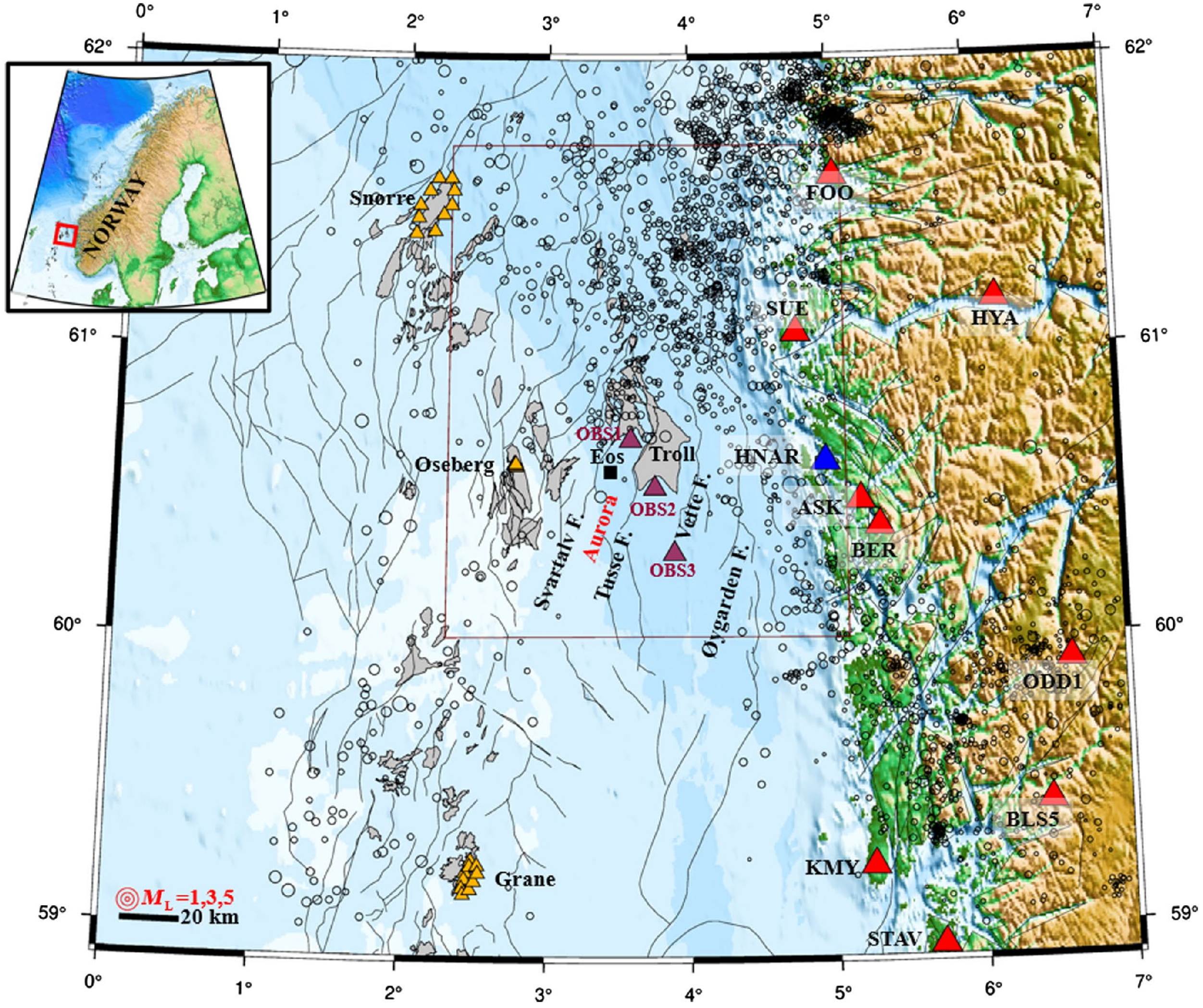
Open

09 February 2023

Project findings so far

1. Normal tectonic activity observed:
   - Gutenberg-Richter b-value of 1
2. Horda platform Magnitude of completeness is $M_C = 1.5$
3. Integration of the offshore geophones with the onshore BroadBand (BB) seismometers gives:
   - Better azimuthal coverage $\Rightarrow$ improved location
   - Improved detection using array processing methods
4. Combining oilfield PRM (offshore array) and HNAR (onshore array) with single station analysis from the onshore BB stations (NNSN) can significantly improve the location accuracy
5. Improved understanding of stress sate:
   - Direction of σ_1 in Horda is NW-SE /W-E
   - Indications of stress relaxation in/below the sedimentary basin package

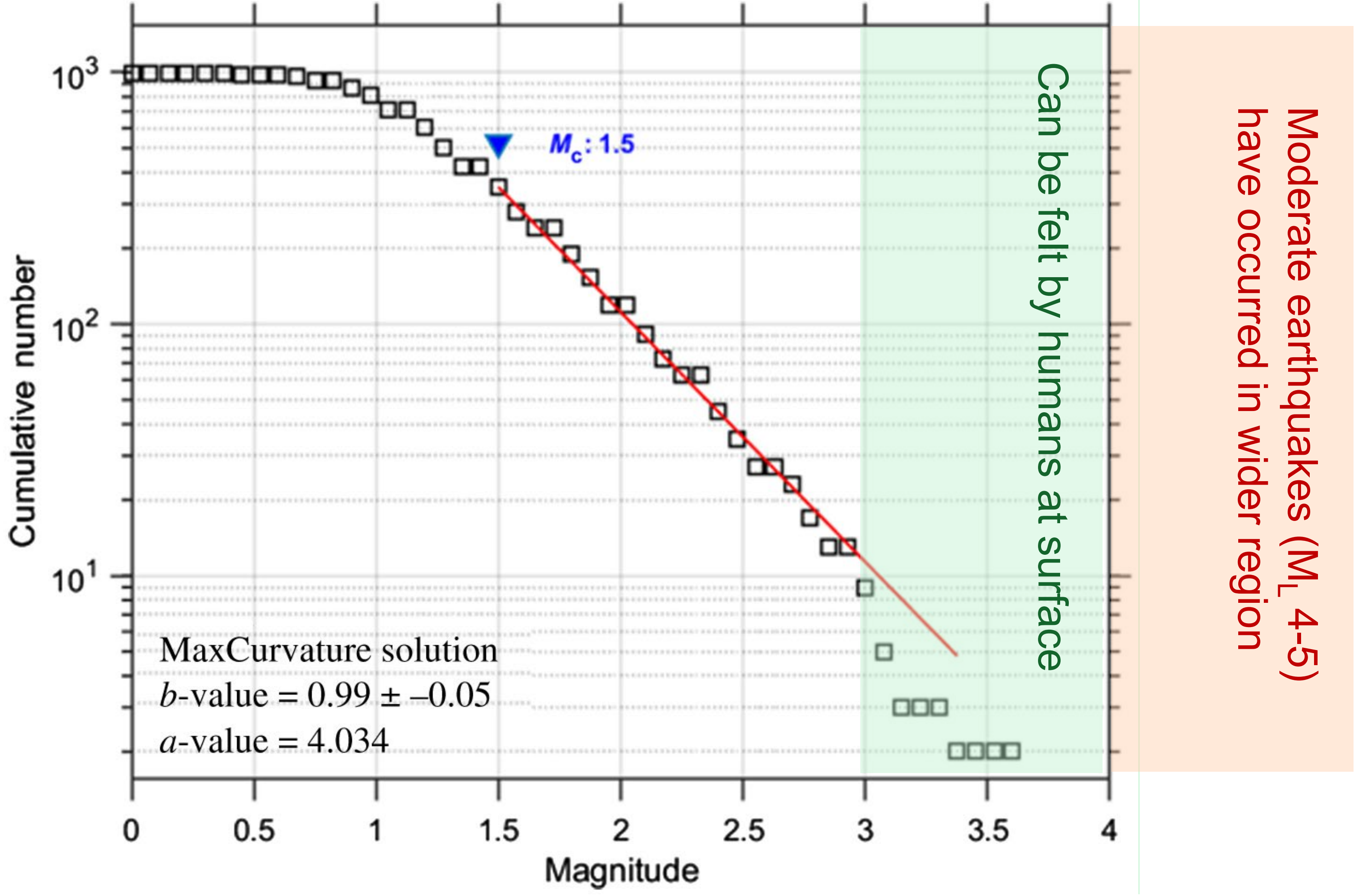
Seismicity in the Horda platform and surrounding areas



How often do earthquakes occur in this region?

Statistical analysis of seismicity:

- Gutenberg-Richter relationship for the Horda platform and its extended area
- Data since 1990 (NNSN catalog)



Improving location accuracy

Effect of adding offshore stations:

- Earthquake of 21 November 2019 (M_L 1.8)
- Red = location error ellipse using only onshore NNSN stations
- Green = location error ellipse when integrating offshore nodes on Grane and Oseberg with the NNSN stations.

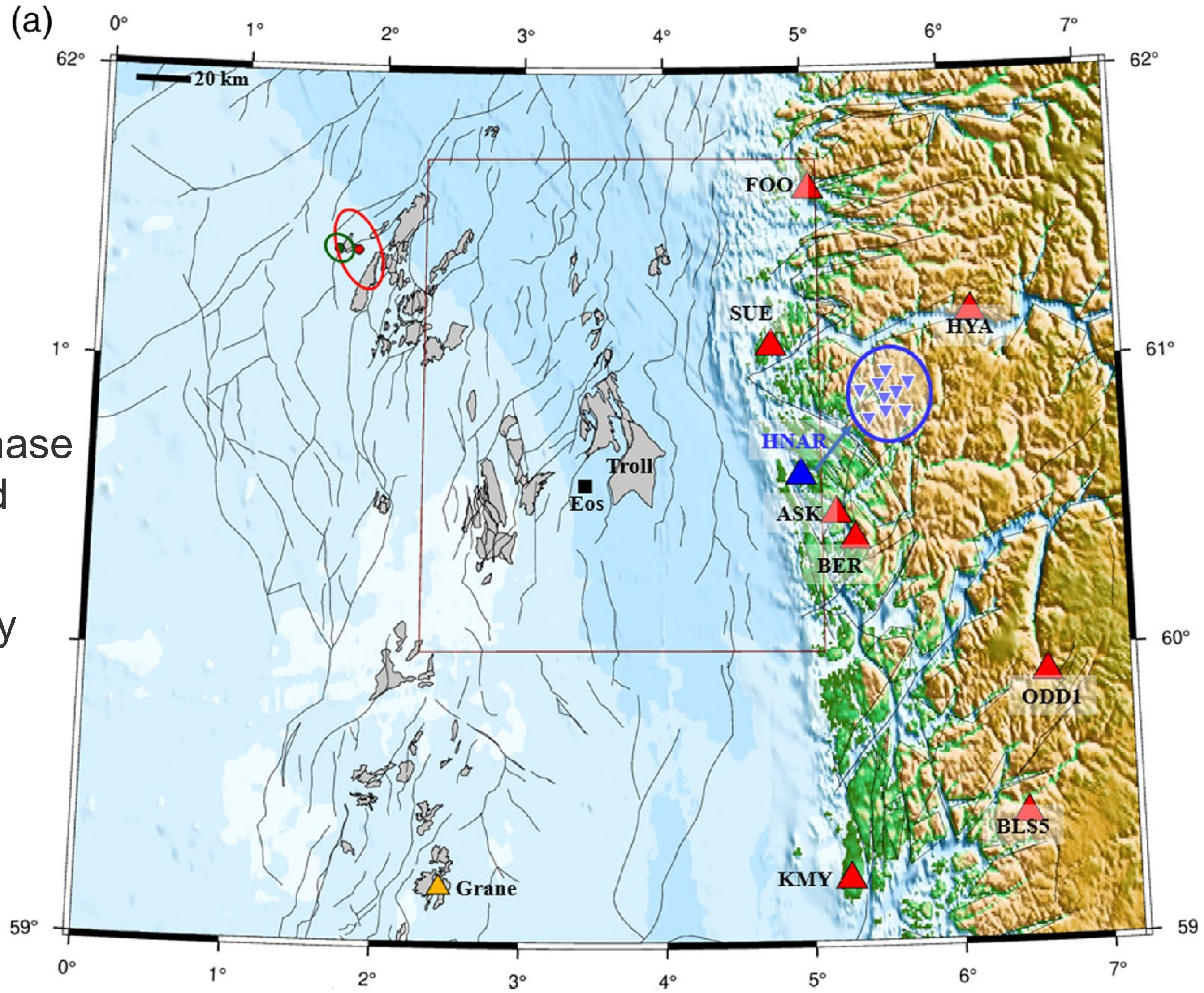
From Zarifi et al. (2022)

Improving location accuracy

Effect of using array processing:

- Earthquake of 1 July 2020 (M_L 1.6)
- Red = location error ellipse using P- and S-phase arrivals using onshore (HNAR and NNSN) and offshore (Grane) stations
- Green = location error ellipse when using array processing on HNAR and Grane

From Zarifi et al. (2022)

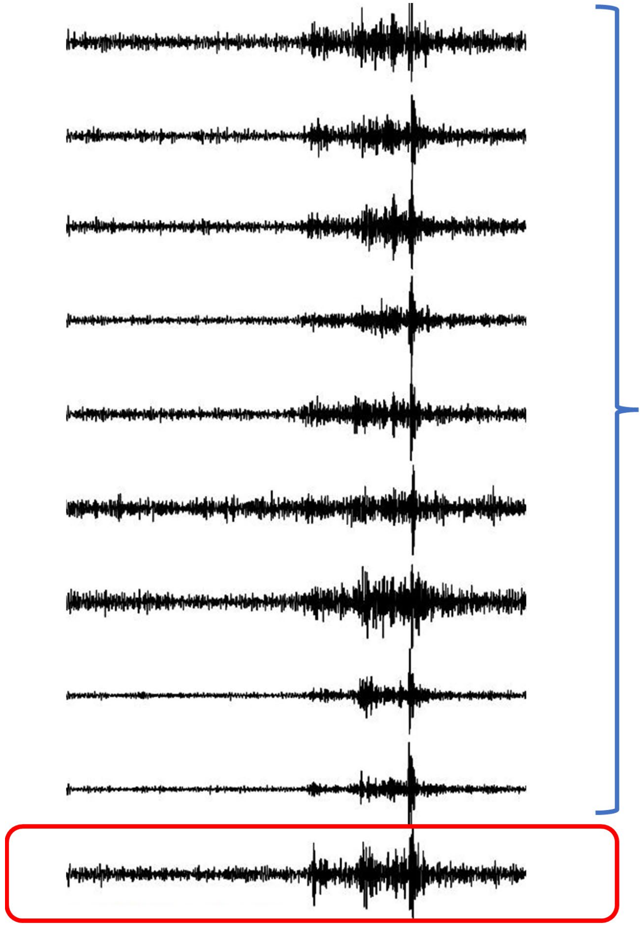


 Open 09 February 2023

Array processing example

- Minor events M<0.5 (close to detection limits) significantly enhanced by beam forming

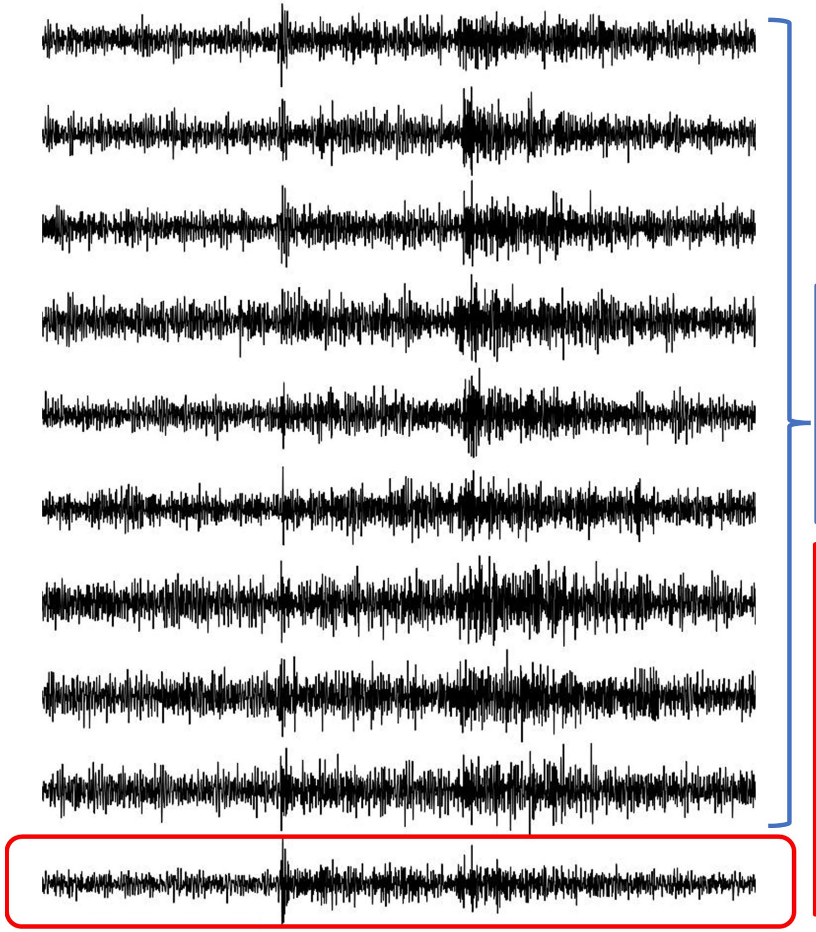
Event 1



Vertical traces of HNAR seismic array

Array P wave beam: time-shifts for given direction and P-wave velocity + stacking

Event 2



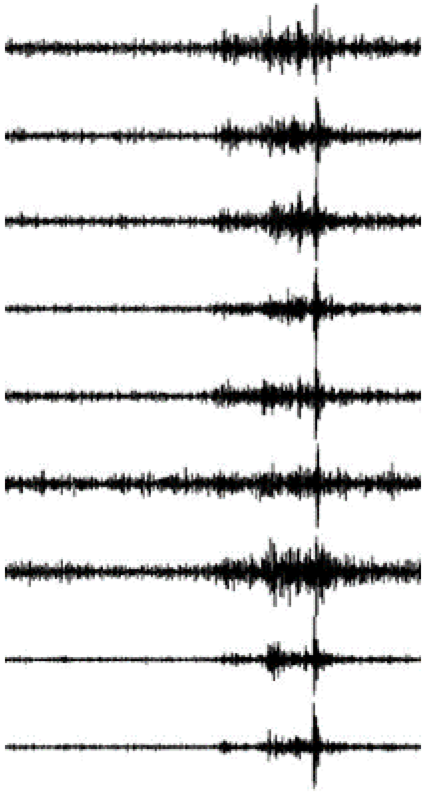
Vertical traces of HNAR seismic array

Array P wave beam: time-shifts for given direction and P-wave velocity + stacking

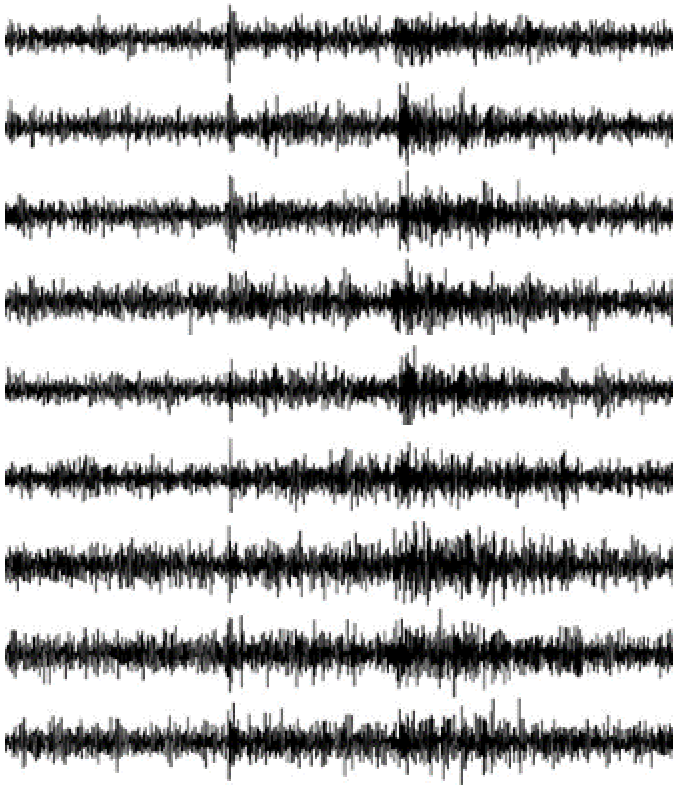
Array processing example

See Jerkins et al. (2023) for full study

Event 1



Event 2



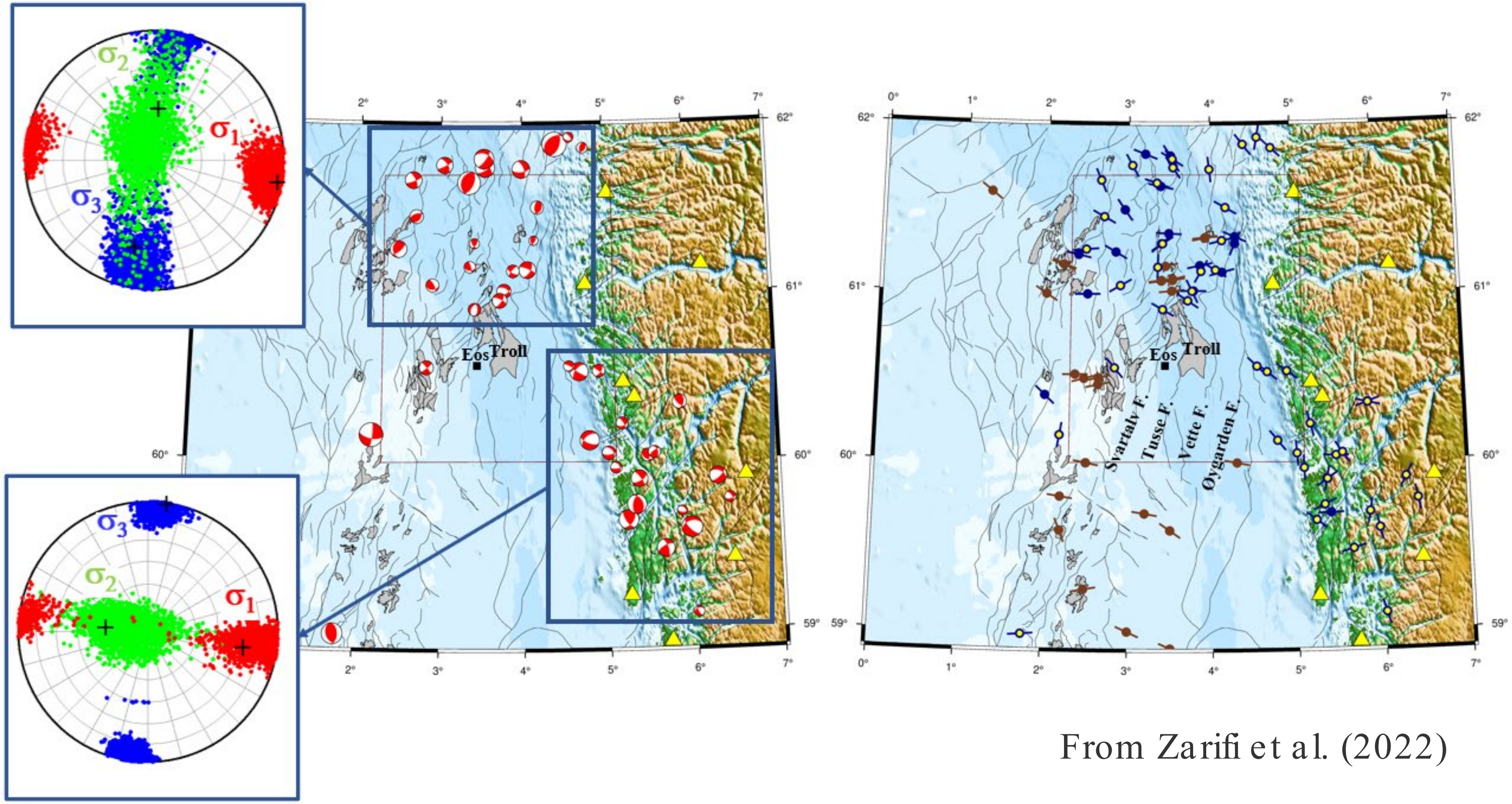
Building knowledge on the state of stress in the region

Focal mechanism of earthquakes
(based on NNSN report: Tjaland and Ottemoller, 2018).

World Stress Map data
(Heidbach et al, Tectonophysics, 2007)

σ_1:100.1°, 57.3°
$\sigma_{2:}$3.5° , 57.3°
$\sigma_{3:}$−167.3° , 32°
$\varphi = 0.44$

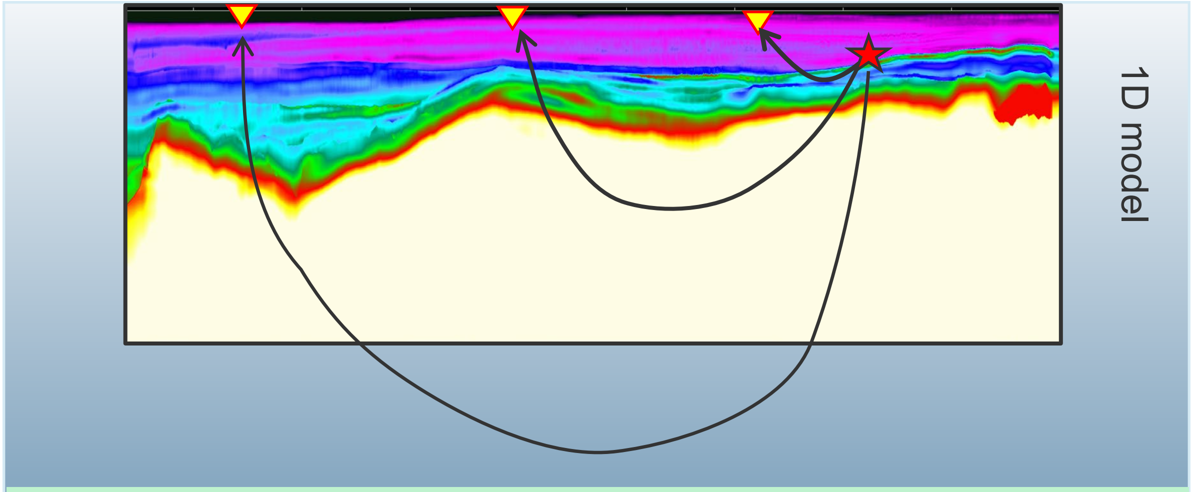
$\sigma_{1:}$98.8°, 26.9°
$\sigma_{2:}$−83.8° , 63.1°
$\sigma_{3:}$8.3° , 1°
$\varphi = 0.68$



From Zarifi et al. (2022)

Ongoing work and way forward

1. Improved automation of event detection (NNSN and HNAR) (NORSAR and U. Bergen)
2. Gain insights from OBS deployments (Led by U. Bergen)
3. Insights from Fibre-Optic DAS field trial on Troll platform (Led by TotalEnergies)
4. Optimal utilization of improved velocity models (CGG and NORSAR)
5. Summarize preferred codes and workflows (Led by Equinor)

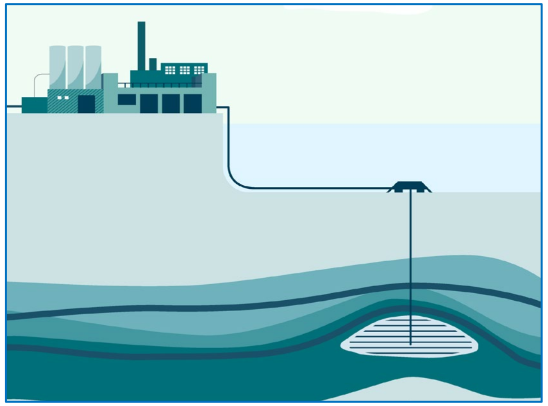


Embedding CGG's model into current 1D model

6. Develop an induced-seismicity response protocol for Horda region (led by Shell)
7. Make improved seismicity dashboard for Horda region (Led by U. Bergen)
8. Hold Scientific Advisory Review in May/June (Led by Equinor)

Deployment and operational phase

Agree optimal seismicity monitoring system for large-scale CO_2 storage in the Horda platform area



Thanks to our sponsors

CLIMIT DEMO project 621148
Phase 3 of the Seismic Monitoring Network for the Horda Platform Region (H-Net) Project

HNET project (hordanet.no)

Main references

Zarifi, Z., Köhler, A., Oye, V., Ringrose, P., Niri, R.D., Bakke, R. and Jerkins, A., **2021.** Development of a baseline seismic monitoring network for the Horda Platform region in support of CO2 storage at the Northern Lights project. *HNET Phase2 Report - https://hordanet.no*

Zarifi, Z., Köhler, A., Ringrose, P., Ottemöller, L., Furre, A.K., Hansteen, F., Jerkins, A., Oye, V., Dehghan Niri, R. and Bakke, R., **2022.** Background Seismicity Monitoring to Prepare for Large-Scale CO 2 Storage Offshore Norway. *Seismological Research Letters.* https://doi.org/10.1785/0220220178

Zarifi, Z., Ringrose, P., Koehler, A., Oye, V., Ottemöller, L., Bakke, R., Rebel, E., Dehghan Niri, R., Sørensen, M., Jerkins, A. and Karlsen, M., **2022.** Background seismicity monitoring prior to CO2 injection in the Horda Platform: The HNET project. *16th Greenhouse Gas Control Technologies Conference* (GHGT-16) 23-24 Oct 2022, Available at SSRN: http://dx.doi.org/10.2139/ssrn.4282685

Jerkins, A.E., Köhler, A. and Oye, V., **2023.** On the potential of offshore sensors and array processing for improving seismic event detection and locations in the North Sea. *Geophysical Journal International*, *233*(2), pp.1191-1212. https://doi.org/10.1093/gji/ggac513

Elin Skurtveit

STRUCTURAL GEOLOGY

Improved workflow for fault risk assessment in faulted CO_2 storage sites

Elin Skurtveit holds a PhD in structural geology, employed at NGI (Norwegian Geotechnical Institute) and an Associate Professor II at University of Oslo, Dept. of Geosciences. Elin follows up several projects related to CO_2 storage and has a passion for integrated research combining geology, geomechanics and rock physics

CLIMIT SUMMIT

#CLIMITSUMMIT2023
7–9 February

The Research Council of Norway

GASSNOVA

Improved workflow for fault risk assessment in faulted CO_2 storage sites

Climit Summit, Larvik, February 9th

Elin Skurtveit

Tore I. Bjørnarå, Emma A. H. Michie, Sarah E. Gasda, Eirik Keilegavlen, Alvar Braathen

FRISK - Quantification of fault-related leakage risk

https://www.ngi.no/Prosjekter/FRISK-storage-risk-related-to-faults-in-reservoirs

The work has been produced under grant number 294719 and
the Norwegian CCS Centre, grant number 257579/E20

Team of Researchers, collaborators and funding partners

UiO : Universitetet i Oslo

TEXAS Geosciences
The University of Texas at Austin
Jackson School of Geosciences

equinor

Forskningsrådet

UNIVERSITY OF BERGEN

HERIOT WATT UNIVERSITY

TotalEnergies

CLIMIT

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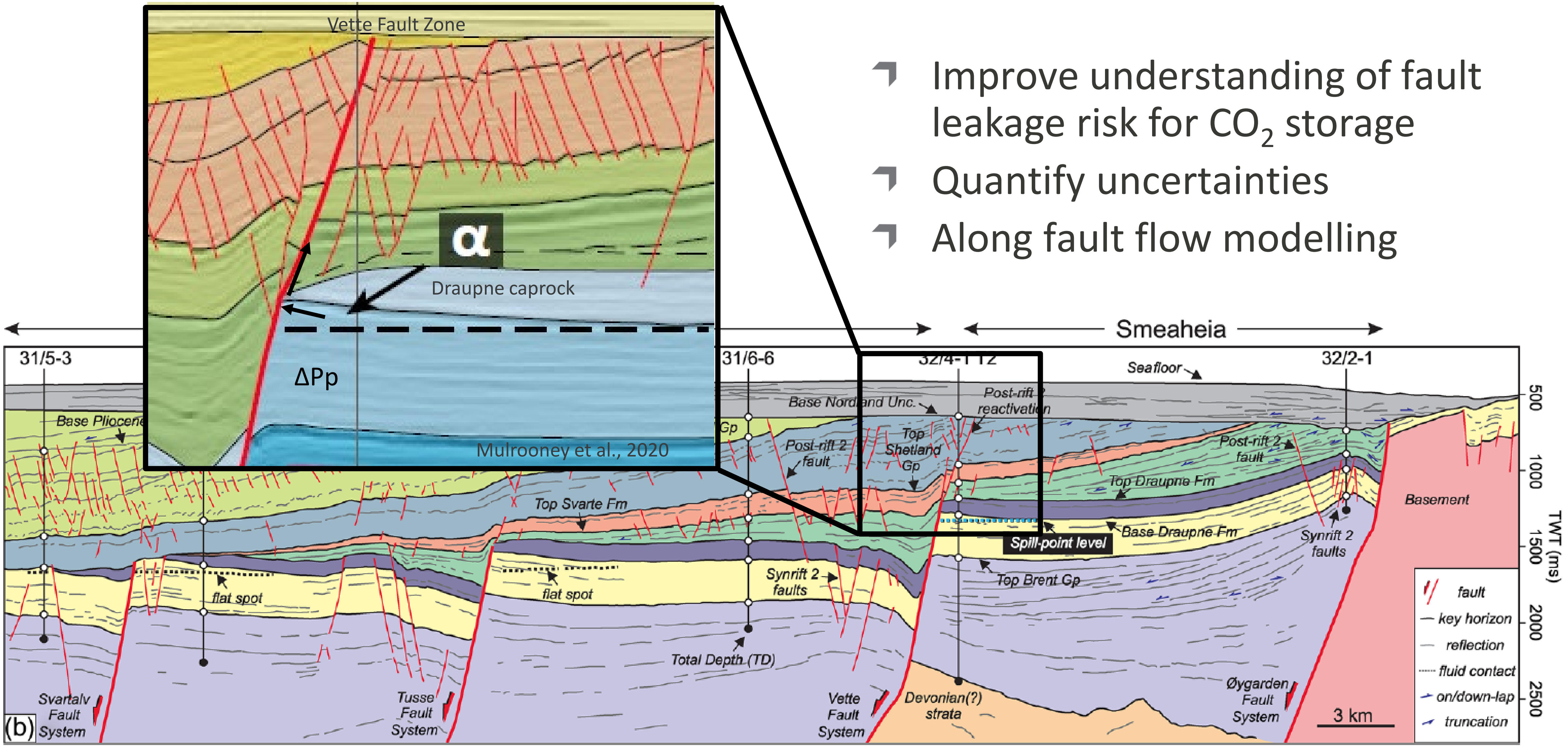
NCCS

Introduction and motivation

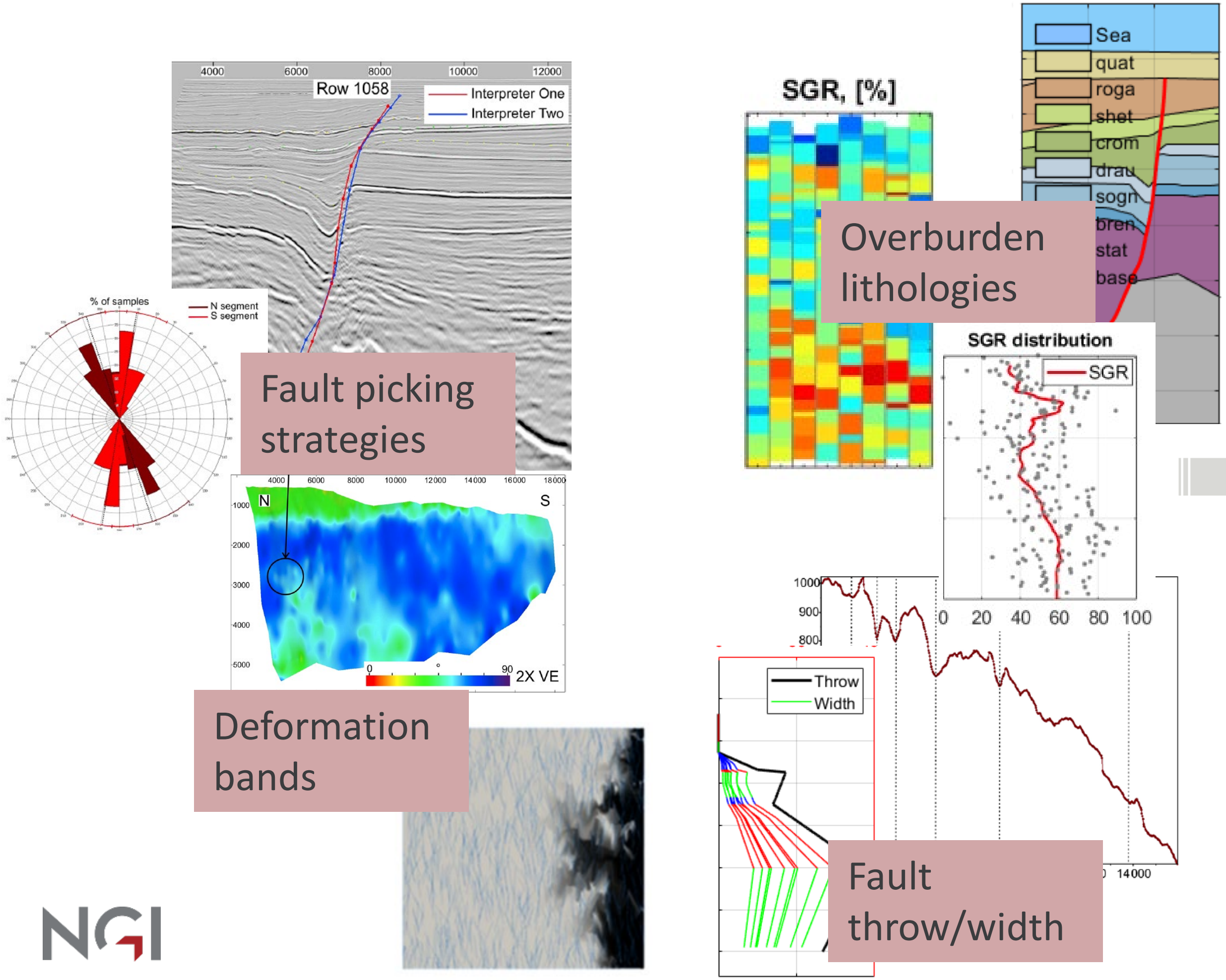
- Improve understanding of fault leakage risk for CO_2 storage
- Quantify uncertainties
- Along fault flow modelling



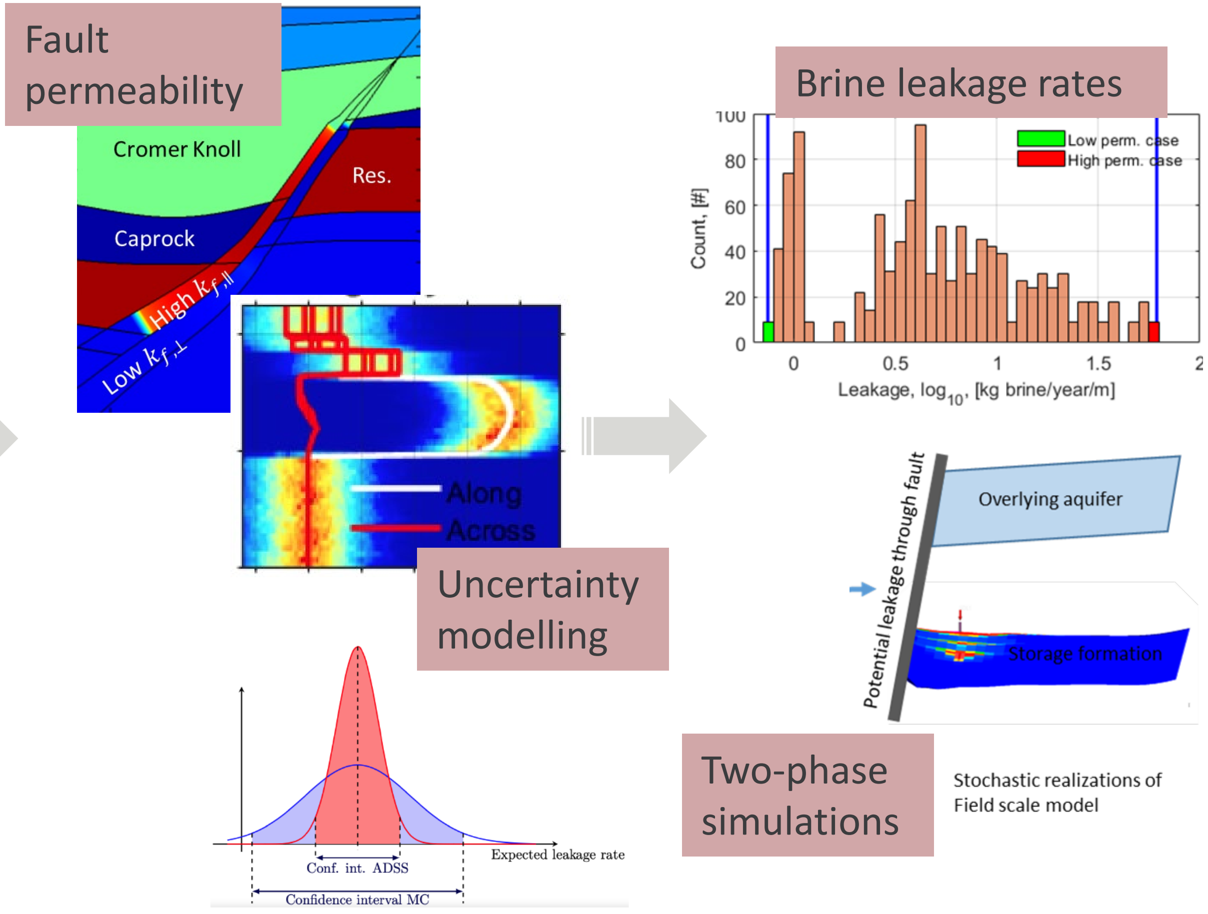
Wu et al., 2021

Improving workflow for fault risk assessment

Quantify uncertainties



Along fault flow models



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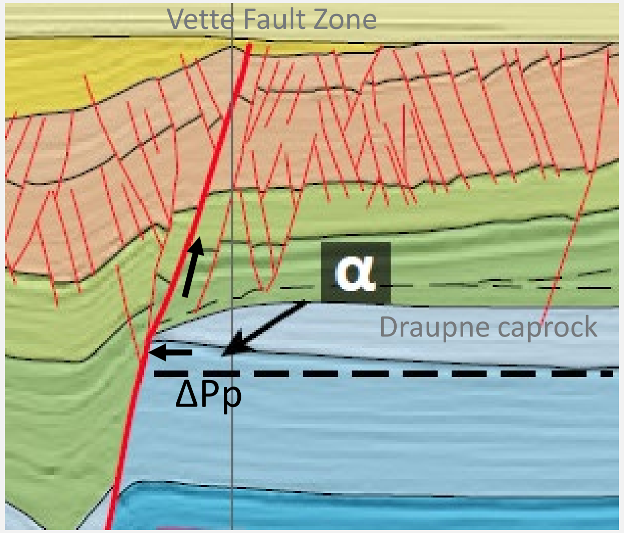
Fault permeability and deformation bands

- CO_2 storage aspects

  CO_2 reaching the fault

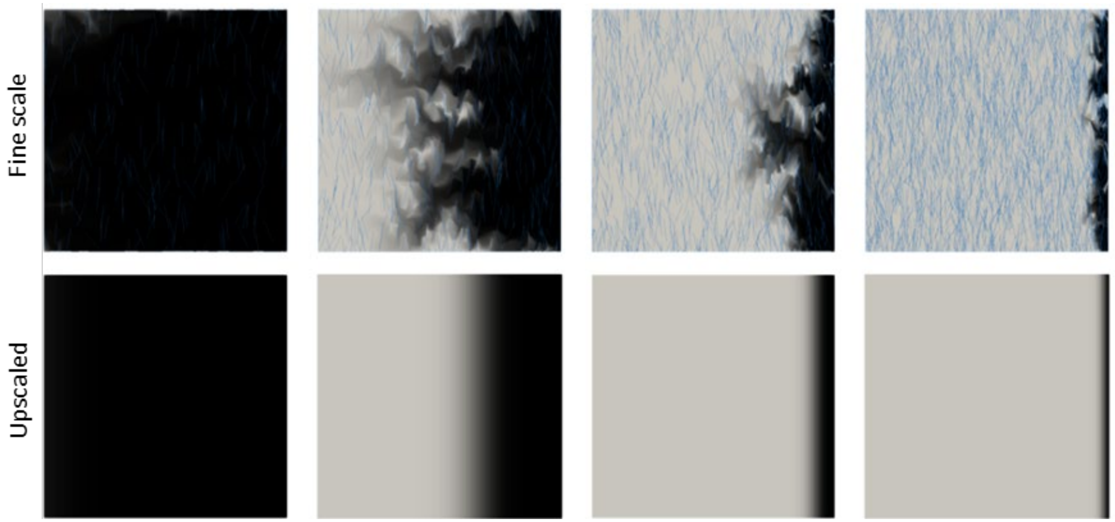
  CO_2 entry pressure

  Reduced reservoir permeability



Mulrooney et al., 2020

Tracer flow through stochastically generated deformation bands



Berge et al., 2021

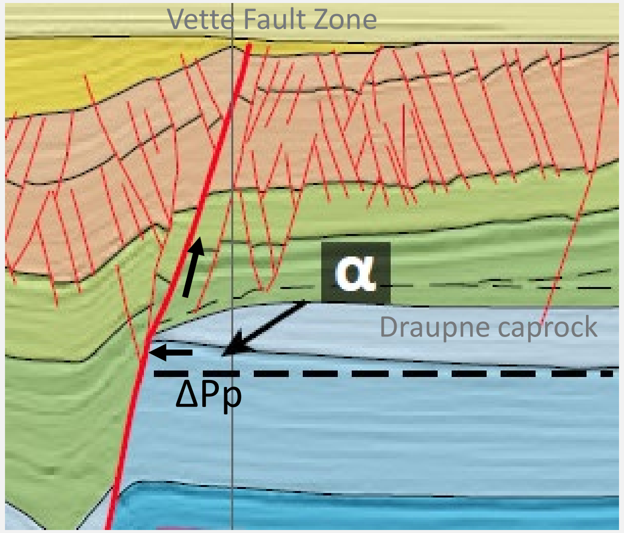
- Deformation bands showed minor impact for sealing faults
- For high permeability faults, deformation bands can baffle the CO_2 migration from reservoir and into the fault

Along fault flow models - Vette Fault Zone

Along fault flow

Static flow inside the fault

Overburden lithology



Mulrooney et al., 2020

Fault zone properties - permeability

Shale Gauge Ratio (SGR) mixing

Clay smear – high anisotropy

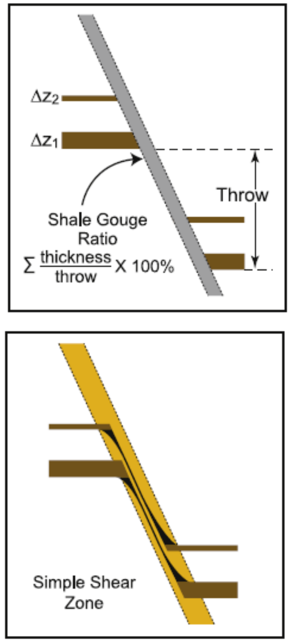
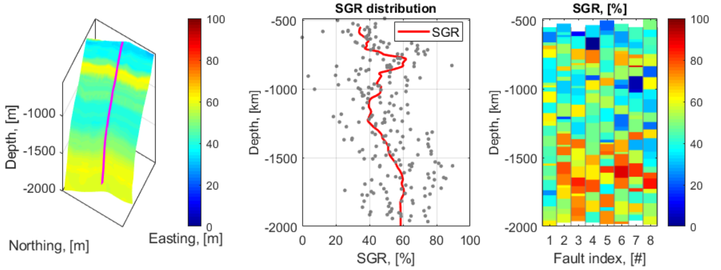


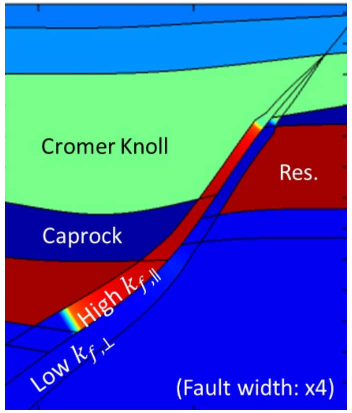
Fig from Vrolijk et al., 2016

Fault facies – Braathen et al., 2009



Bjørnarå et al., 2021

Algorithms from Bense and Person, 2006

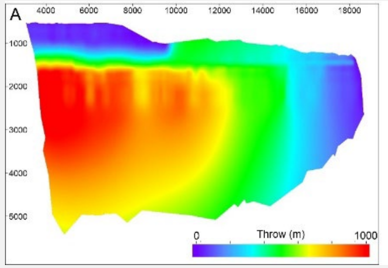


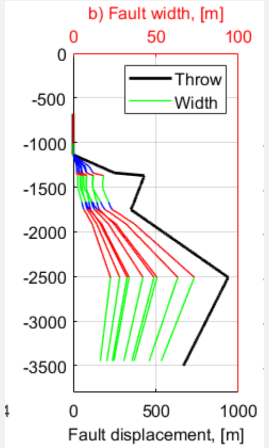
Along fault flow > across fault flow

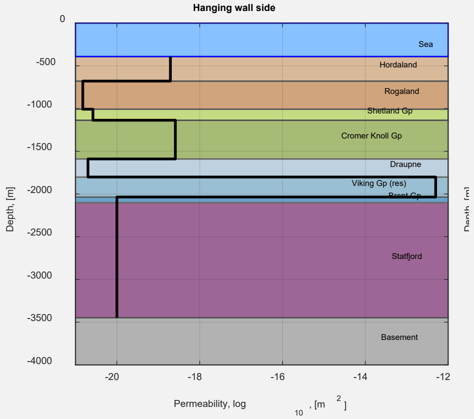
Simulations – leakage rates

- Along fault flow

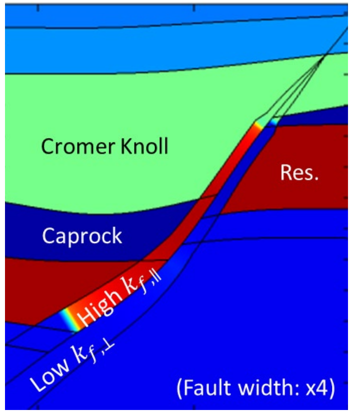
  Input for static model

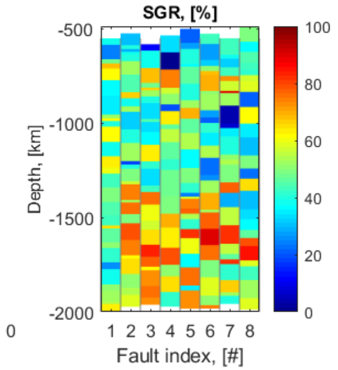






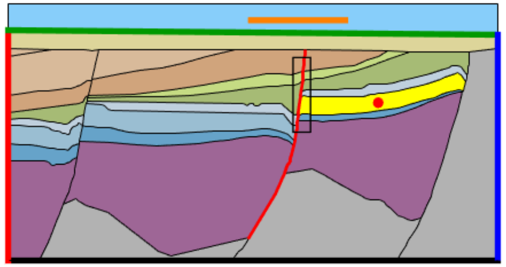
- Parametric study: Fault width (based on throw) and permeability variations

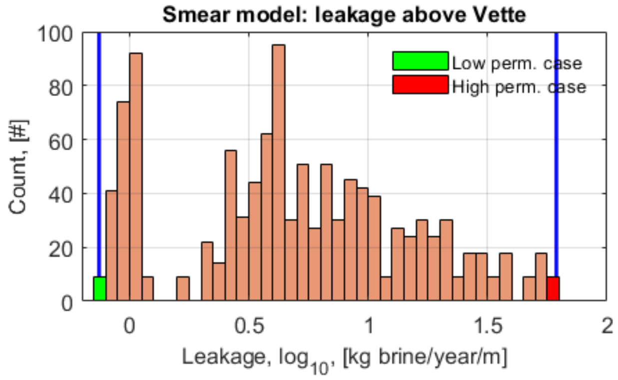


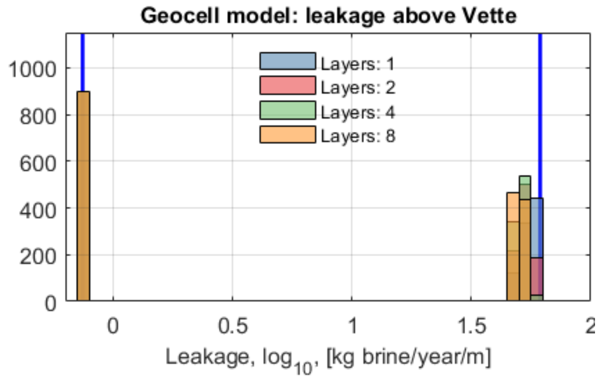


Regional model

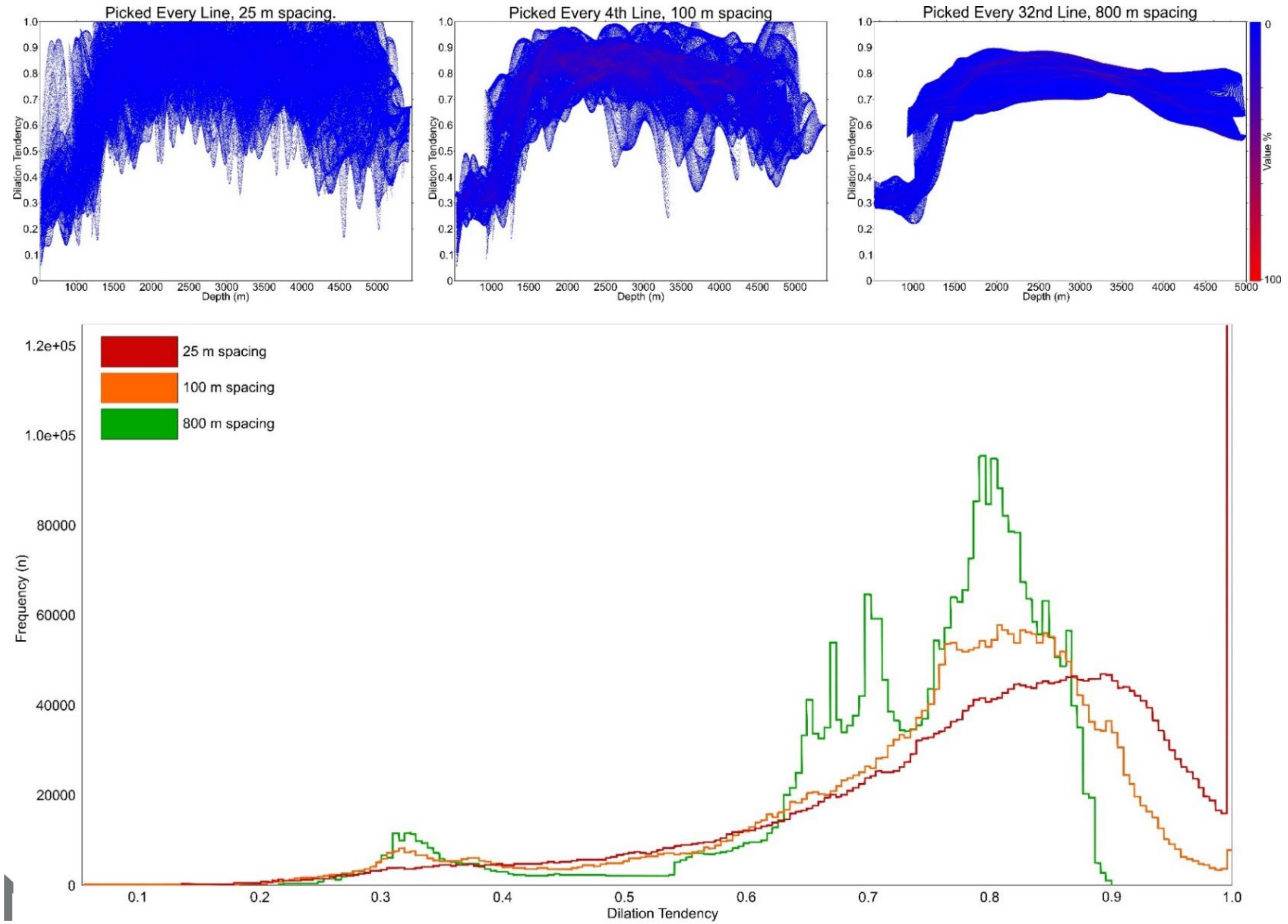
Single phase: brine







Uncertainties in fault interpretation – effects on fault reactivation

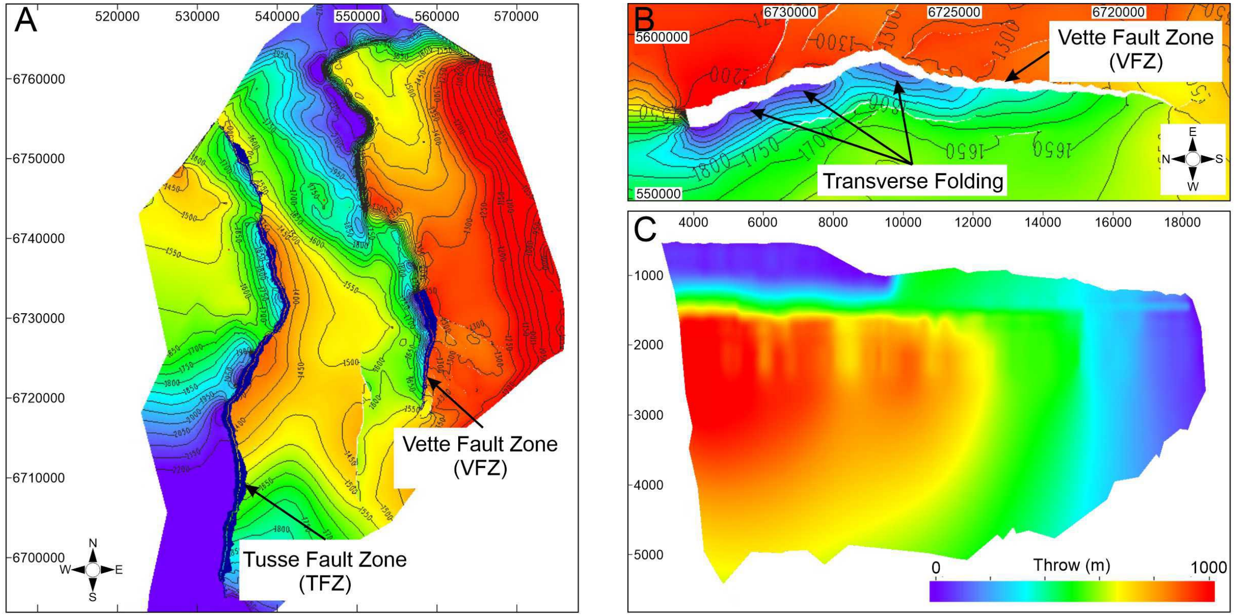


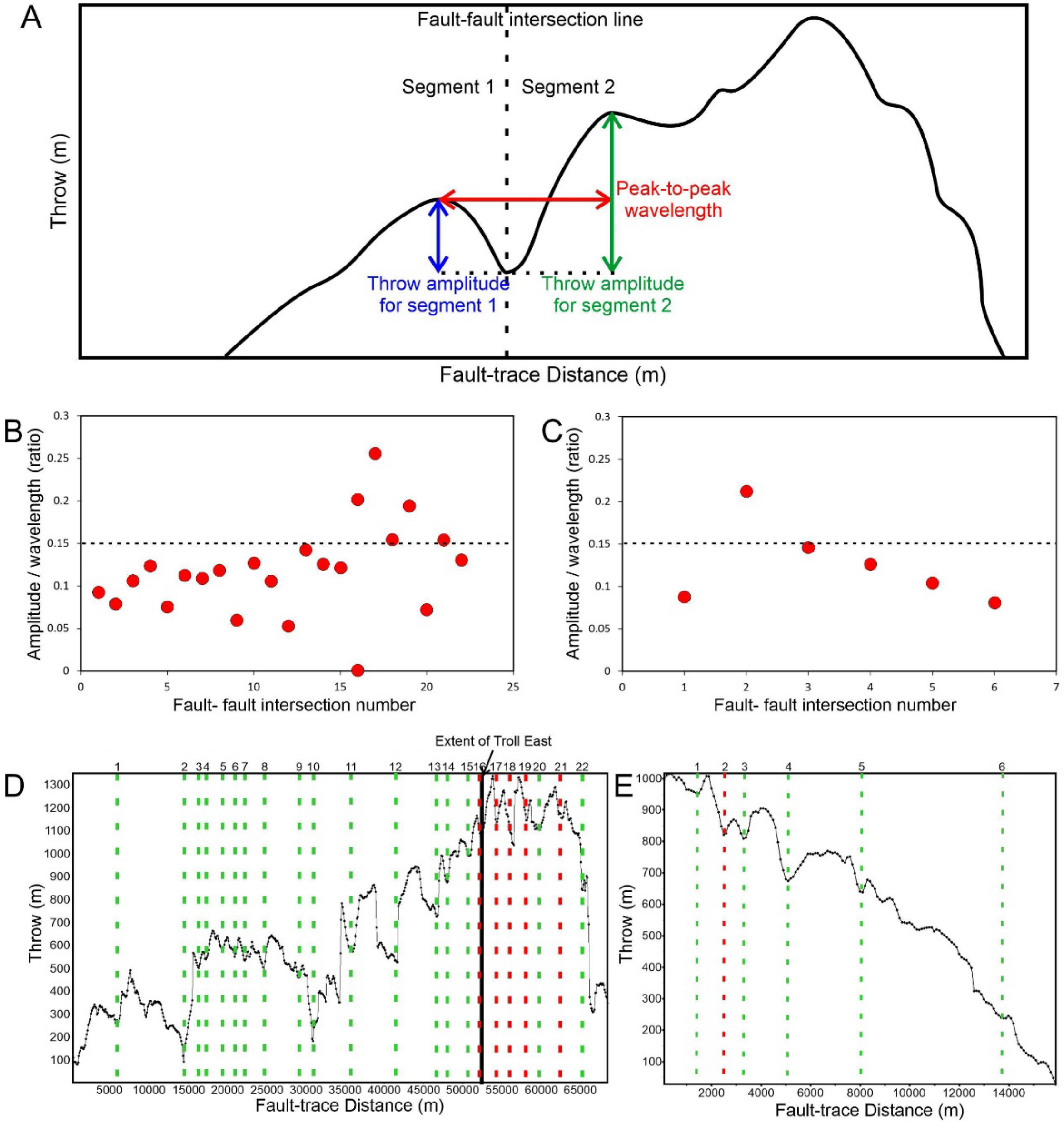
Dilation tendency

- Incorrect picking strategy (such as line spacing) can create a fault that may be interpreted as having an inaccurate stability prediction.
- Here, too narrow spacing creates a fault that is interpreted to be unstable, however picking on every line may not necessarily create the most geologically accurate model, and may in fact introduce significant ‘noise’ from inherent human error.
- We predict a 100 m line spacing, for this specific study, creates the most geologically accurate model; adding some level of smoothing but incorporating all inherent irregularity.

Michie et al., 2021

Fault growth structures in Vette

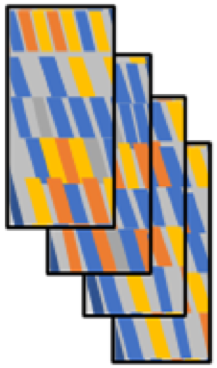




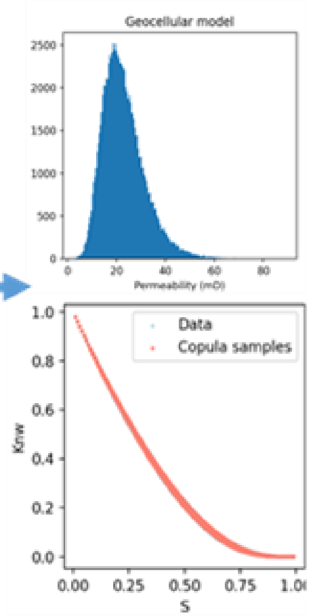
- The Vette Fault Zone grew by a minimum of 7 segments.
- Using knowledge by the nextdoor Troll field, bound by the Tusse Fault, we can assess a potential key control on high risk areas for across fault fluid flow.
- Areas where the amplitude / wavelength is high (>0.15) may result in across fault fluid flow: highlighted by red vertical dashed lines.

Michie & Braathen, in review

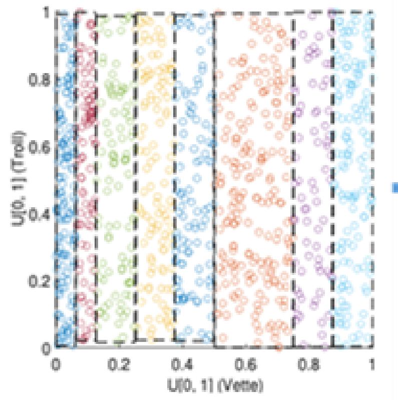
Efficient uncertainty quantification for reservoir and fault properties in field-scale two-phase simulations



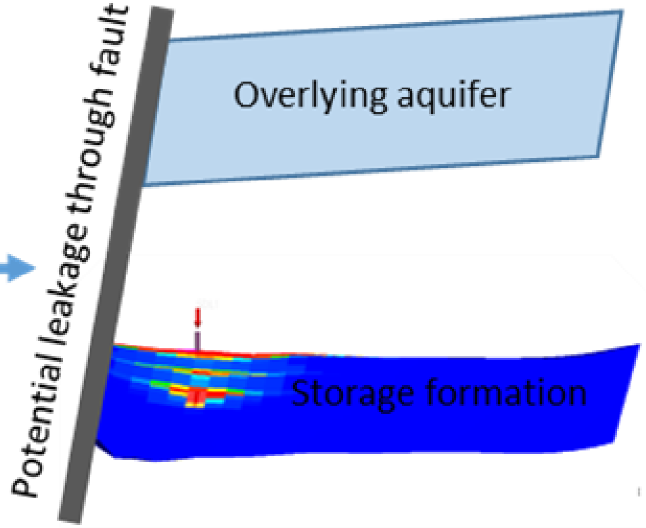
Stochastic fault facies model



Stochastic fault permeability and flow functions



Efficient sampling of stochastic properties



Stochastic realizations of Field scale model

Berge et al., 2021, Pettersson and Krumscheid, 2021, Gasda et al., 2022

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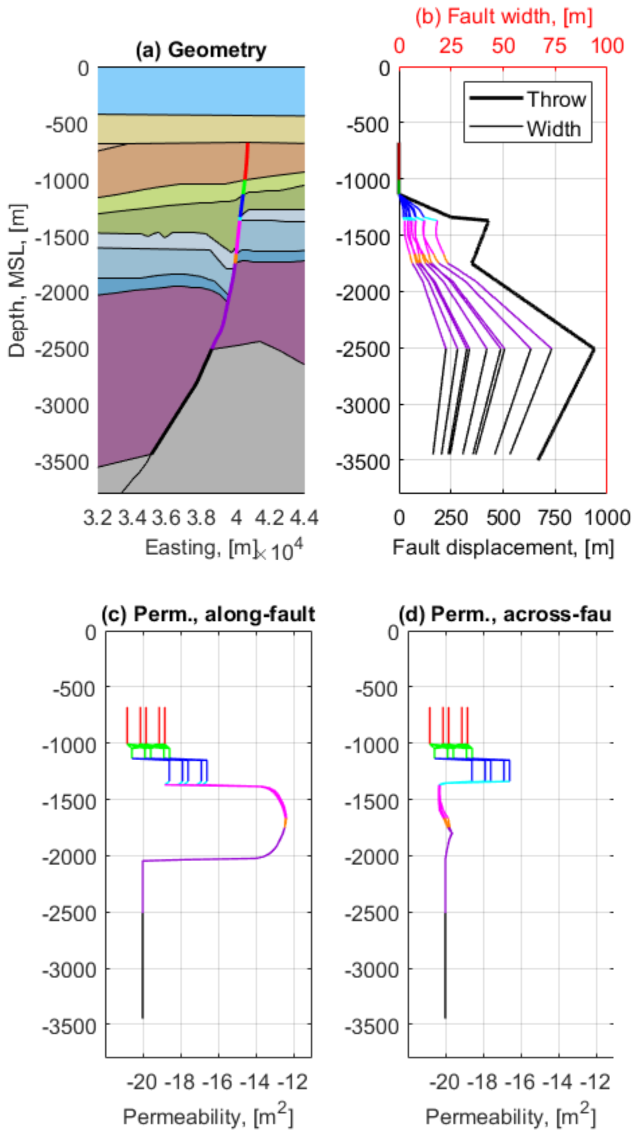
Implications for Alpha structure, Vette Fault Zone

- Fault throw is small in overburden – giving a **small fault** thickness
- Derived fault permeabilities for overburden is **very low**, in similar range as sealing formation
- Calculated brine leakage rates along the fault are **very small** - in order of 0.5-50 kg/year/m
- CO_2 flow not considered, capillary sealing along the fault is expected



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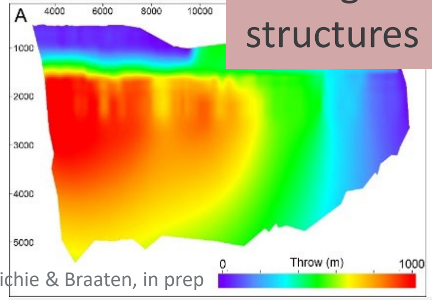
Way forward & Highlights

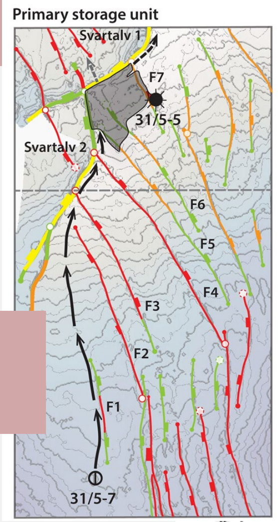
- Continue developing and integration with NCCS Task 9

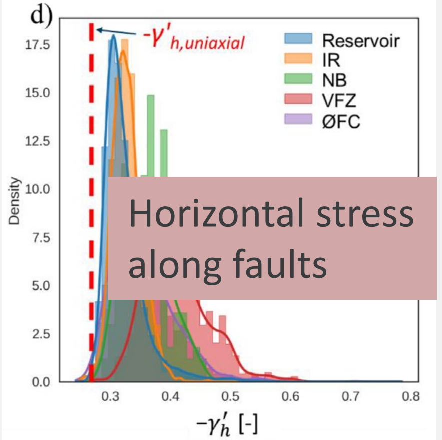
Fault growth structures



Michie & Braaten, in prep

Holden et al., 2022





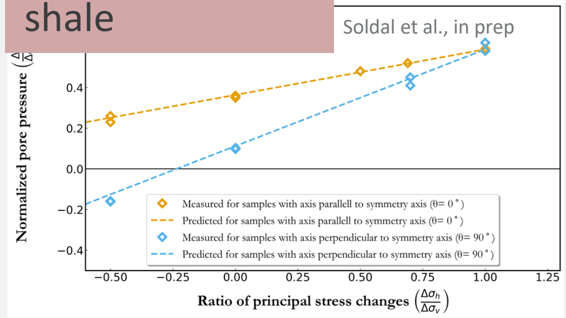
Horizontal stress along faults

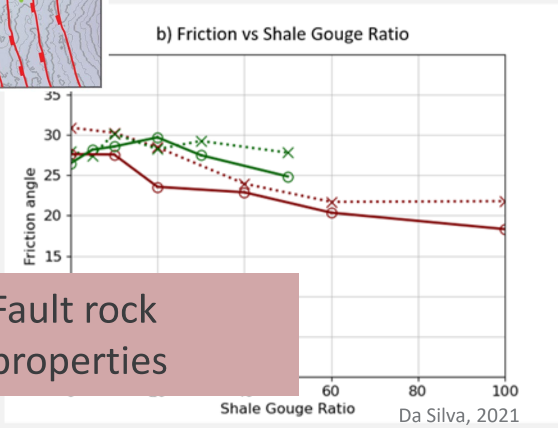
Choi et al., 2022

Seal mapping and confidence

Pore pressure in shale

Soldal et al., in prep





Fault rock properties

Da Silva, 2021

- Quantification of fault uncertainties provides useful input for modelling and probabilistic risk assessments
- Framework for along fault flow calculations in place
- Further model calibration and application for different cases

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