Structural characterization and across-fault seal assessment of the Aurora CO_2 storage site, northern North Sea

FORCE lunch and learn 23rd of November 2021

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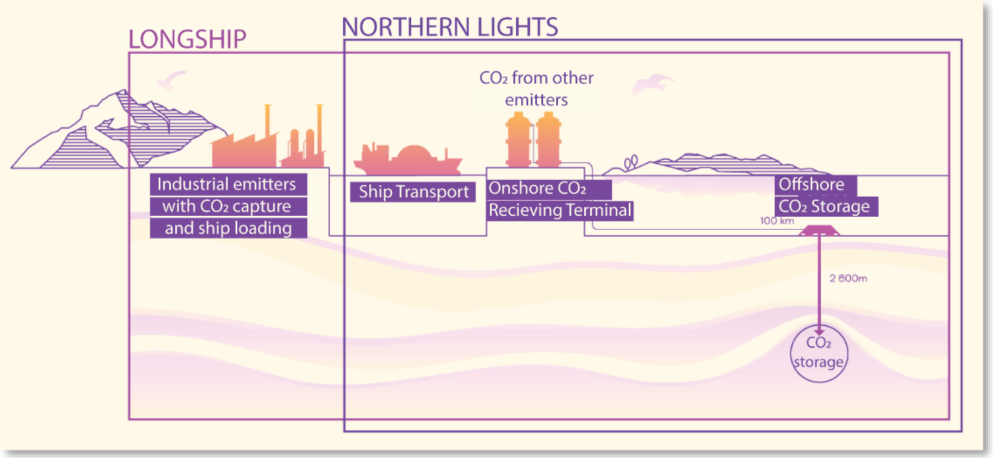
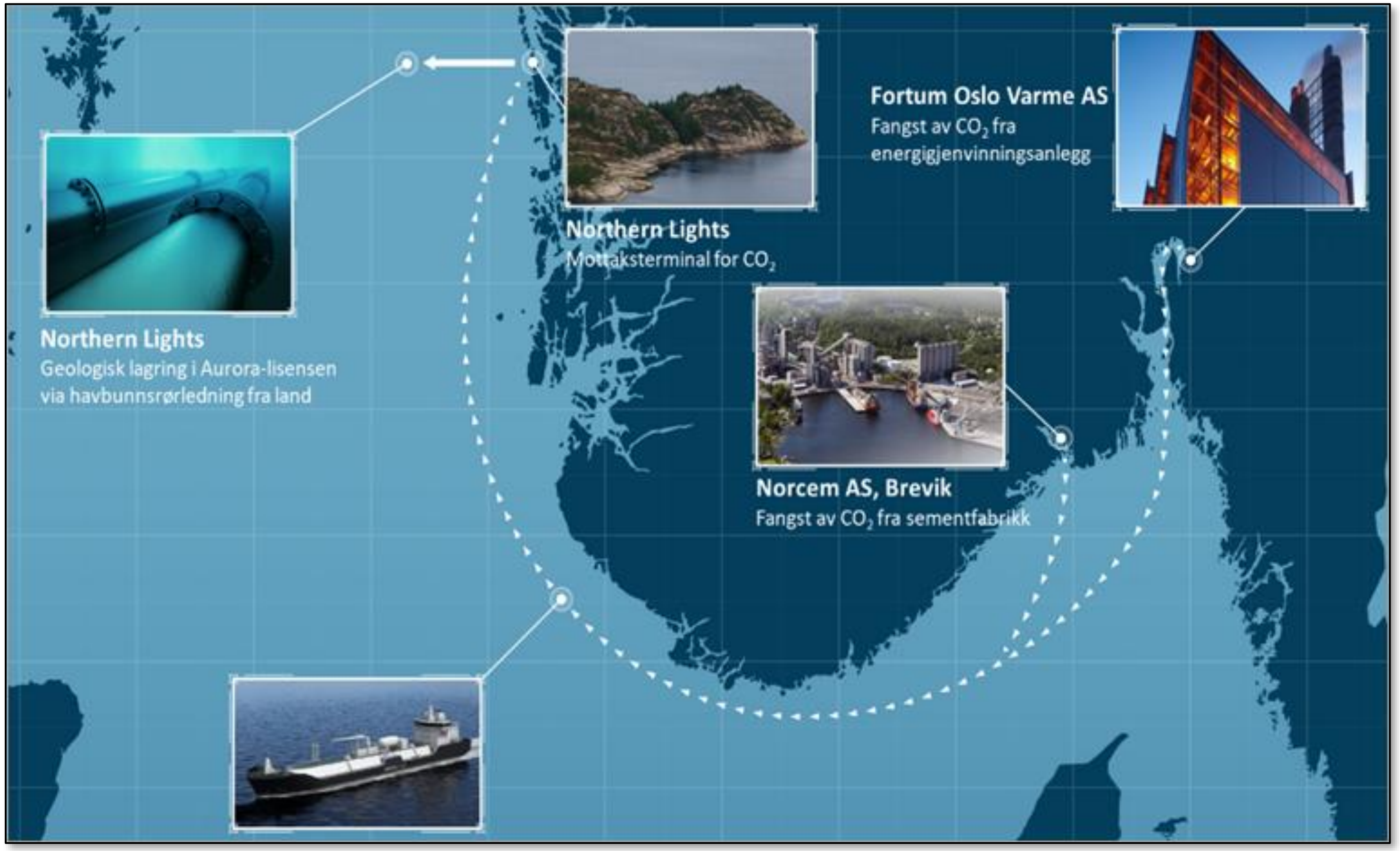
CCS operations in Norway

- 25 years of experience, Snøhvit and Sleipner
- IPCC (2018) and IEA (2021) – CCS is necessary to reach climate targets
- Full-chain CCS operation by 2024/2025
- **Longship** (Norwegian Government)
- **Northern Lights project** (Equinor, Total, and Shell)



Credit: The Northern Lights JV



Credit: Gassnova

Norwegian CCS Research Centre (NCCS)

- Centre for Environment-Friendly Energy Research (FME)
    - 2016 – 2024
- Co-financed by the Research Council, industry, and research partners
- **Aim**: Fast-track CCS deployment in Norway, Europe and the world
- **Task 9 – Structural de-risking**

Elin Skurtveit (NGI),
Task 9 leader

Alvar Braathen (UiO),
UiO representative

- The CO_2 value chain and legal aspects (Task 1)
- Solvent technology - environmental issues (Task 2)
- Low emission H_2 production (Task 3)
- CO_2 capture and transport-conditioning through liquefaction (Task 4)
- Gas turbines (Task 5)
- CO_2 capture process integration (Task 6)
- CO_2 transport (Task 7)
- Fiscal metering and thermodynamics (Task 8)
- Structural derisking (Task 9)
- CO_2 storage site containment (Task 10)
- Reservoir management and EOR (Task 11)
- Cost-efficient CO_2 monitoring technology (Task 12)

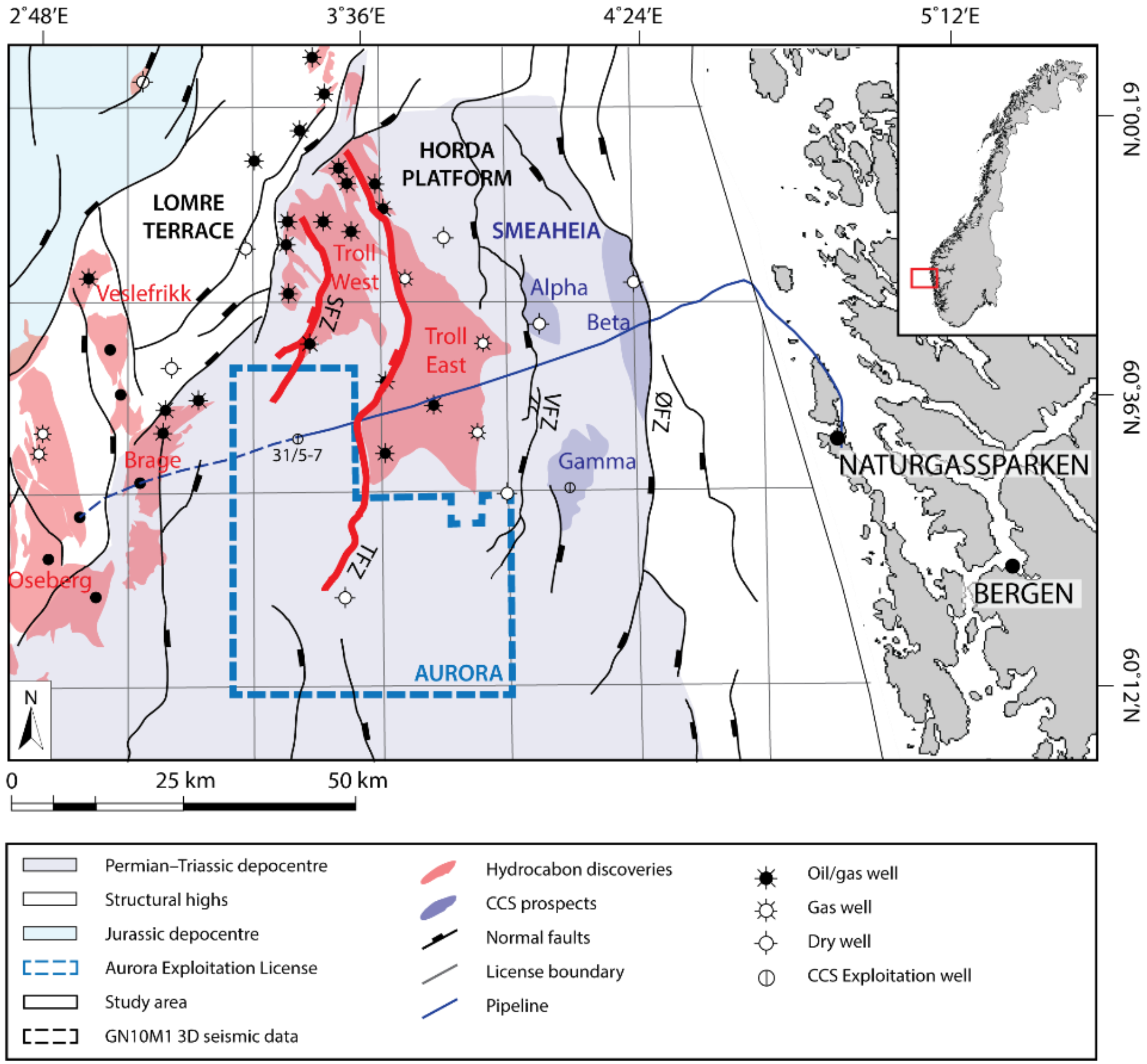
RESEARCH PARTNERS

INDUSTRY AND VENDOR PARTNERS

ASSOCIATE PARTNERS

The Aurora Exploitation License (EL001)

- First CO_2 exploitation license (EL001)
- **Northern Lights project:** up to 5 $MtCO_2$/y (ca. 10%)
- **Eos well** (31/5-7)
    - Re-enter, sidetrack, and use as a CO_2 injector
- **Storage complex**
    - Lower Jurassic Dunlin Group
- **Structural architecture**
    - Svartalv and Tusse fault zones
    - Smaller-scale intra block faults



Project goals and objectives

Project goal

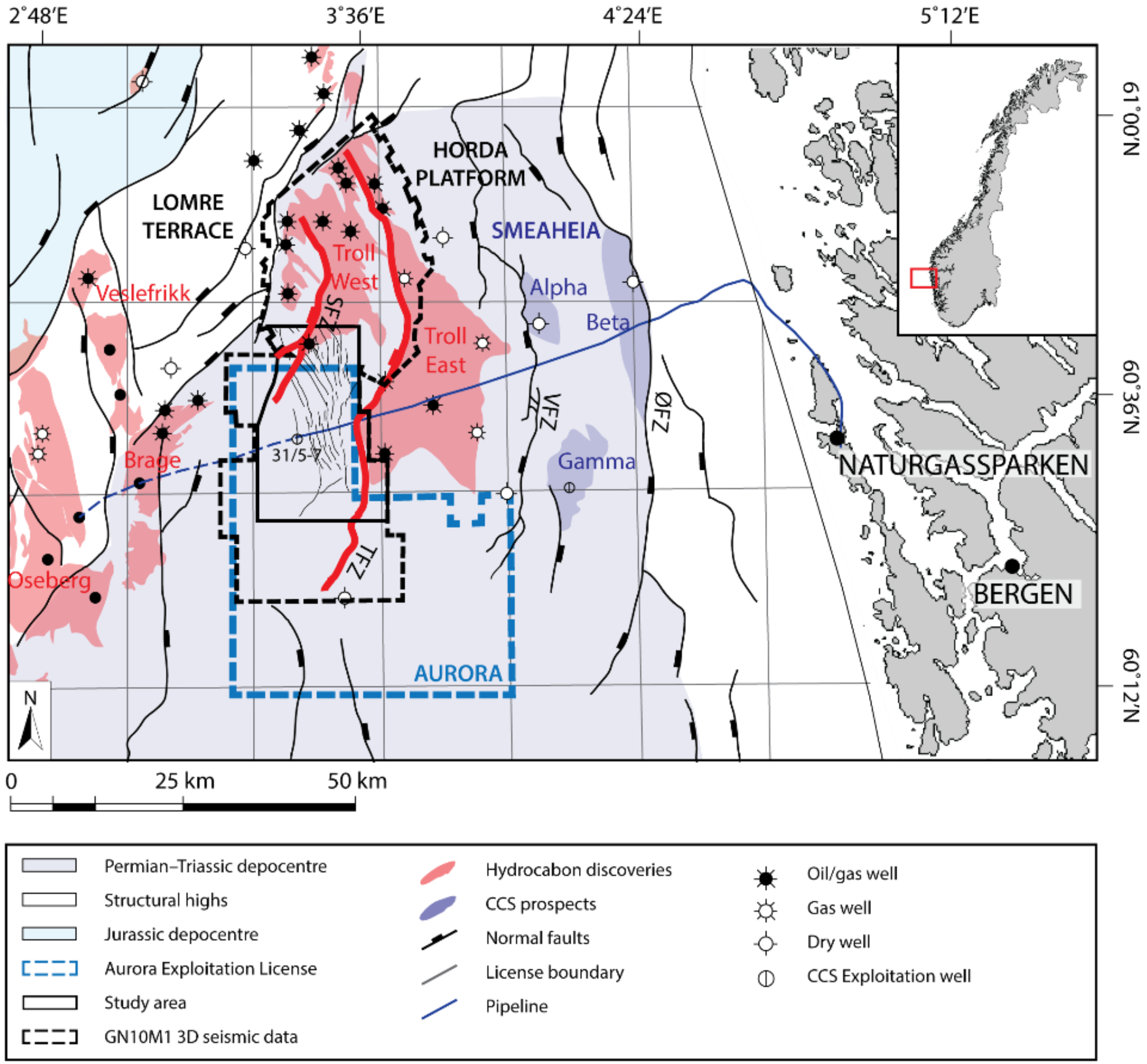
- Increase knowledge on how faults within Aurora will influence CO_2 migration

Objectives

- Structural characterization
- Assess presence of across-fault seals
- Discuss CO_2 migration paths and gross rock volume of structural traps

Data

- GN10M1 3D seismic, 2D seismic, well data
- Velocity model – Emma Michie Haines (UiO)



Seismic data courtesy of Gassnova SF

Geological evolution and framework

Rift events

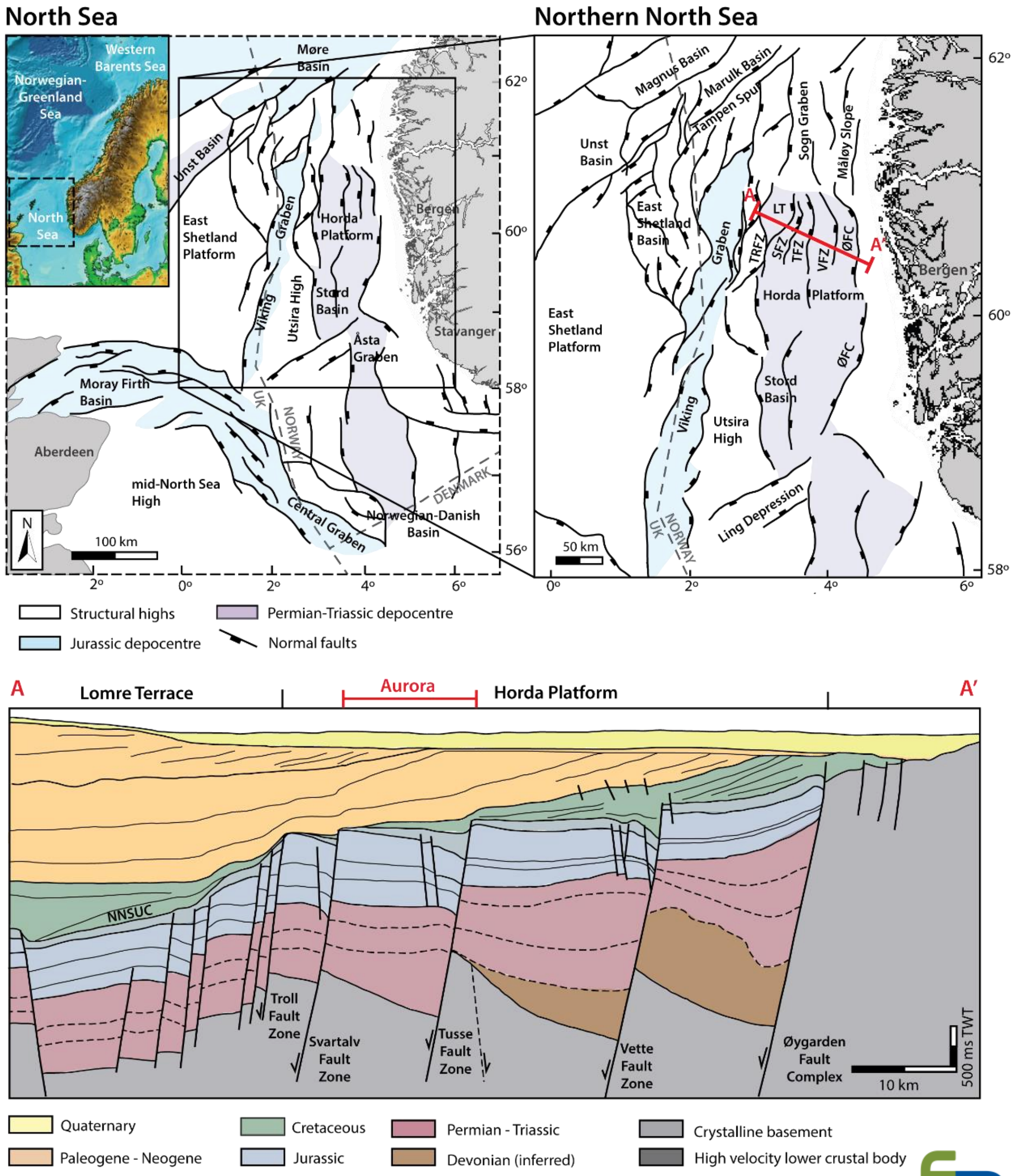
- Permian to Triassic – **Rift Phase 1 (RP1)**
- Middle Triassic to Middle Jurassic – **inter-rift phase (PR1)**
- Middle Jurassic to Early Cretaceous – **Rift Phase 2 (RP2)**

(e.g., Ziegler, 1982; Bell et al., 2015; Deng et al., 2017)

Horda Platform

- First-order faults
  - Basement-involved, N–S striking, W-dipping
  - Rotated fault blocks
  - Permian to Quaternary successions
- Second-order faults
  - Basement-detached

(e.g., Whipp et al., 2014



Modified from Faleide (2010), Færseth (1996), and Whipp et al. (2014).

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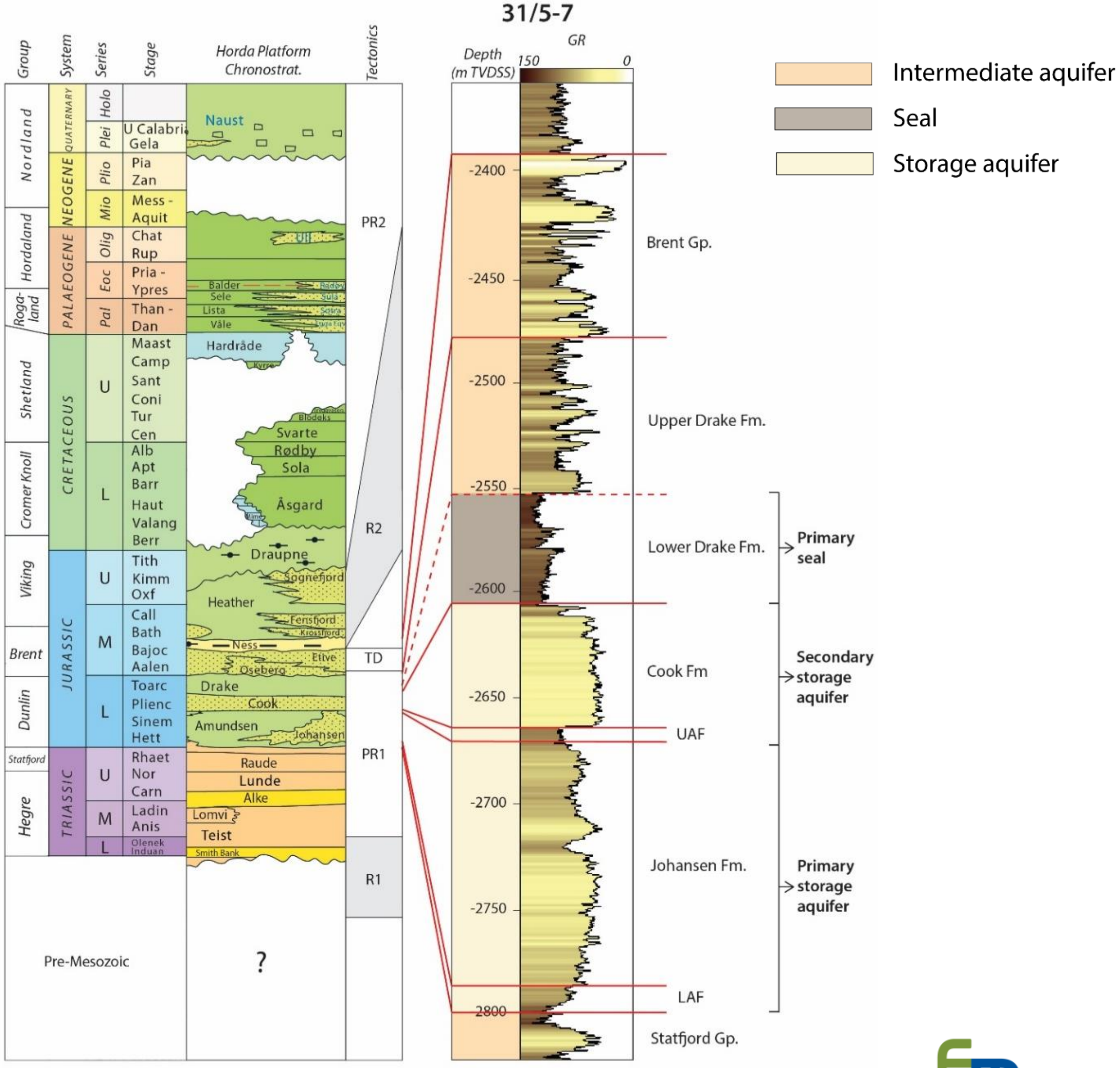
Lower Jurassic storage complex

Storage complex

- Deposited during the inter-rift phase
- Storage aquifers
  - Johansen Fm. (primary storage aquifer)
  - Cook Fm. (secondary storage aquifer)
- Seal units
  - Lower Drake Fm. (primary seal)
  - Amundsen Fm. – not continuous



Well data courtesy of the Northern Lights project (Equinor ASA, Total E&P Norge AS, A/S Norske Shell)

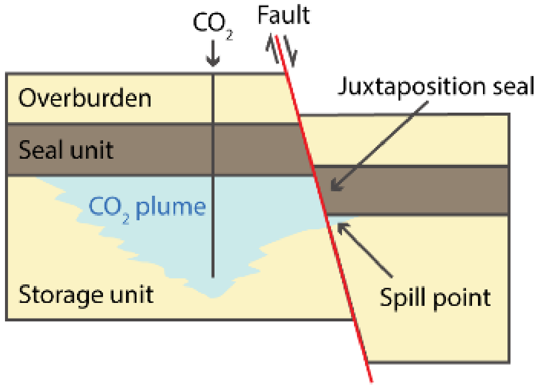
Structural characterization and across-fault seal assessment

Influence of faults on CO_2 migration

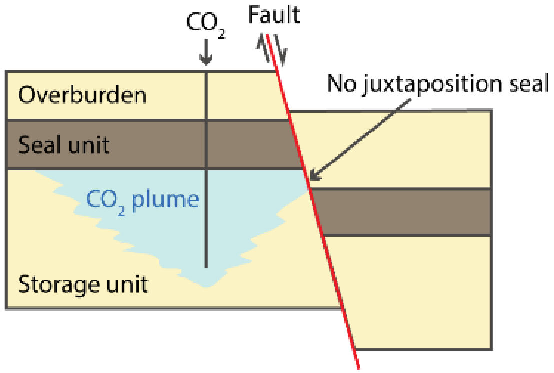
- Storage complex thickness and continuity
- Fault geometry – strike, dip, throw
- Assessment of across-fault seals
    - Juxtaposition seals
    - Membrane seals
        - Clay smears – Shale Gouge Ratio (SGR)
        - SGR < 15–20% = leaking

          SGR > 15–20% = sealing

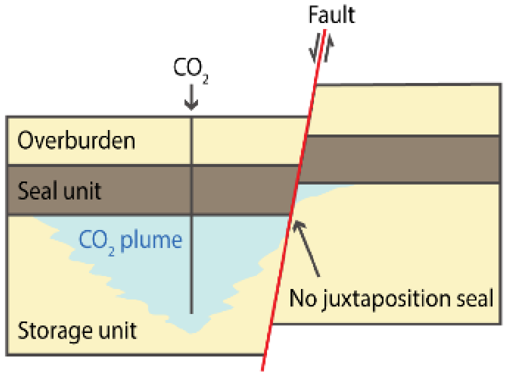
(e.g., Allan, 1989; Yielding et al., 1997; Yielding, 2002; Bretan et al., 2011)



Scenario 1: Throw < seal thickness
Juxtaposition seal



Scenario 2: Throw > seal thickness
No juxtaposition seal



Scenario 3: Oppositely dipping fault
No juxtaposition seal

Structural characterization and across-fault seal assessment

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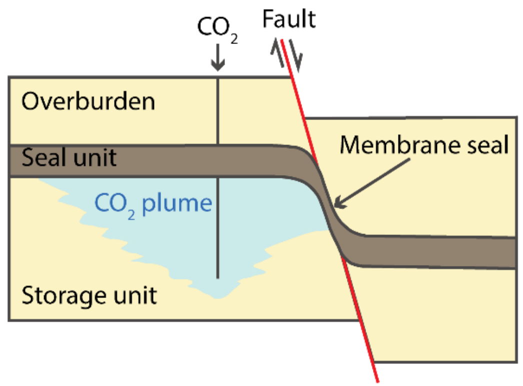
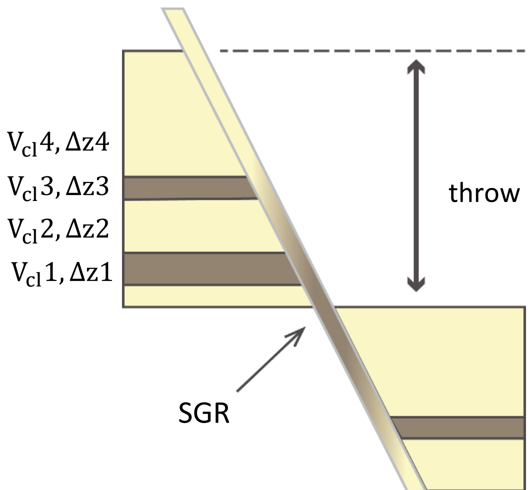
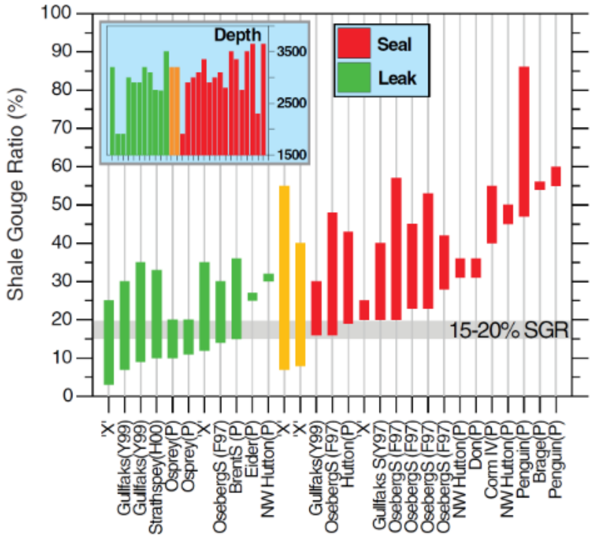


Scenario 4: throw > seal thickness
Presence of clay smear → membrane seal



$$SGR = \frac{\sum(V_{cl} \times \Delta z)}{throw} \times 100\%$$

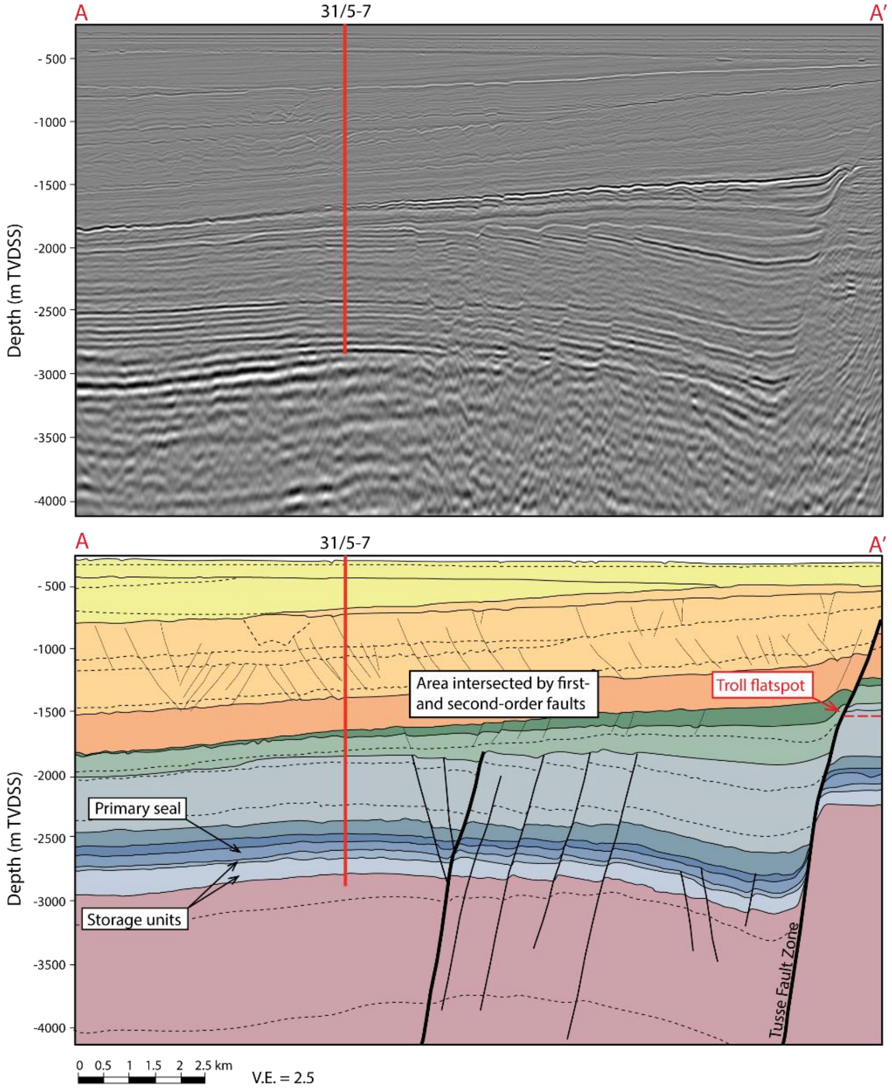
Modified from Yielding et al. (2010)



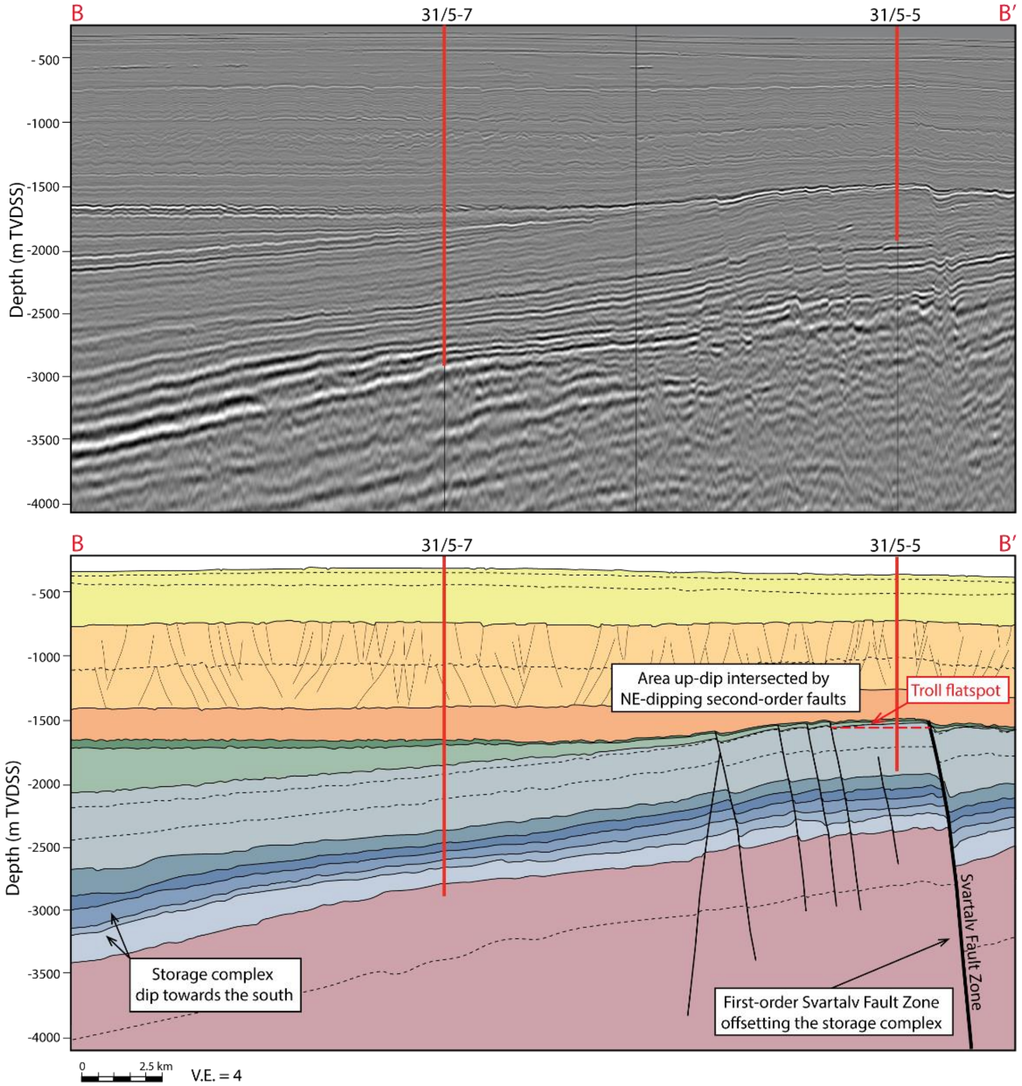
From Yielding (2002)

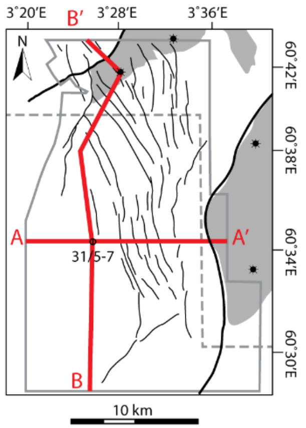
Tectonostratigraphic framework of Aurora

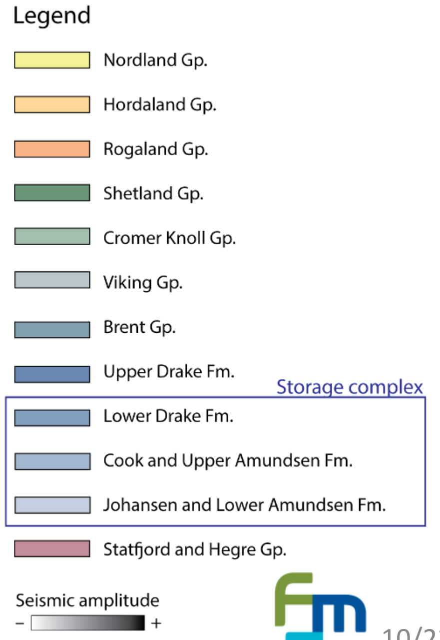
E – W cross-section



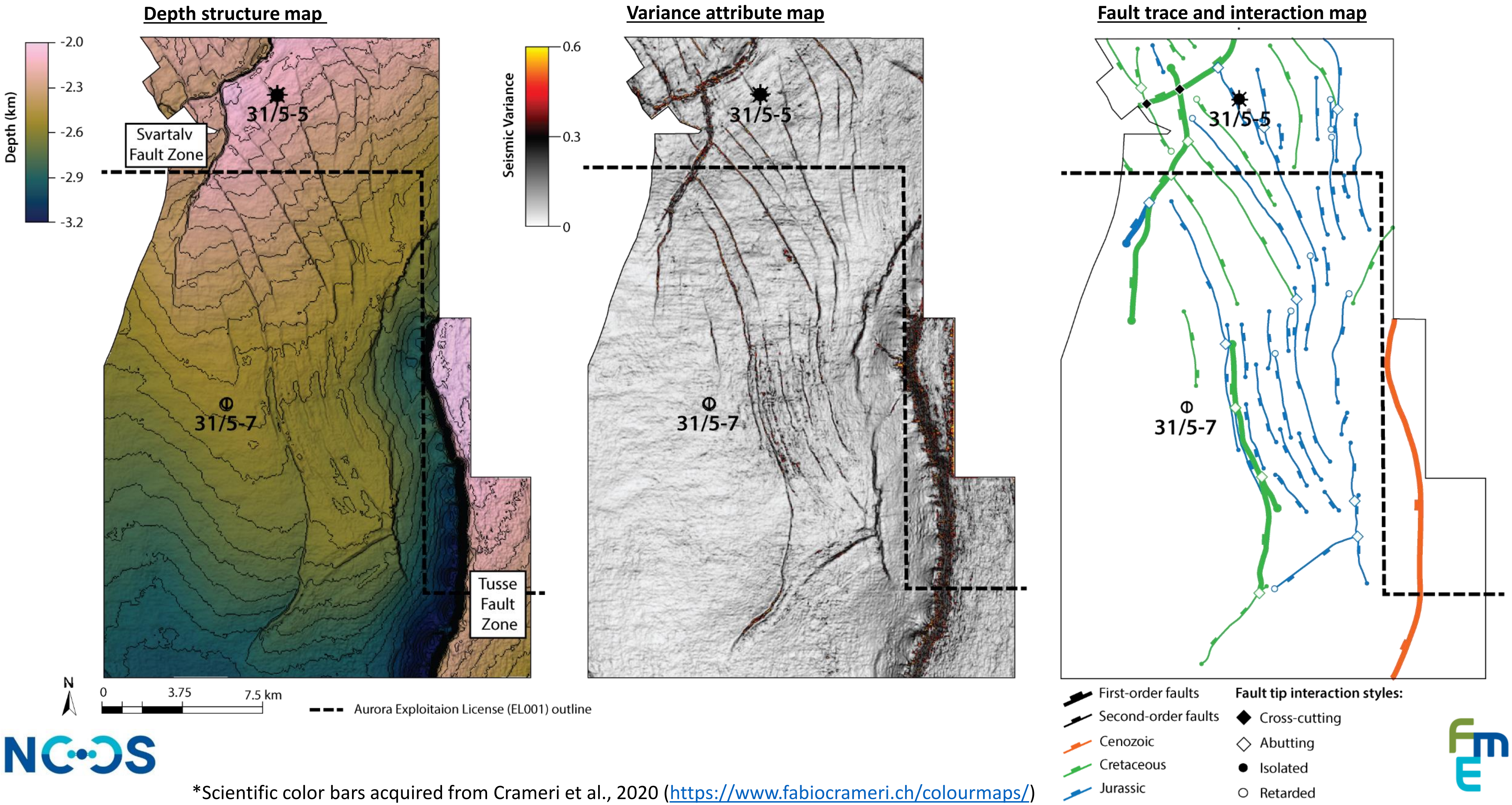
N – S cross-section





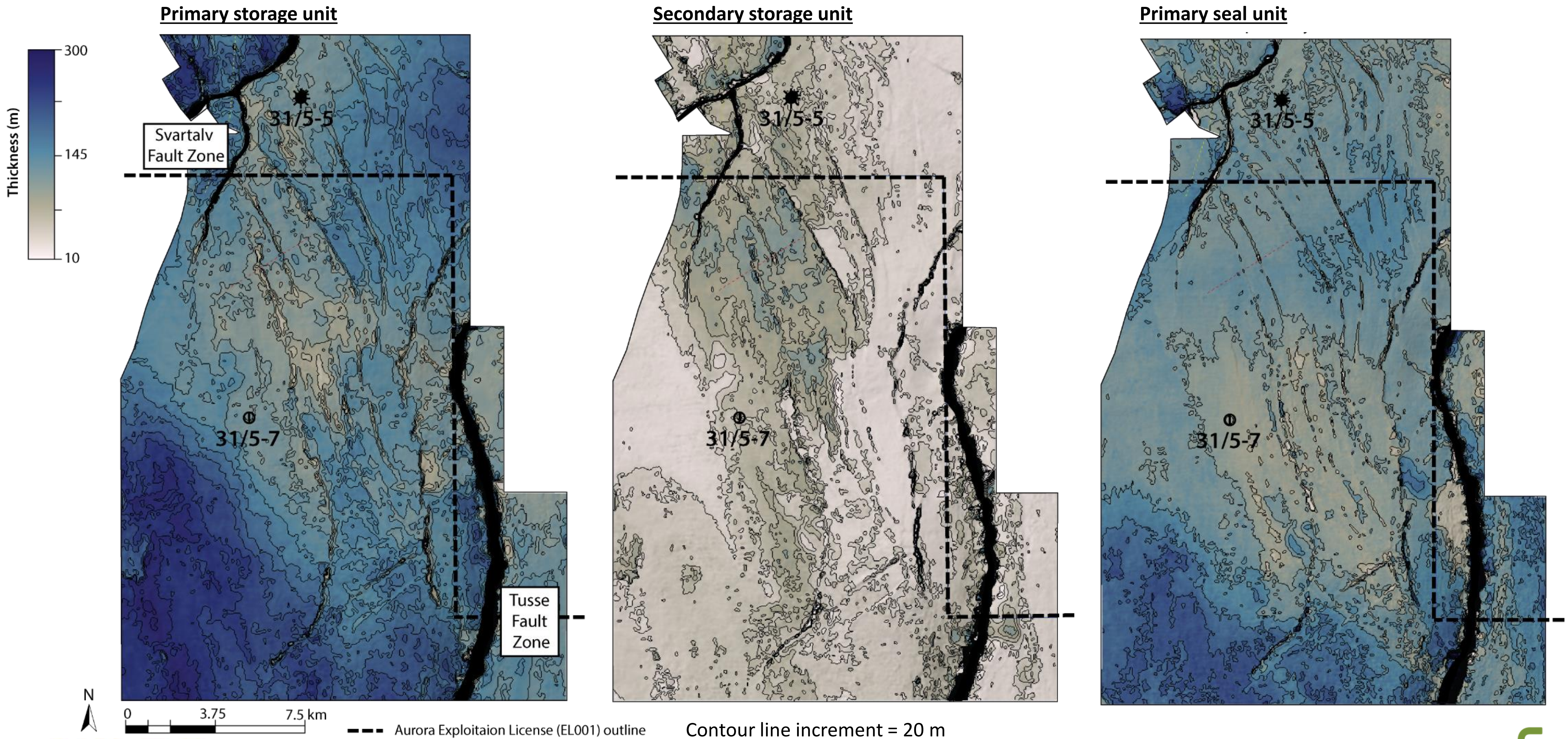


Structural framework of Aurora – Top Lower Jurassic storage



*Scientific color bars acquired from Crameri et al., 2020 (https://www.fabiocrameri.ch/colourmaps/)

Storage complex thickness



*Scientific color bars acquired from Crameri et al., 2020 (https://www.fabiocrameri.ch/colourmaps/)

Structural characterization - Fault populations

First-order faults

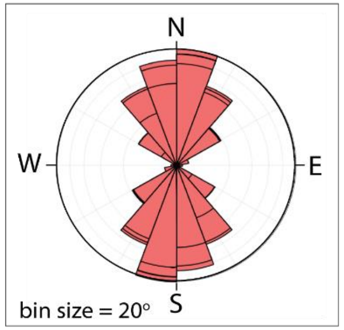
- Basement involved
- W-dipping, N–S striking
- c. 7km long, 43–900 m throw*

Second-order faults

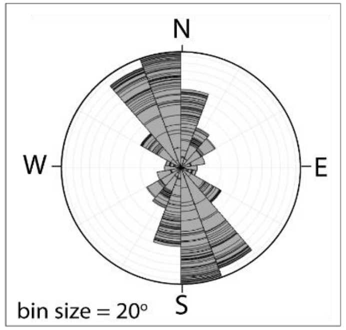
- Basement detached
- N–S to NW–SE striking
- c. 3.6 km long, 15–50 m throw*

*throw measured in the Top Cook Fm.

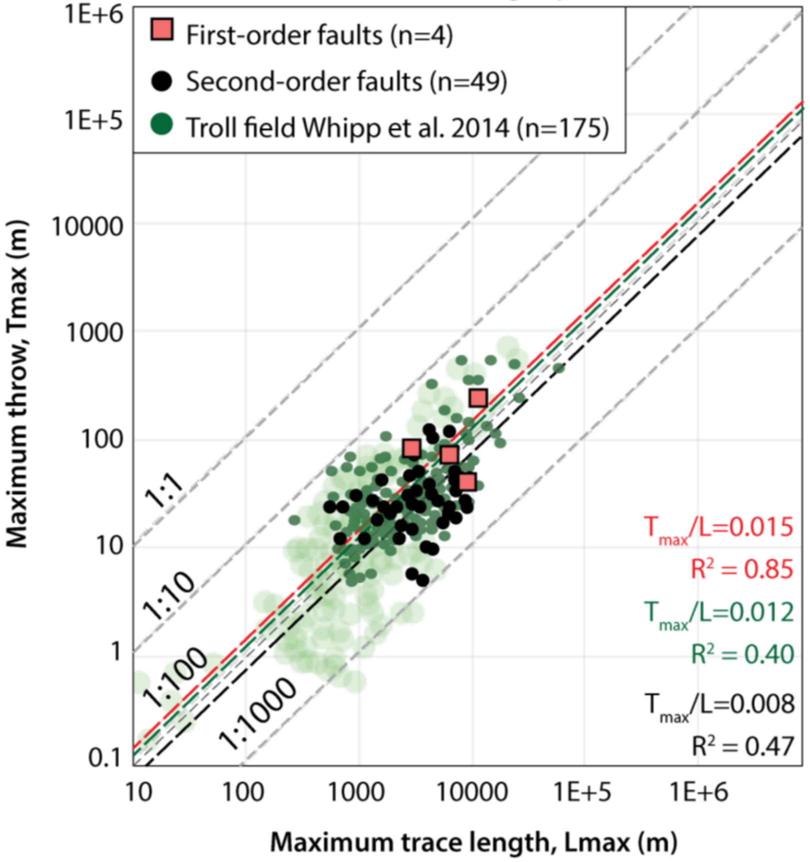
First-order faults



Second-order faults

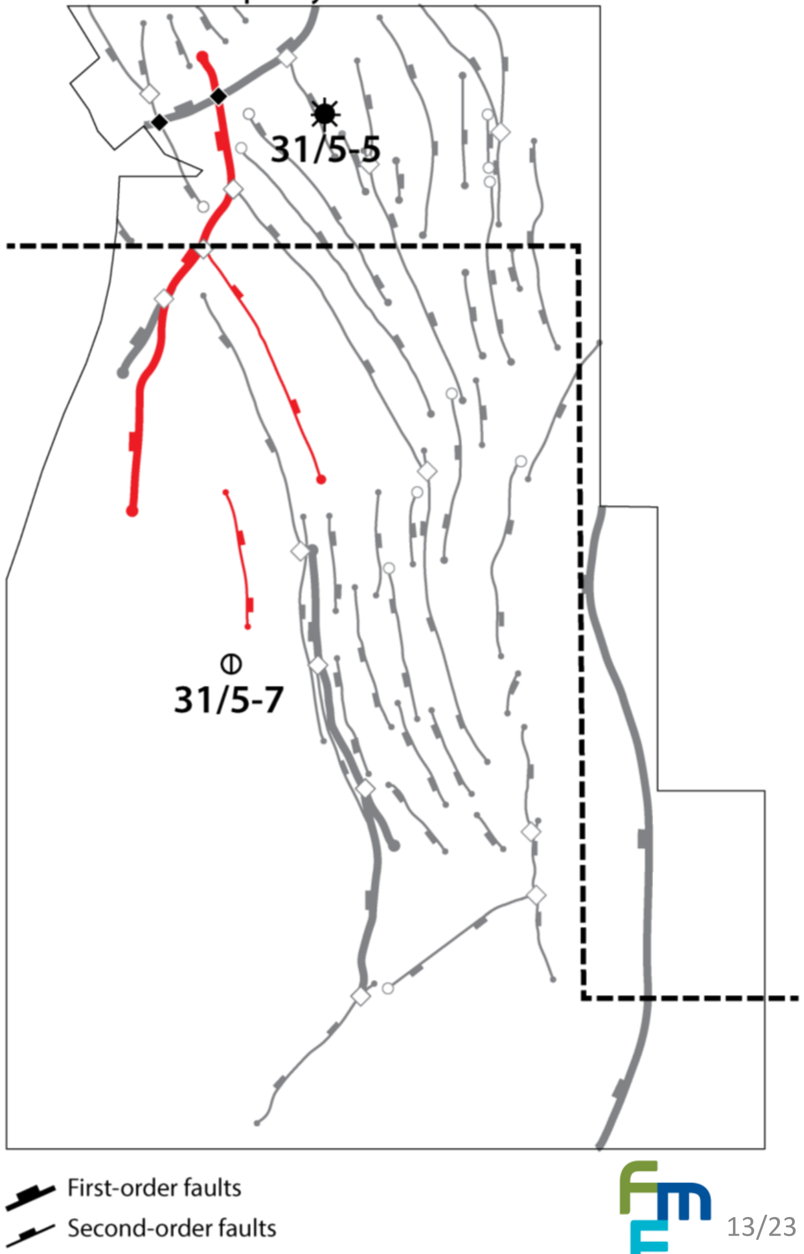


Maximum throw vs. trance length plot



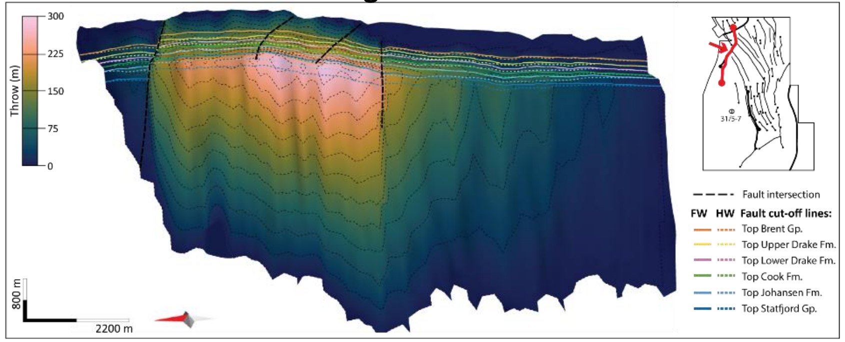
Global data compiled from Kim and Sanderson (2005).

Fault trace map - key faults

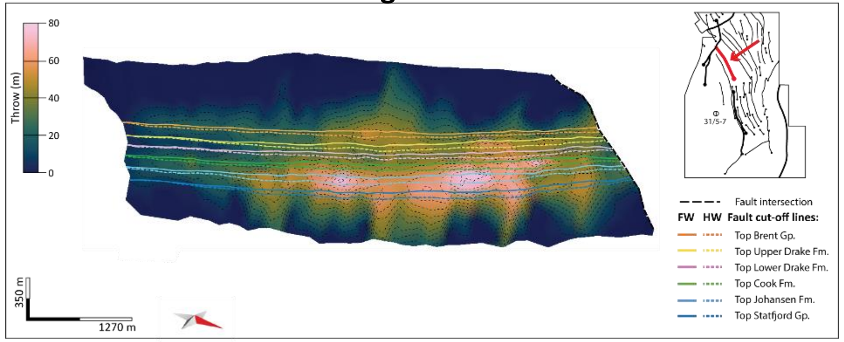


Structural characterization – Key faults

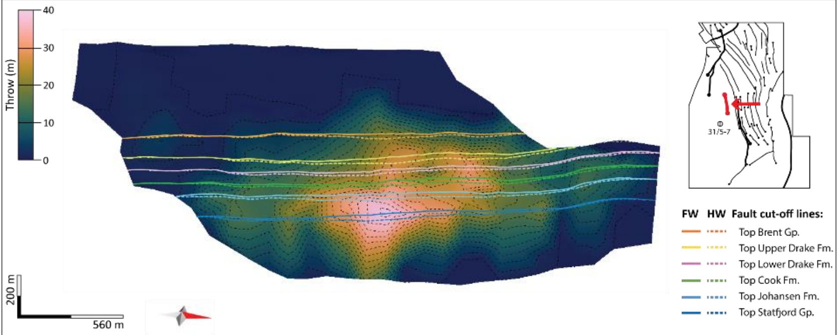
First-order Svartalv fault segment



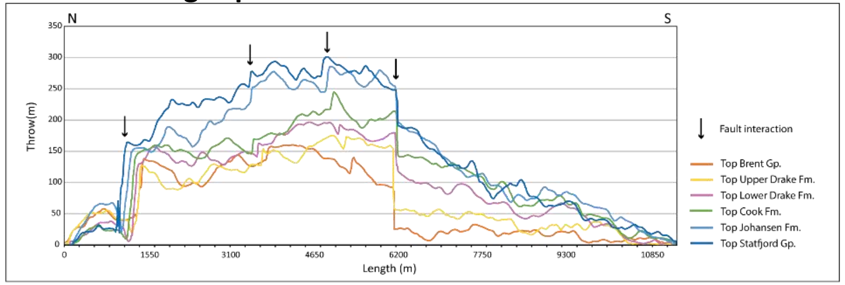
Second-order NW-SE striking fault

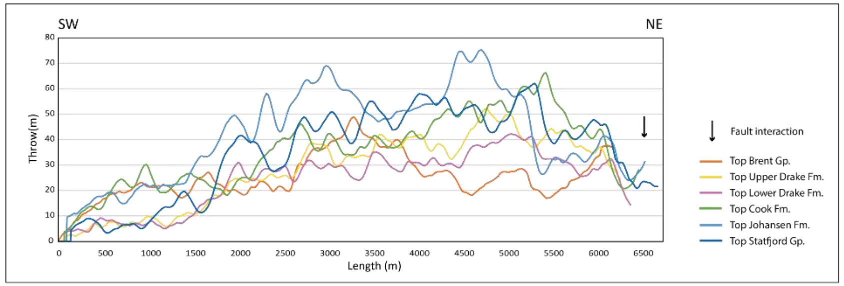


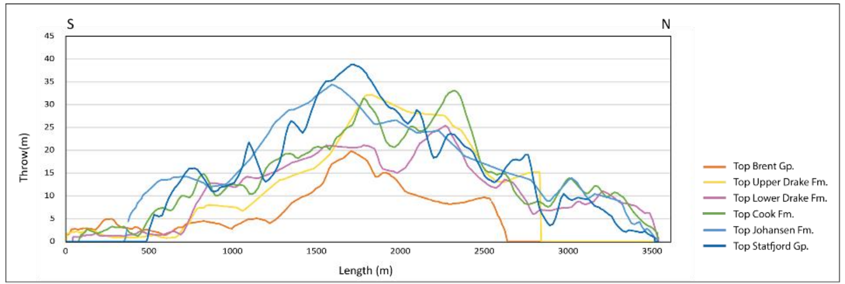
Second-order N-S striking fault



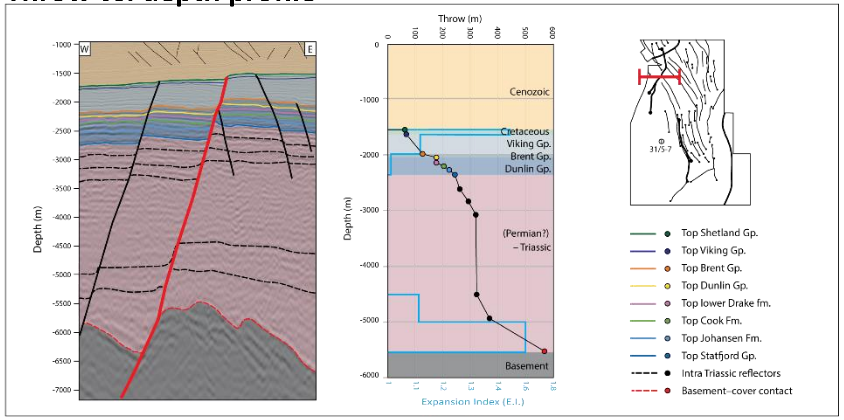
Throw vs. length profile

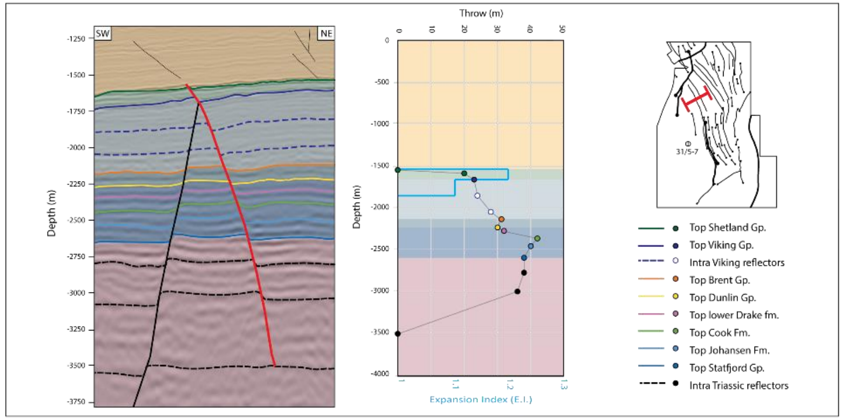


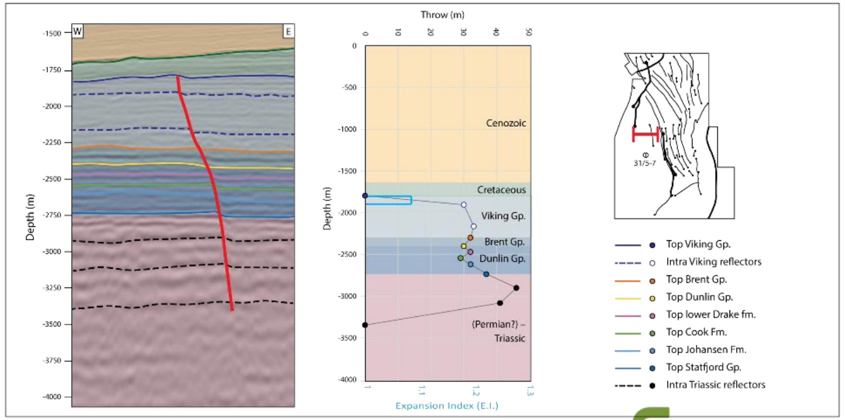




Throw vs. depth profile

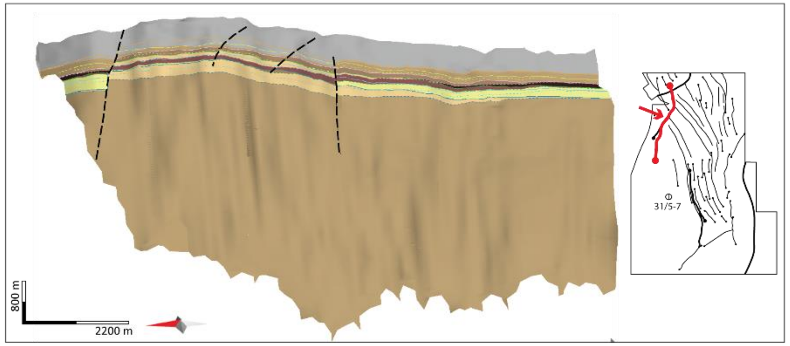




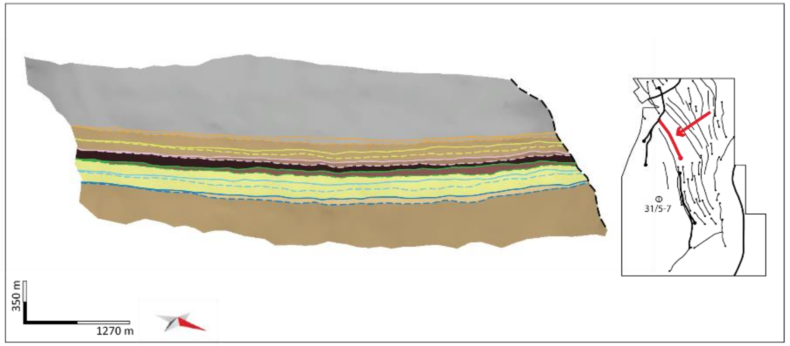


Across-fault seal assessment – juxtaposition assessment

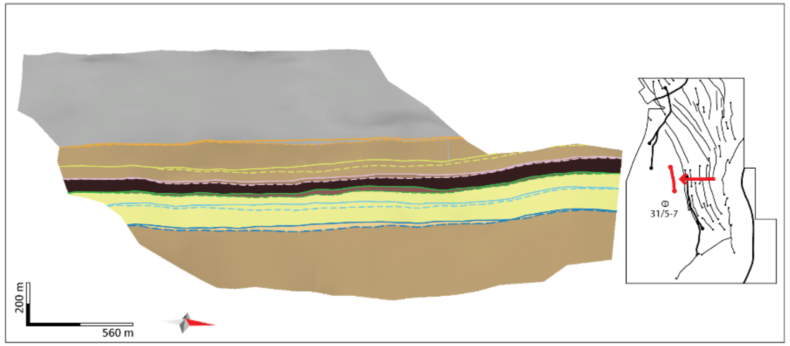
First-order Svartalv fault segment



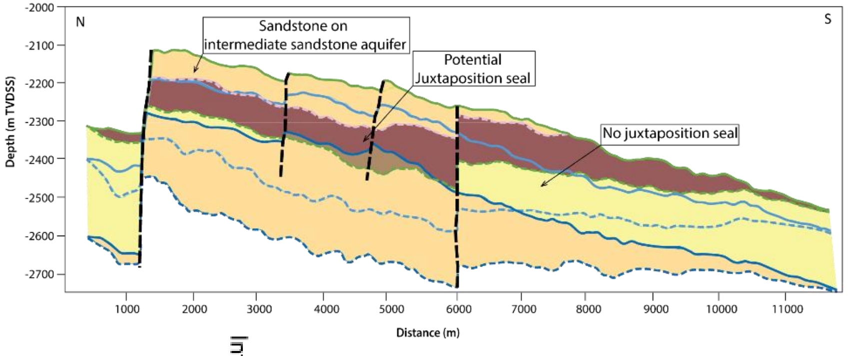
Second-order NW-SE striking fault



Second-order N-S striking fault



Close-up of storage aquifer juxtapositions



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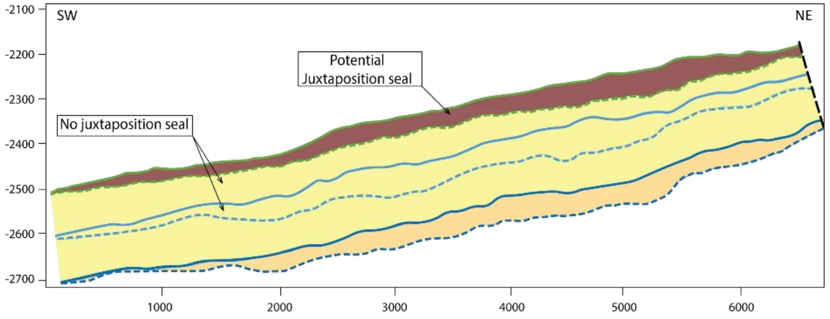

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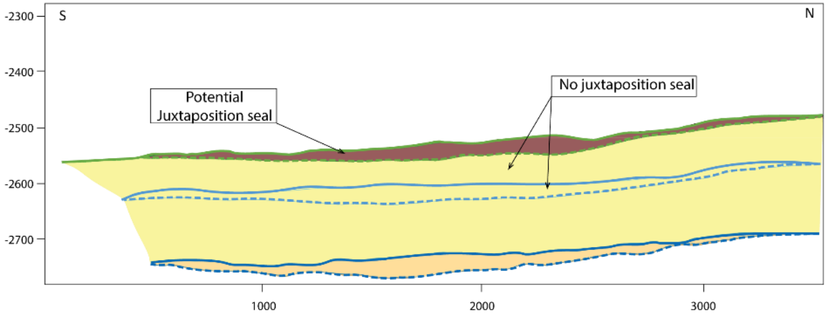
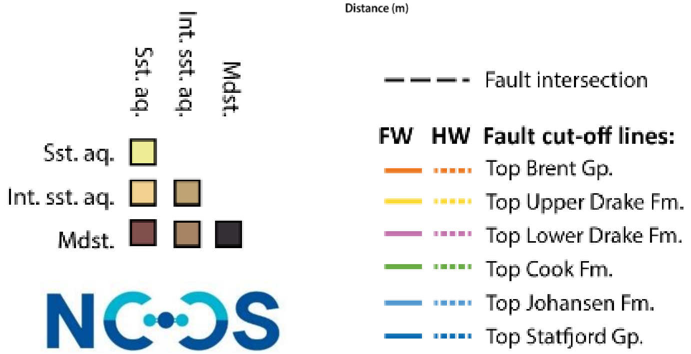
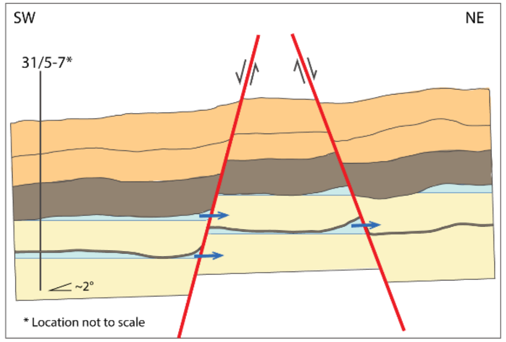


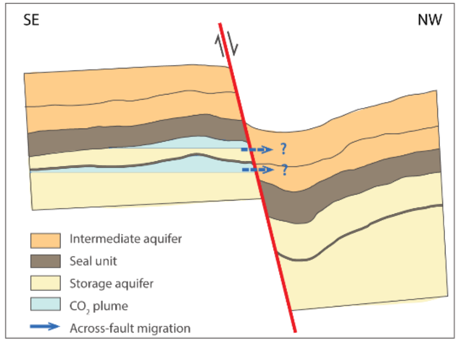


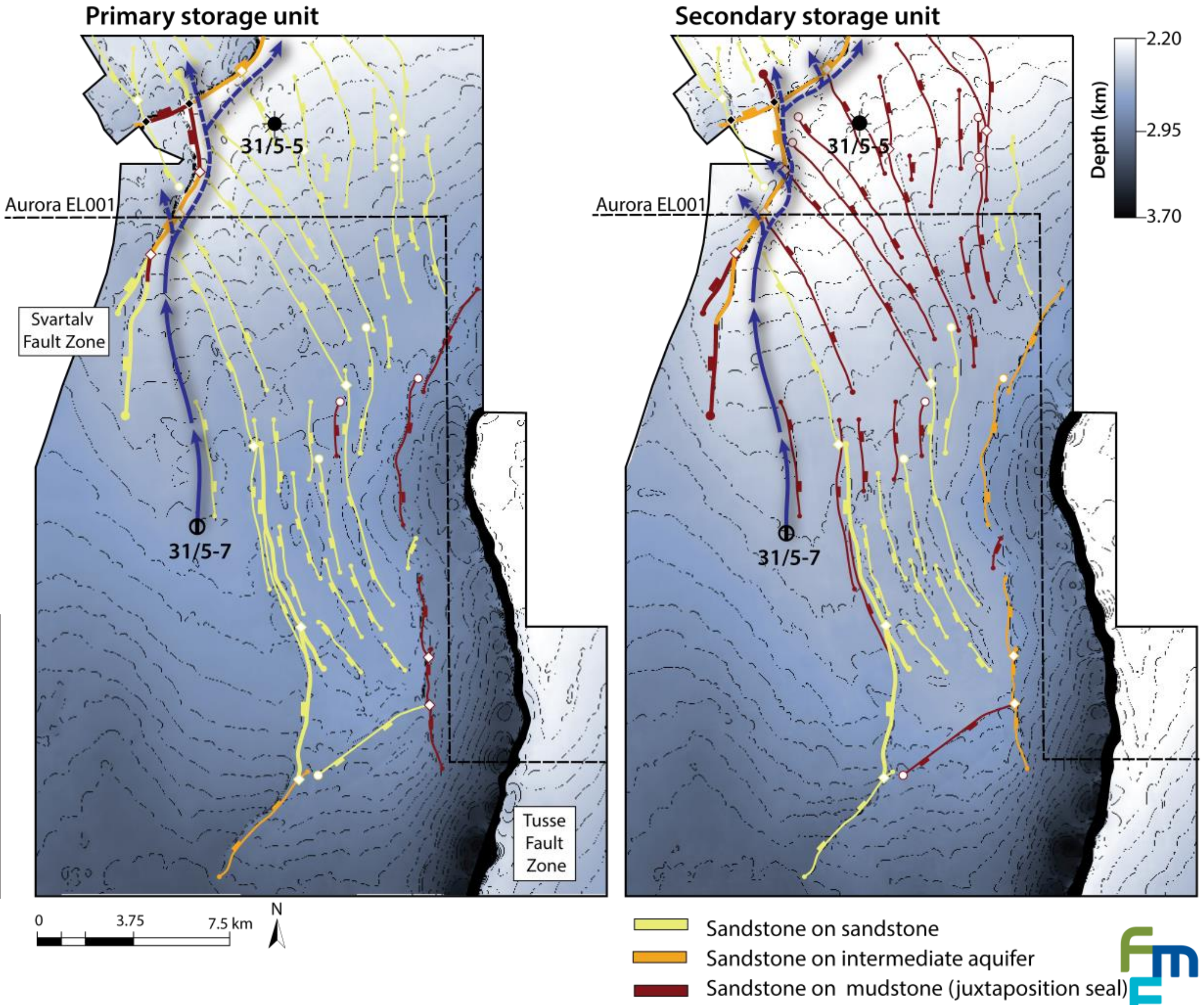
Across-fault seal assessment – Influence on CO_2 migration

Juxtaposition seal scenarios

Faults	Dip	Primary storage unit		Secondary storage unit	
		Juxt. seal	Mem. seal	Juxt. seal	Mem. seal
2nd-order	E/NE	No		Yes	
	W/SW	No		No	
1st-order	W	Partly		No	







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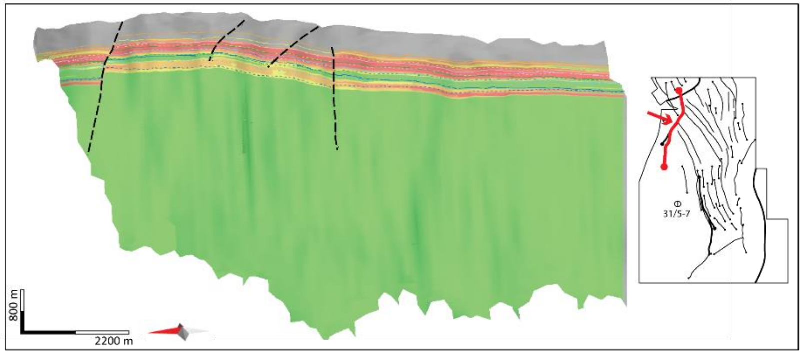
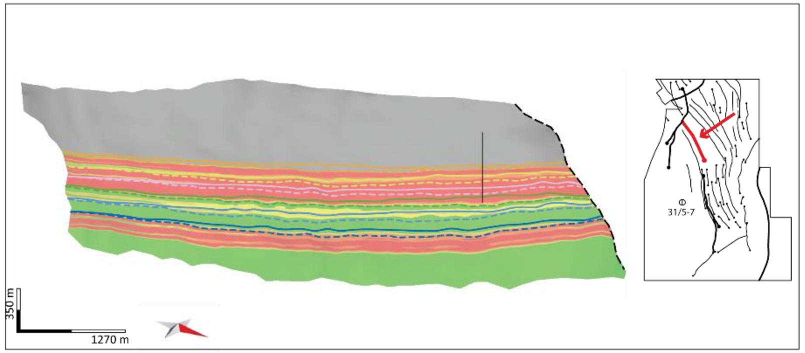
Across-fault seal assessment – Membrane seal assessment

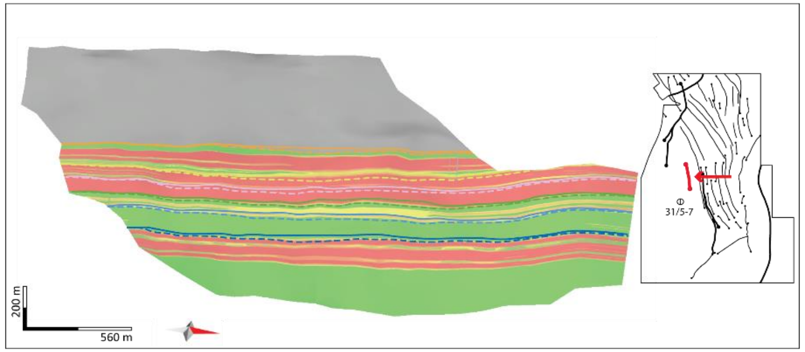
First-order Svartalv fault segment



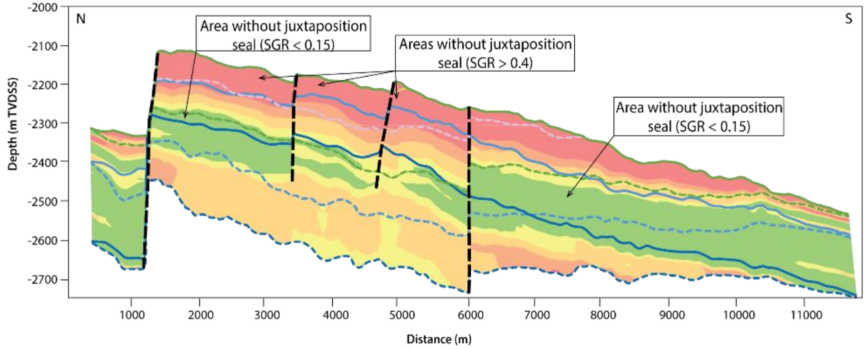
Second-order NW-SE striking fault



Second-order N-S striking fault



Close-up of storage aquifers



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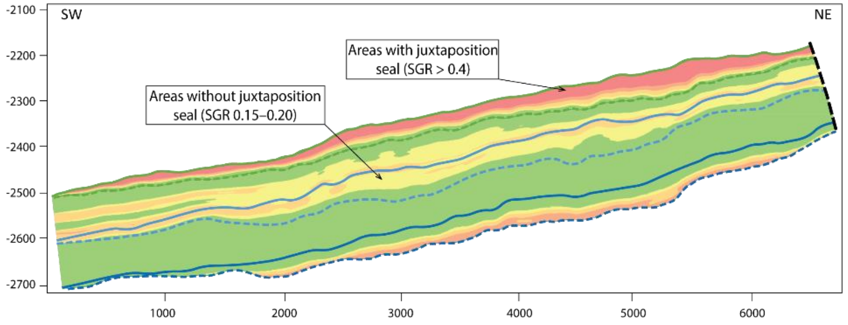
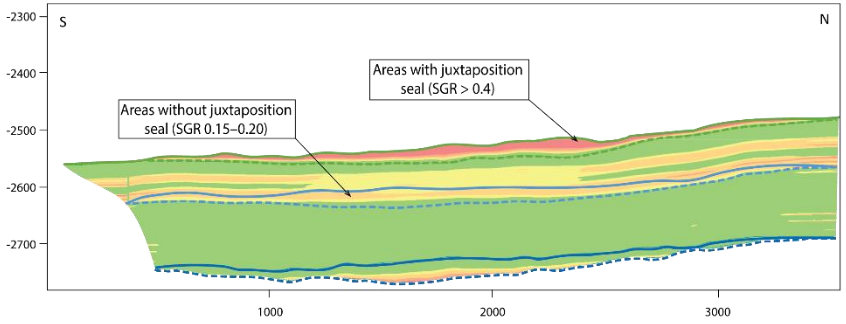
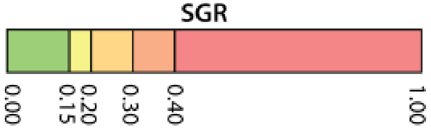


Close-up of storage aquifers





Fault intersection

FW HW Fault cut-off lines:

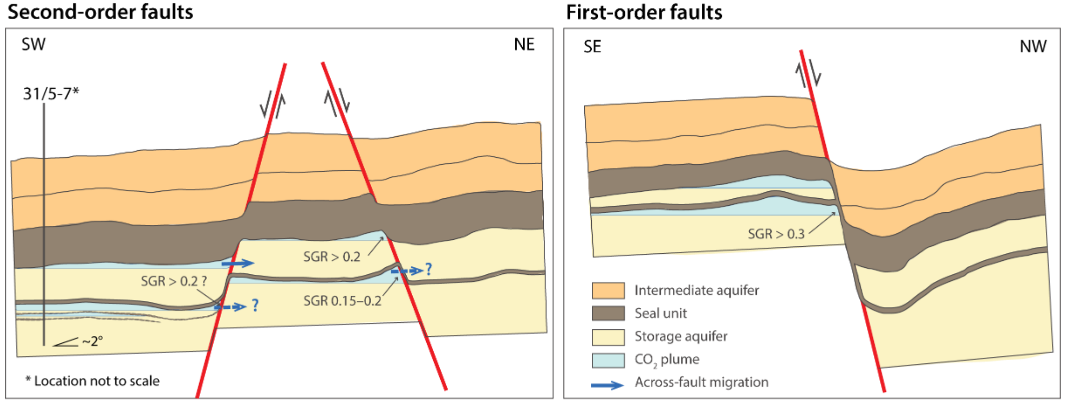
- Top Brent Gp.
- Top Upper Drake Fm.
- Top Lower Drake Fm.
- Top Cook Fm.
- Top Johansen Fm.
- Top Statfjord Gp.

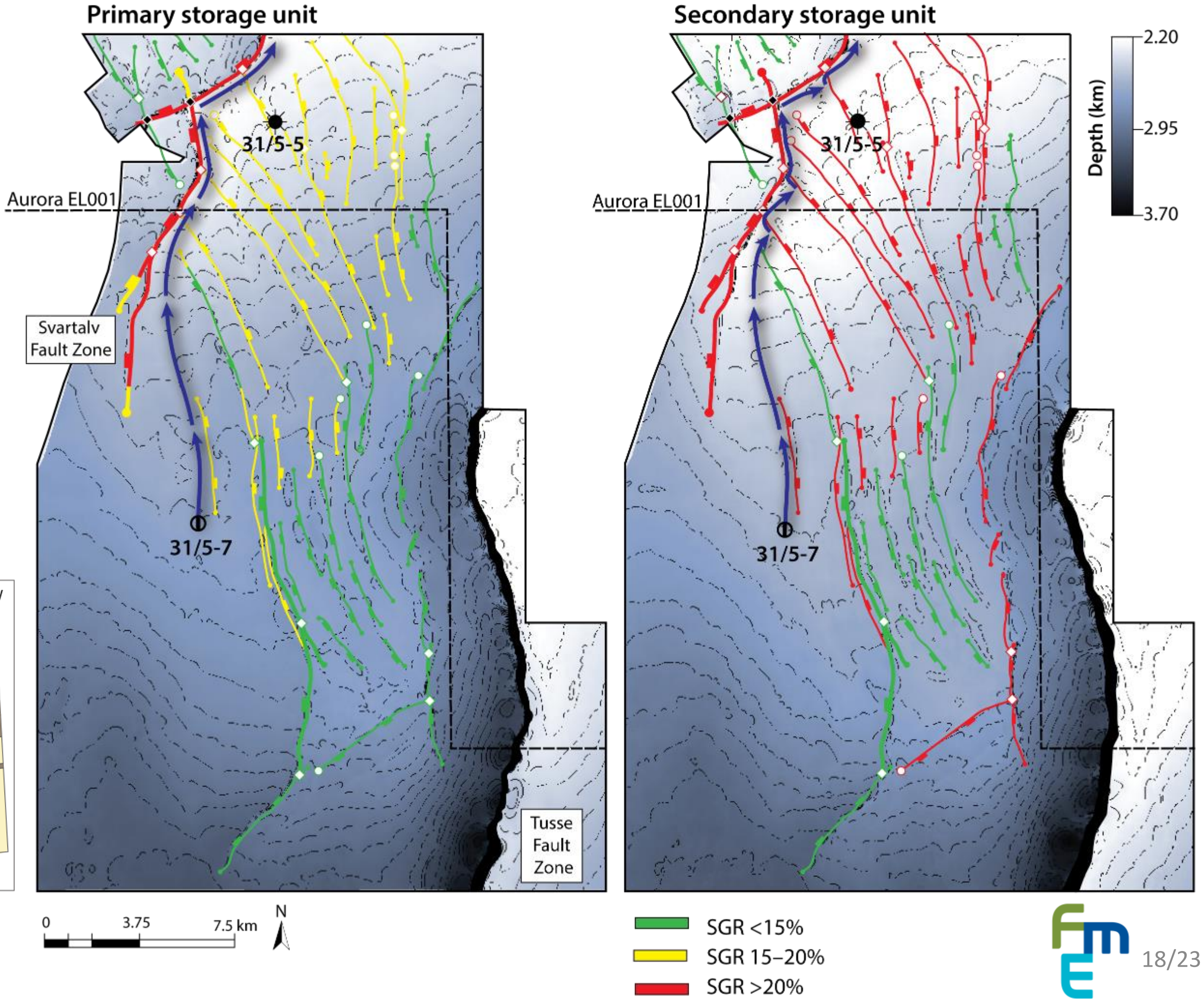
NCCS

Across-fault seal assessment – Influence on CO_2 migration

Membrane seal scenarios

		Primary storage unit		Secondary storage unit	
Faults	Dip	Juxt. seal	Mem. seal	Juxt. seal	Mem. seal
2nd-order	E/NE	No	Partly	Yes	Yes
	W/SW	No	No	No	No
1st-order	W	Partly	Yes	No	Yes





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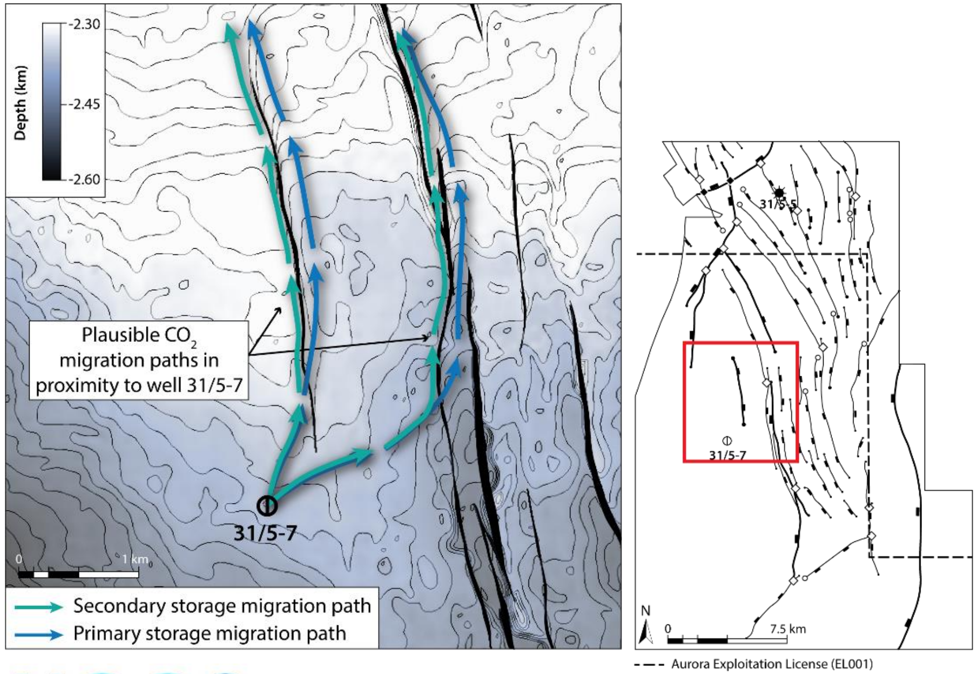
Across-fault seal assessment – Structural traps (‘baffles’)

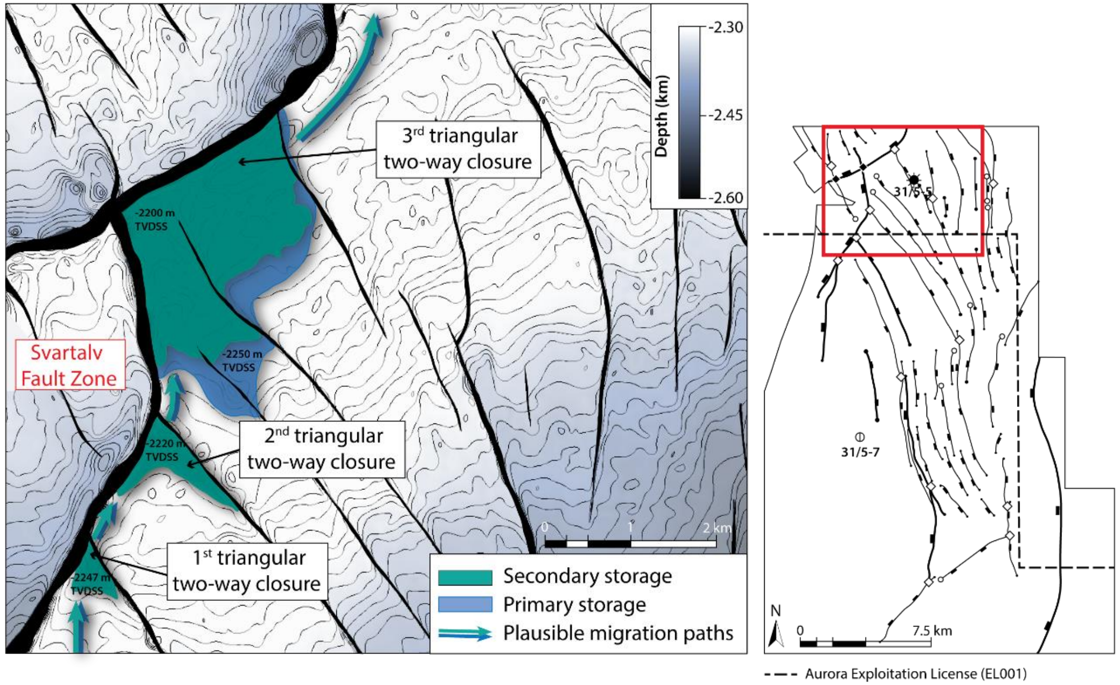
CO_2 migration near well 31/5-7:

- CO_2 plume in secondary storage unit → faults larger influence on migration
- Heterogeneities, injection scheme, anisotropy in relative permeabilities *(Sundal et al., 2016)*



Structural traps:

- After 150–210 years *(Sundal et al., 2015)*
- GRV – 68 x 10^6 m^3 (primary storage unit), 93.6 x 10^6 m^3 (secondary storage unit)
- Rough estimate of storage capacity – 0.23 Mt CO_2



Limitations, uncertainties, and other considerations

Fault zone complexities

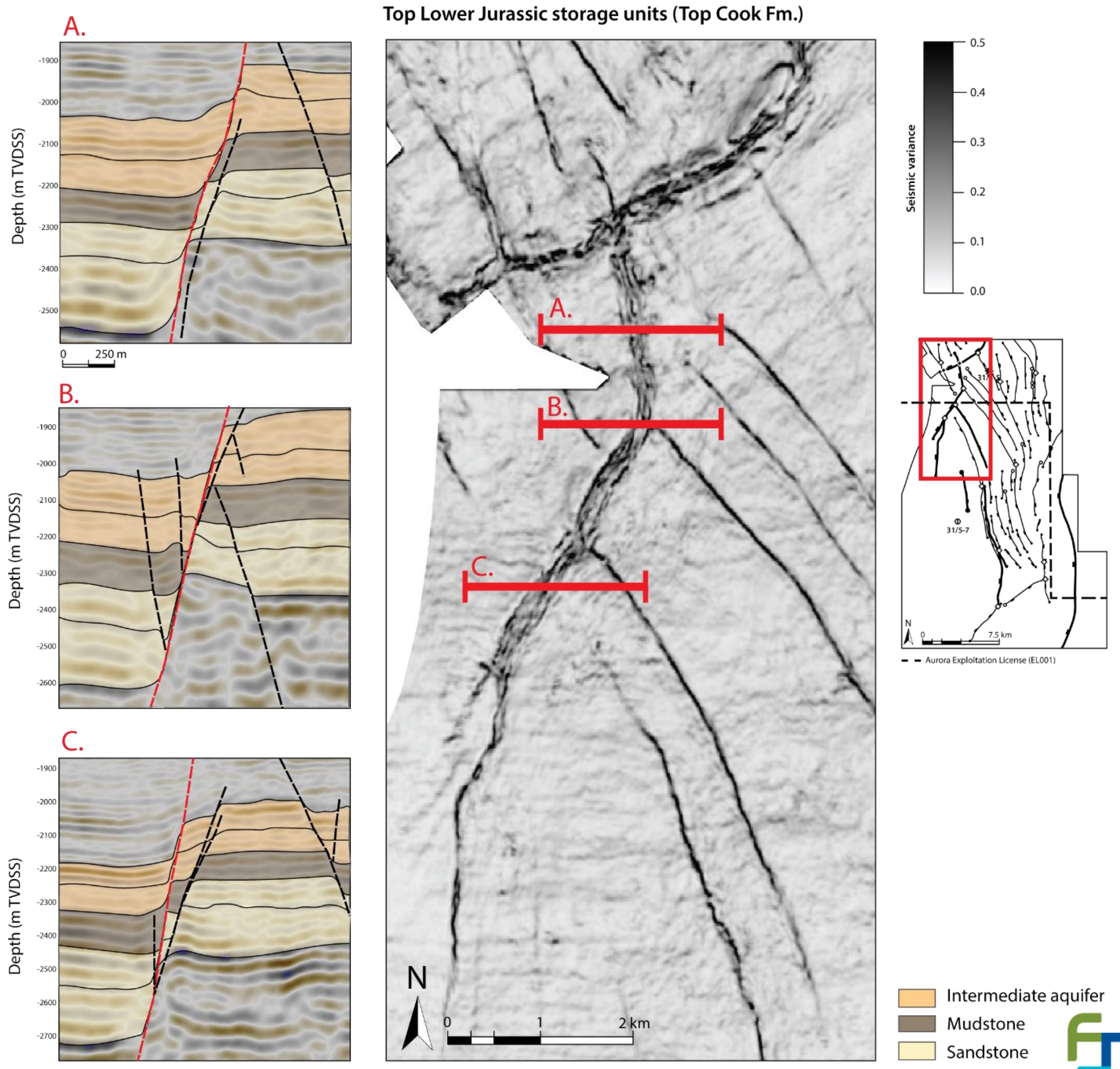
- Influence across-fault seals *(Færseth et al., 2007)*
- Svartalv Fault Segment – multiple slip planes, antithetic and synthetic splays

Sub-seismic features

- Deformation bands, damage zone, process zone

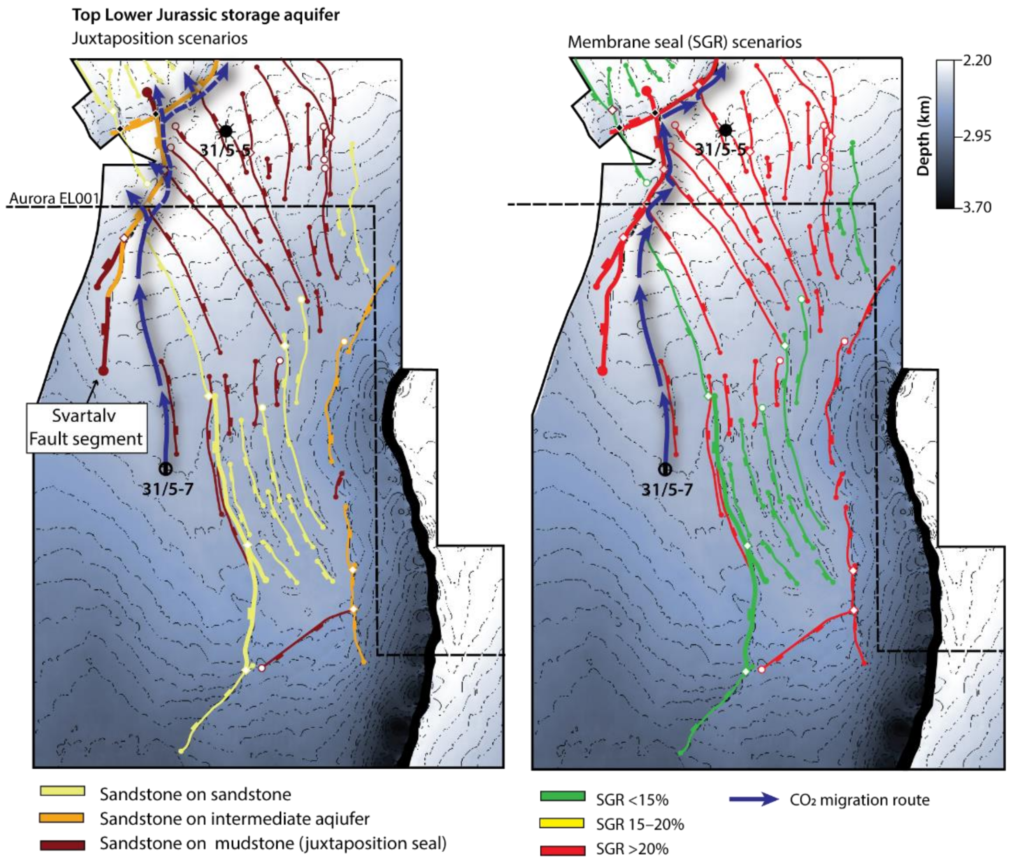
Membrane seal assessment

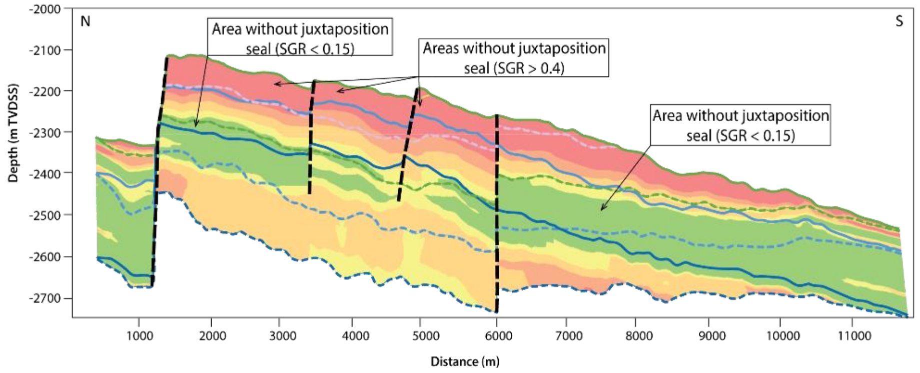
- SGR calibration
- Applying present-day methods to CO_2 storage sites *(Miocic et al., 2019; Karolyte et al., 2020)*

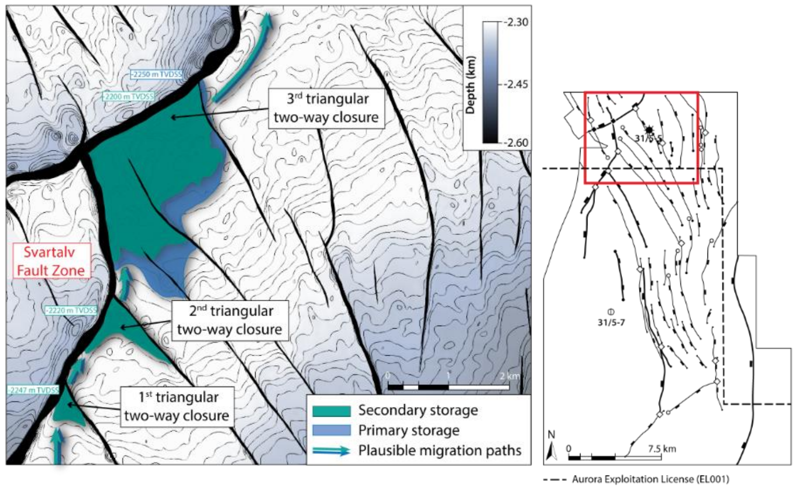


Conclusions and take away messages

- The Aurora storage site is faulted, likely influencing the migration of injected CO_2
- E and NE dipping second-order faults → baffle migration
- Svartalv Fault Zone exhibit SGR >30% → baffle migrating CO_2
- Small-scale structural traps contribute to the storage capacity
- Highest uncertainty related to the presence of membrane seal across the Svartalv Fault Zone → monitoring important



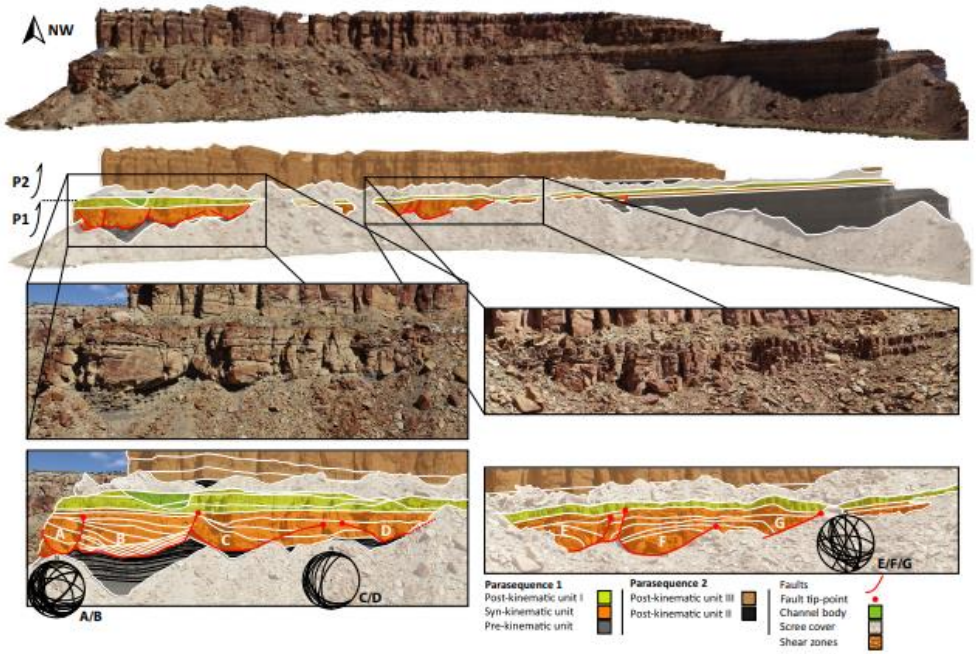




Upcoming projects

Field studies of growth faults in Floy Canyon, Utah

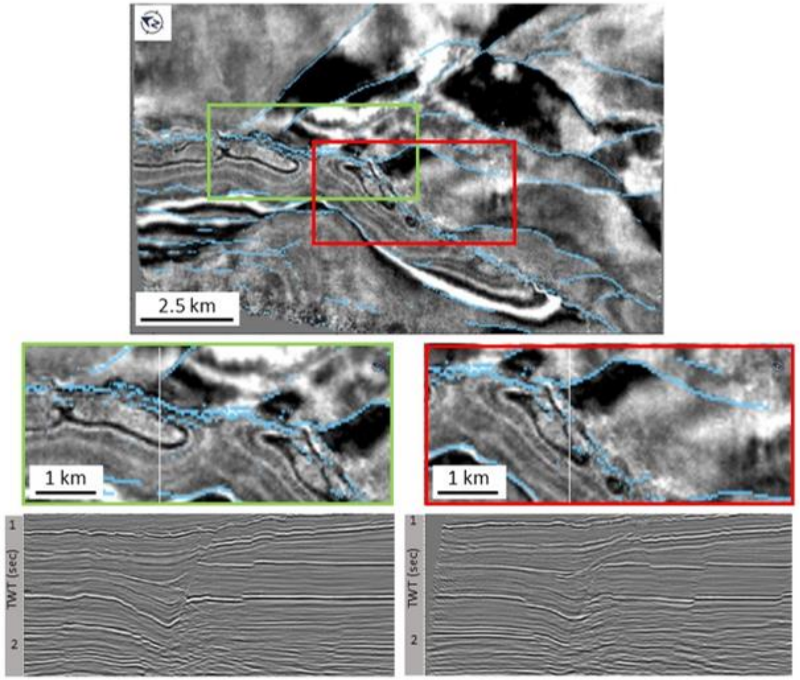
- **Aim**: Assessment of lateral and vertical movement of growth faults and implications for fault seals and fluid migration.



From Braathen et al., 2018

Fault zone complexities and implications for CO_2 storage

- **Aim:** Assessment of structural complexities and implications for faults seals using machine learning techniques



From Michie et al., 2021

Thank you!

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*Scientific colour maps available at: https://www.fabiocrameri.ch/colourmaps/

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