Monitoring of CO_2 injection in depleted gas reservoirs through measurements of **seafloor deformation** and **4D gravity**

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*Spirit Energy, **Reach Subsea

Outline

- The technology

- Monitoring CO_2 storage in the Morecambe fields
    - 4D gravity at the seafloor
    - Maps of seafloor deformation

- Outlook and conclusions

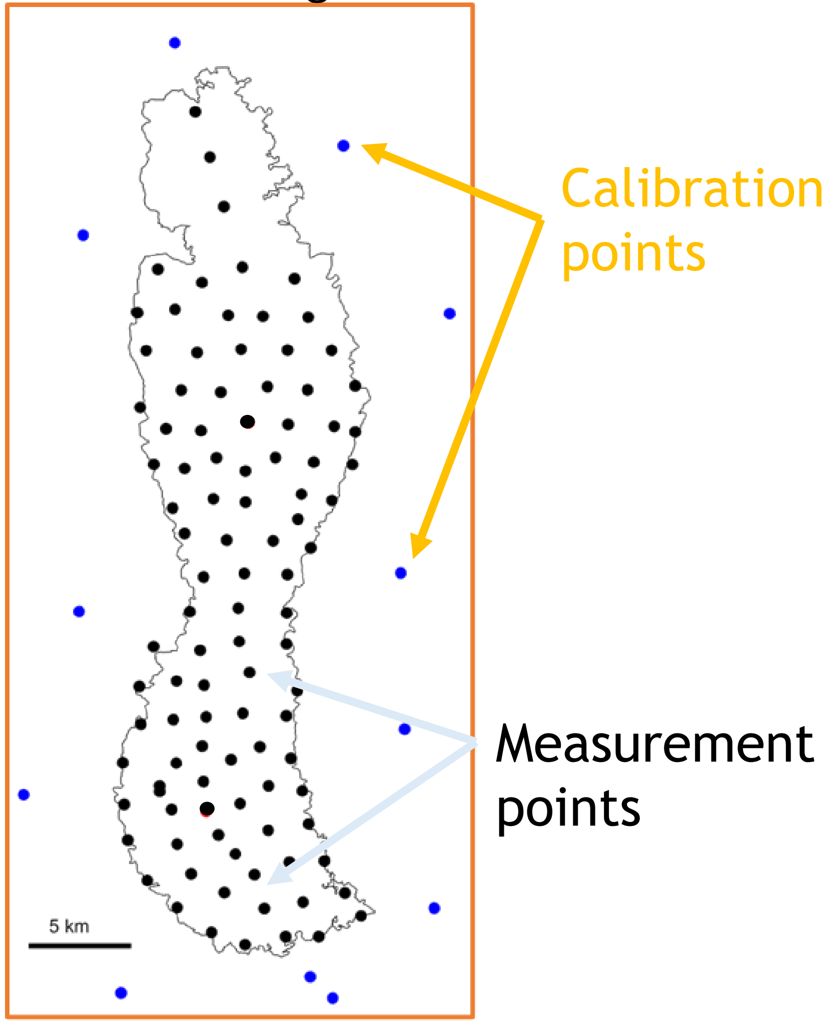
Monitoring principles

- Survey based data **acquisition** to provide field-wide maps of relative gravity and relative depths at the seafloor

- Changes in the property maps between consecutive surveys informs of time evolution in the reservoir
  - 4D gravity –> mass changes
  - Seafloor uplift –> pressure buildup

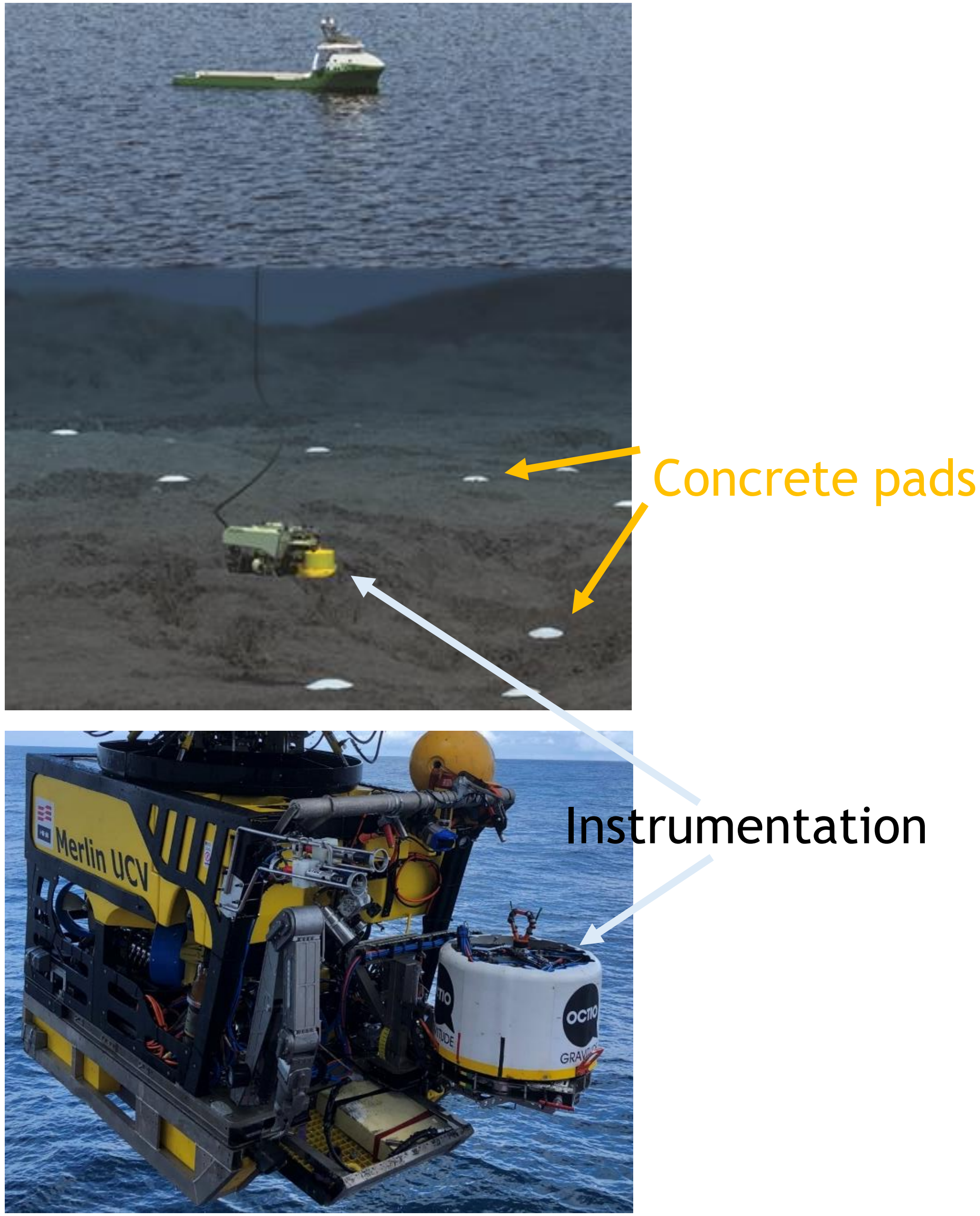
- Calibration points at the distance from the field secures time-lapse consistency

Ormen Lange field



The technology

- The measurement locations are defined utilizing **pre-deployed concrete pads**
- Instrumentation is **carried by ROV**
- ROV operations are easily combined with windfarms or other infrastructure
- Cost-effective
  - 1/10 conventional 4D seismic
  - Simplified operations and logistics
- Minimal environmental footprint
  - Passive method with no active source



Sensitivity evolution

- Dozens of gravity and subsidence surveys over the last two decades: continuous improvement in accuracy, due to advances in equipment and evolution of survey procedures

Published results of gravity and seabed deformation monitoring

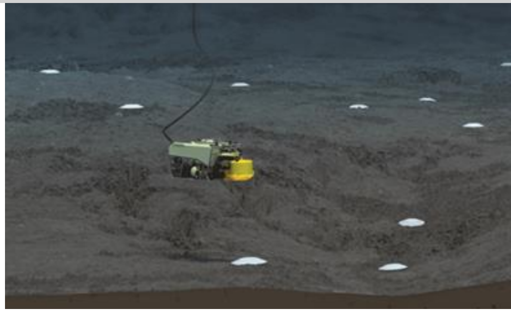
Field	Survey year	Time-lapse Repeatability	
		Gravity (μGal)	Depth (mm)
Snøhvit	2011[1]	3.7	4.6
	2019[1]	1.6	2.8
Mikkel	2022[2]	1	1.4

(1) Ruiz, H., Lien, M., Vatshelle, M., Alnes, H., Haverl, M., & Sørensen, H. (2022). Monitoring the Snøhvit gas field using seabed gravimetry and subsidence. First Break, 40(3), 93-96.

(2) Solbu, Ø. H., Nyvoll, A., Alnes, H., Vassvåg, S. C., Lien, M., & Ruiz, H. (2023). Time-Lapse Gravity and Subsidence Applied in History Matching of a Gas-Condensate Field. First Break, 41(9), 69-74.

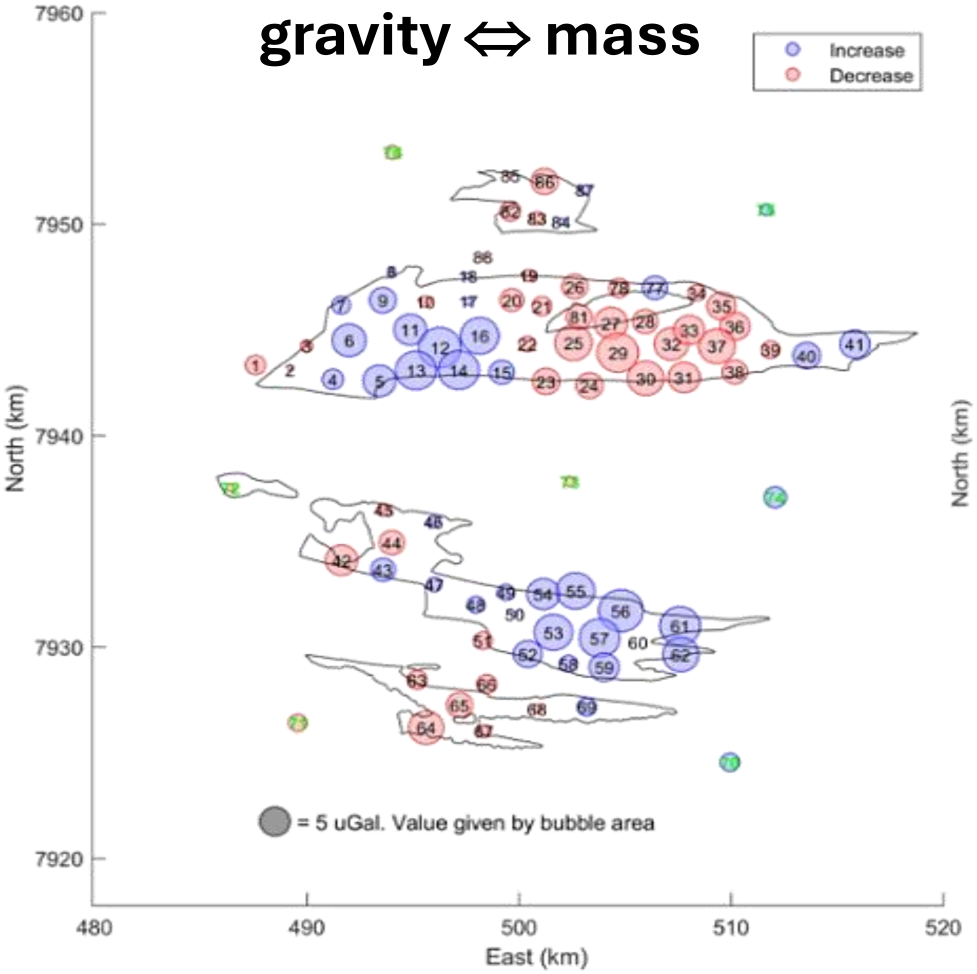
- Recent surveys indicate time-lapse repeatability below 1 μGal for gravity, and in the range of 2-3 millimeters for seabed displacement, allowing for resolving smaller changes in the subsurface

Ruiz, H, et al., Monitoring the Snøhvit gas field using seabed gravimetry and subsidence, First Break, Volume 40, Issue 3, Mar 2022, p. 93 - 96

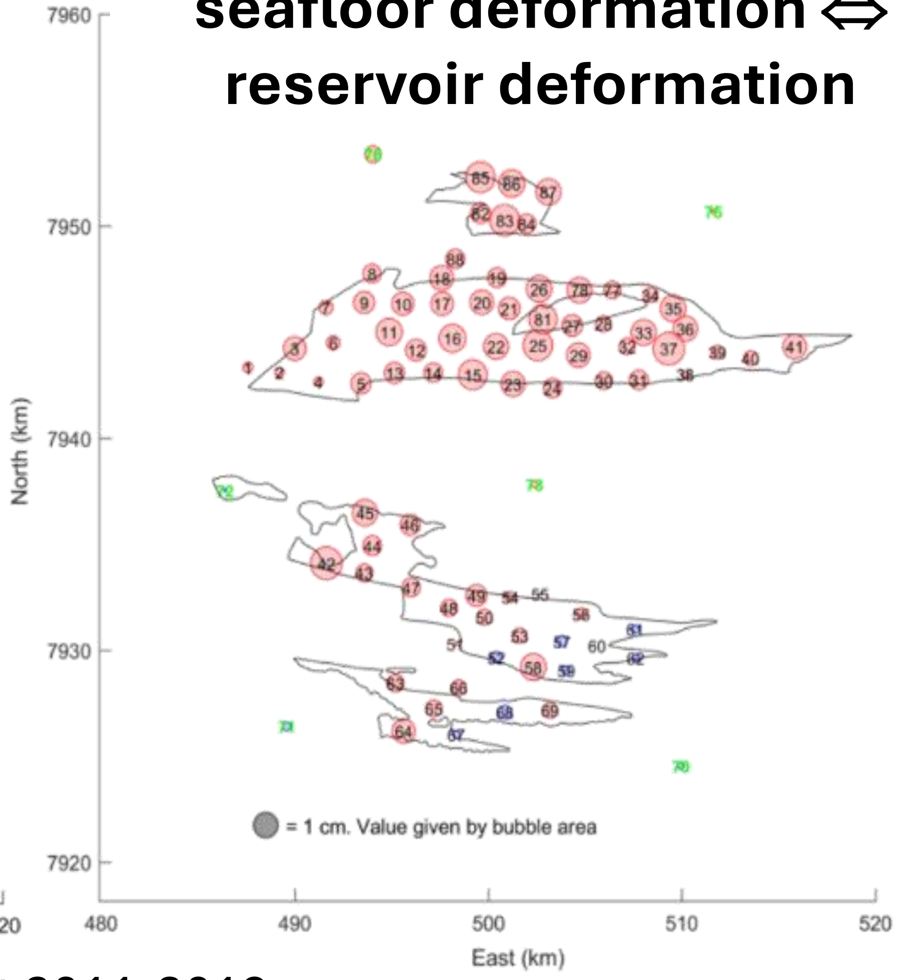


Field case illustrating the value

gravity ⇔ mass



seafloor deformation ⇔ reservoir deformation



Snøhvit 2011-2019

- Map fluid flow
- Map aquifer influx
- Compartmentalization
- Mass balance

- Measure compressibility
- Map pressure depletion
- Compartmentalization
- R-factor

A mature technology

Field	First survey	Nº of surveys	Burial depth (m)	Nº of concrete platforms
Troll	1998	9	1400	113
Slepiner	2002	4	800 - 2350	50
Mikkel	2006	5	2500	21
Midgard	2006	5	2500	60
Ormen lange	2007	8	2000	120
Snøhvit/Albatross	2007	4	1800 - 2300	88
Statfjord	2012	2	2750	53
Aasta Hansteen	2018	3	2300	31
Askeladd	2019	1	250	21

Alnes, H. et al. [2010] Experiences on Seafloor Gravimetric and Subsidence Monitoring Above Producing Reservoirs: 72nd Conference and Exhibition, EAGE, Extended Abstracts, L010.

Vevatne J. et al. [2012] Use of field-wide seafloor time-lapse gravity in history matching the Mikkel gas condensate field: 74th EAGE Conference & Exhibition, Extended Abstracts, F040.

Agersborg, R. et al [2017] Density Changes and Reservoir Compaction from In-situ Calibrated 4D Gravity and Subsidence Measured at the Seafloor: SPE Annual Technical Conference and Exhibition, Extended abstracts, PSE-187224-MS.

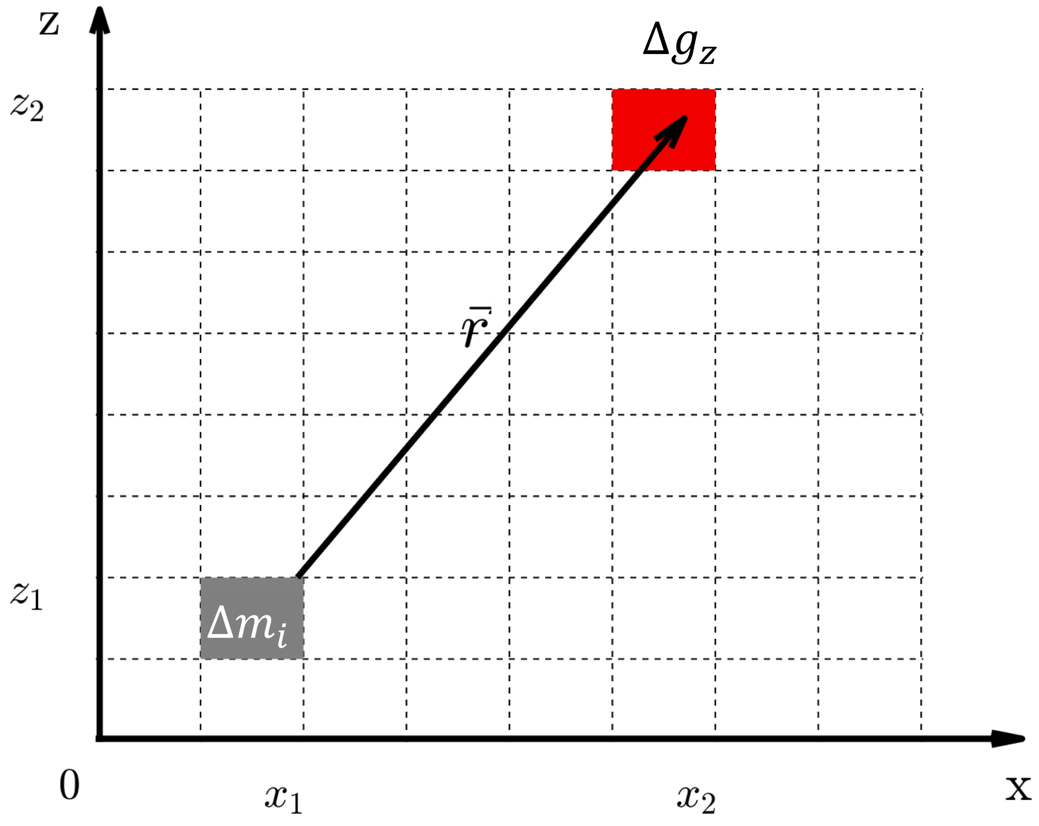
Lien, M. et al. [2017] How 4D Gravity and Subsidence Monitoring Provide Improved Decision Making at a Lower Cost, First EAGE Workshop on Practical Reservoir Monitoring 6-9 March 2017, Amsterdam, The Netherlands

Vatshelle, M. et al. [2017] Monitoring the Ormen Lange field with 4D gravity and seafloor subsidence: 79th EAGE Conference & Exhibition, Extended Abstracts, Th A1 06.

Ruiz, H., et al. [2022] Monitoring the Snøhvit Gas Field Using Seabed Gravimetry and Subsidence, First Break, Volume 40, Issue 3, Mar 2022, p 93-96.

Solbu, Ø. H., et al. [2023]. Time-Lapse Gravity and Subsidence Applied in History Matching of a Gas-Condensate Field. First Break, Volume 41, issue 9, 69-74.

Time-lapse gravity calculation



$$\Delta g_z = G_c \sum_i \frac{(z_i \Delta \boldsymbol{m_i})}{(x_i{}^2 + y_i{}^2 + z_i{}^2)^{3/2}}$$

$$\Delta \boldsymbol{m} = (\rho_{fluid} V_{por})^{\boldsymbol{t_1}} - (\rho_{fluid} V_{por})^{\boldsymbol{t_0}}$$

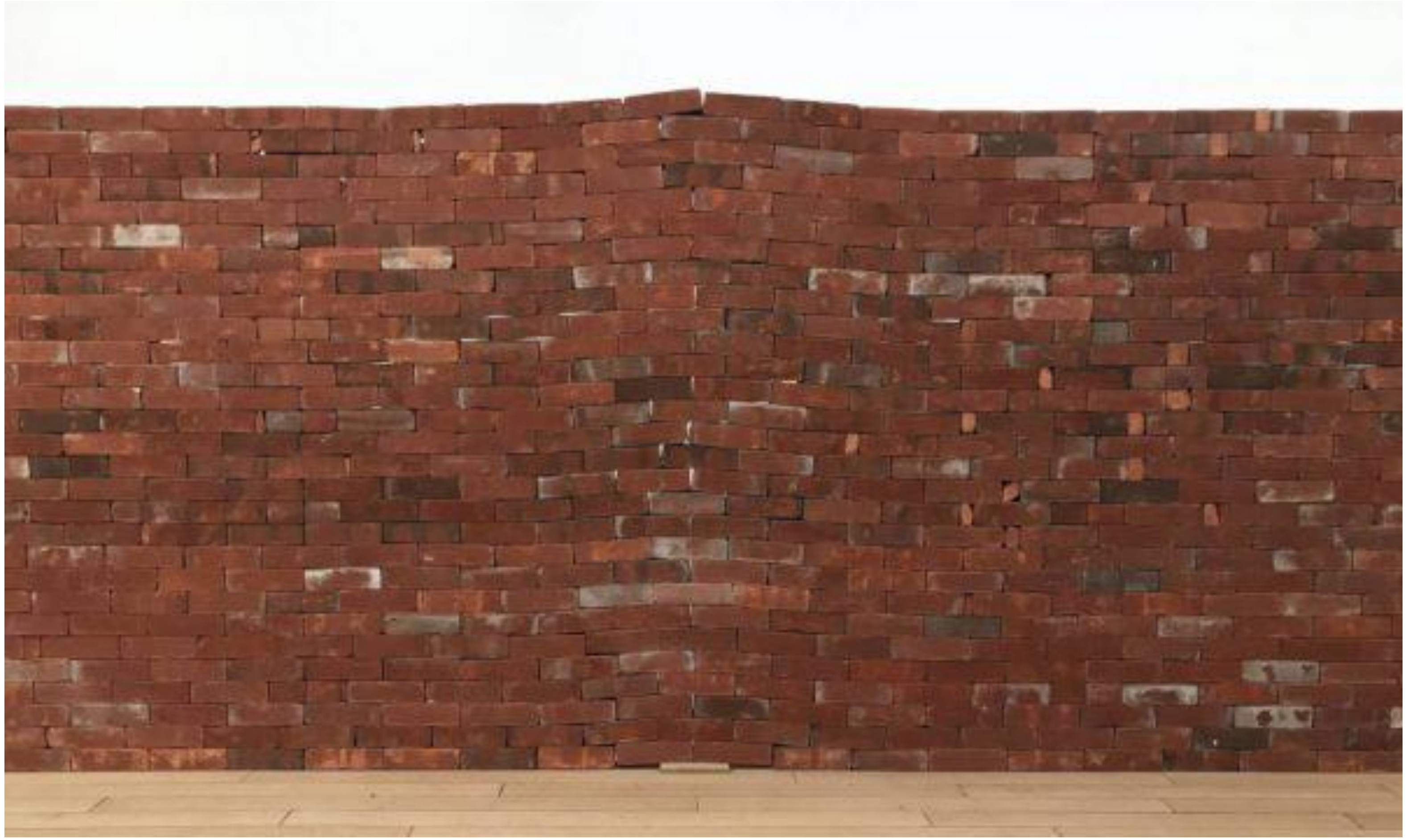
t_0 and t_1: times of baseline and monitor surveys

ρ_{fluid}: fluid density

V_{por}: pore volume

Seafloor deformation modeling

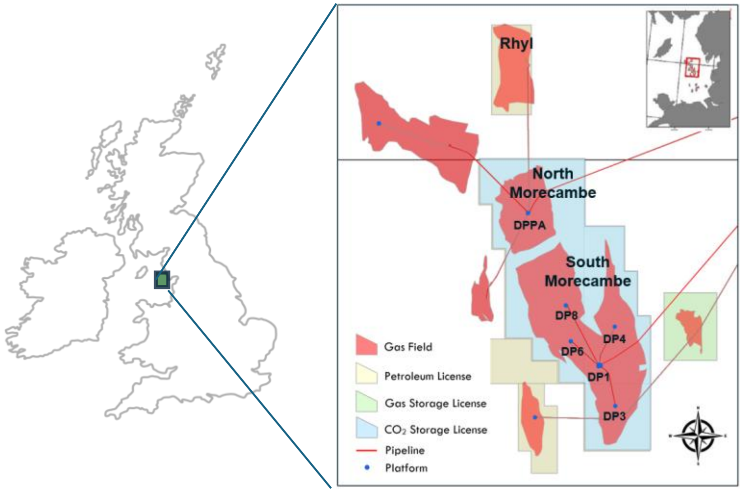
Seafloor deformation modeling

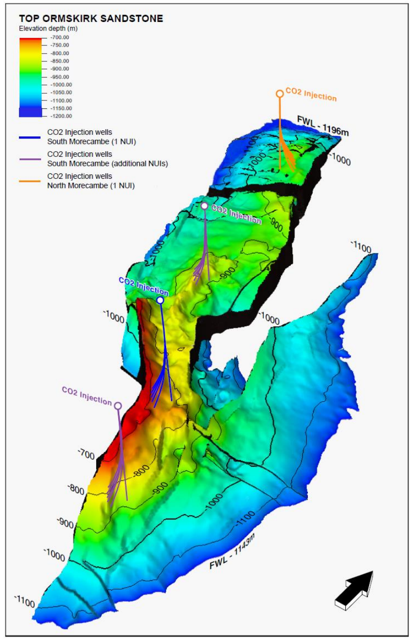


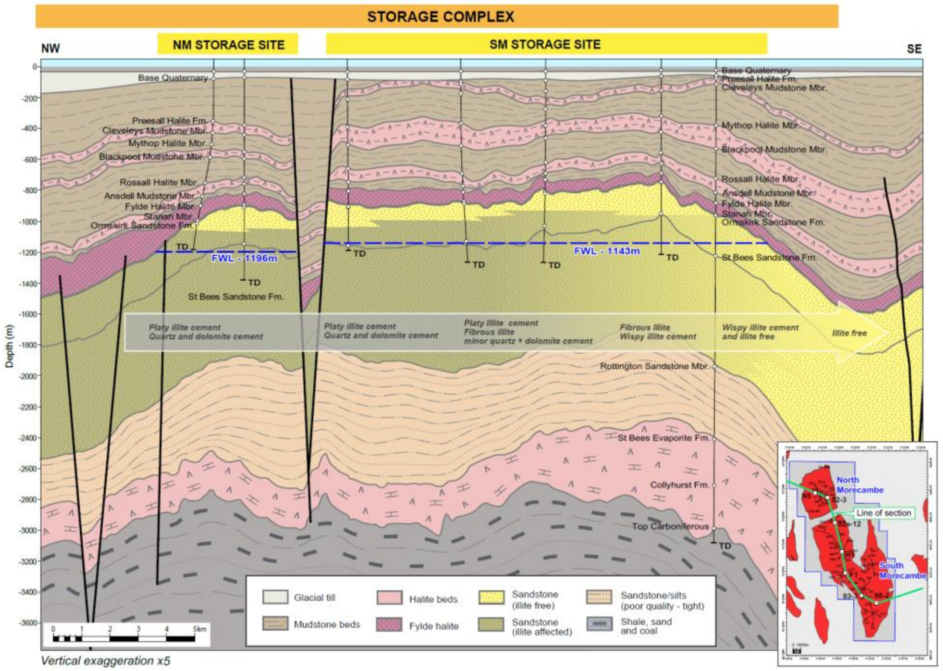
Monitoring of CO_2 injection in the Morecambe depleted gas reservoirs

MNZ Overview

- The Morecambe Hub is a cluster of gas fields in the East Irish Sea approximately 25 km west of Barrow-in-Furness
- Carbon Storage Licence CS010 awarded in 2023 UK licensing round
- Over 6.6 tcf of natural gas produced to date
    - 5.4 tcf from South Morecambe
    - 1.2 tcf from North Morecambe
- The North & South Morecambe fields are fault-bounded / dip-closed structural traps with shallow crests
    - North Morecambe gas column 2950 - 3925 ft
    - South Morecambe gas column 2300 - 4750 ft
- Overall, a high-quality reservoir
- The cap rock and overburden are interbedded mudstones and halites providing excellent top seal integrity
- Depleted gas reservoir
    - Strongly depleted, P ≈10 bar at injection start
    - Initial injection with CO_2 as gas phase
    - Long term - CO_2 mixes with CH_4 & dissolves in underlying brine

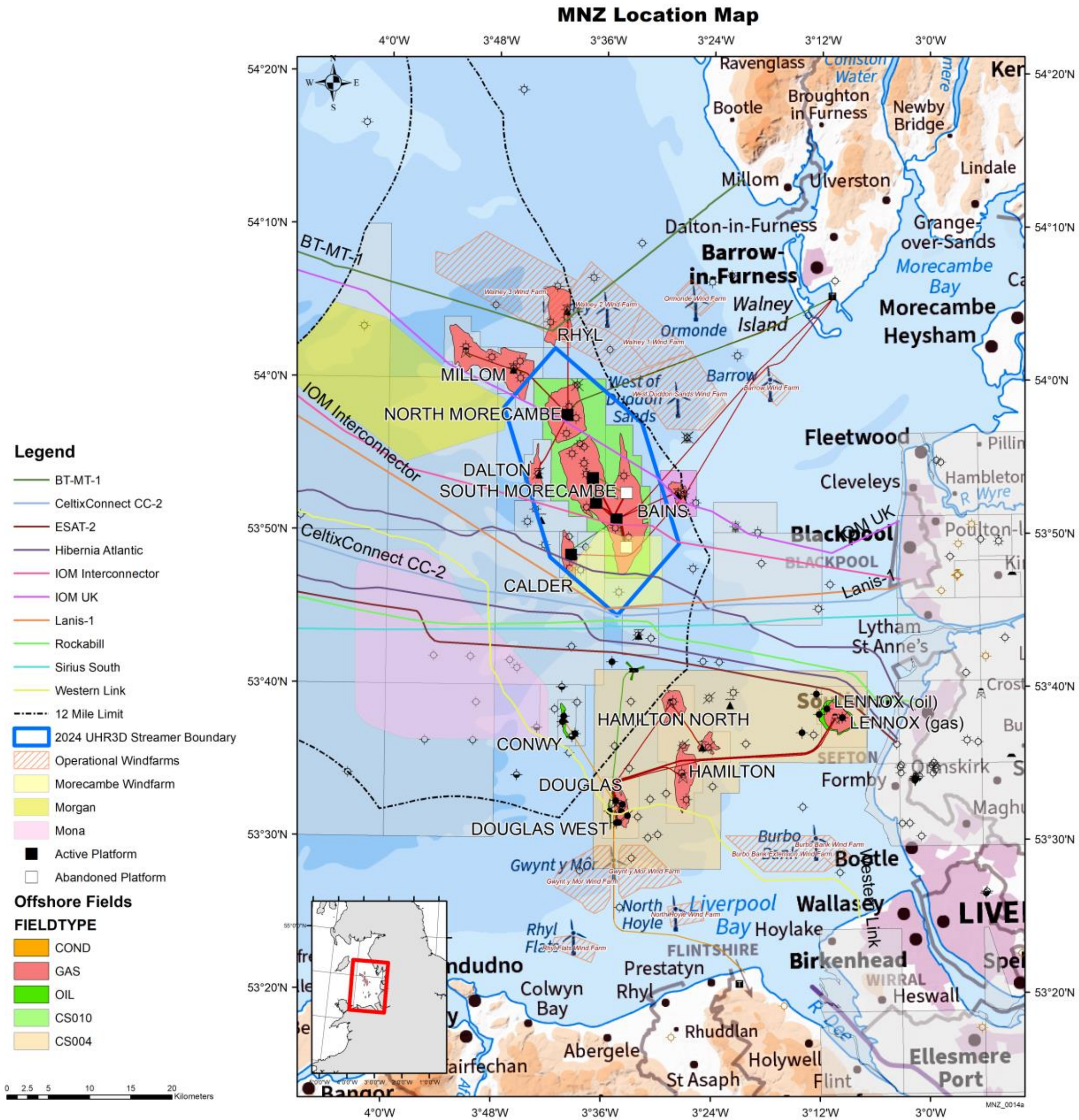






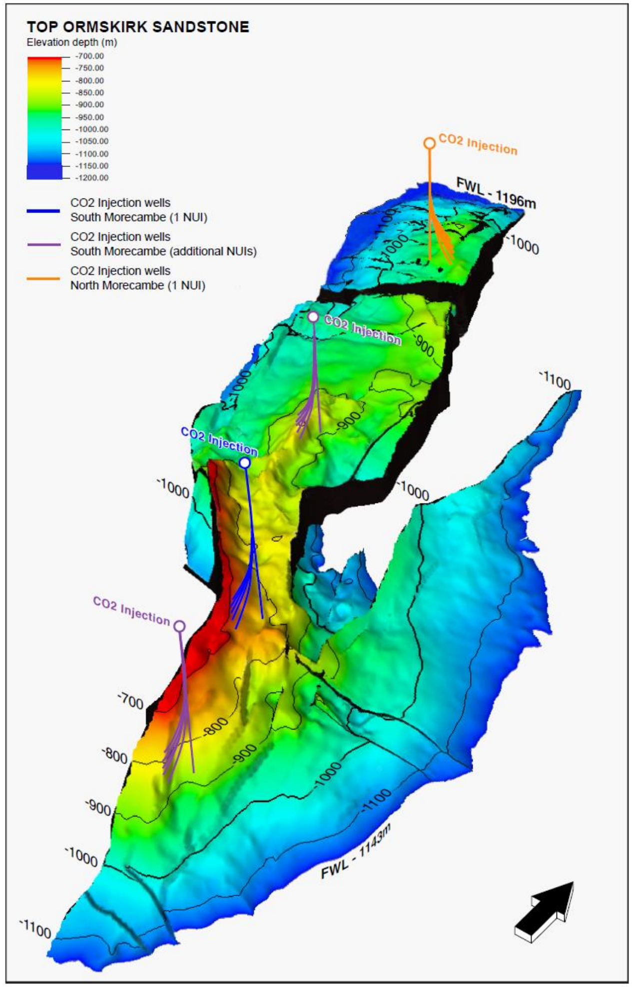
MNZ Location

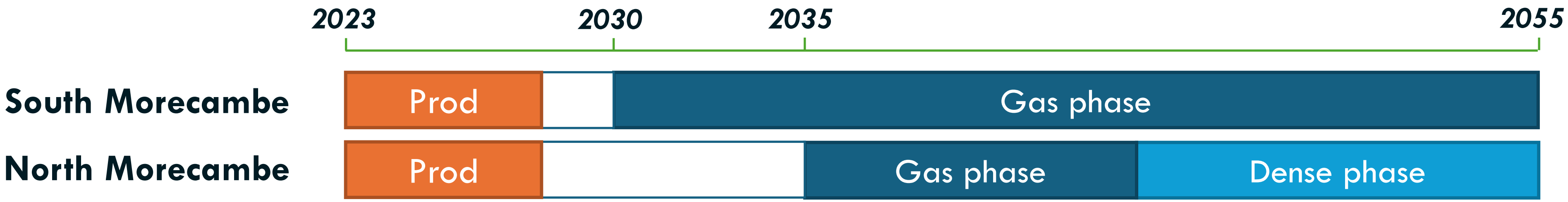
- Water depth ca. ~30 m
- Reservoir 700-1100 m below
- Challenging for 4D seismic
  - Changing infrastructure and windfarms
  - Residual natural gas limits acoustic response



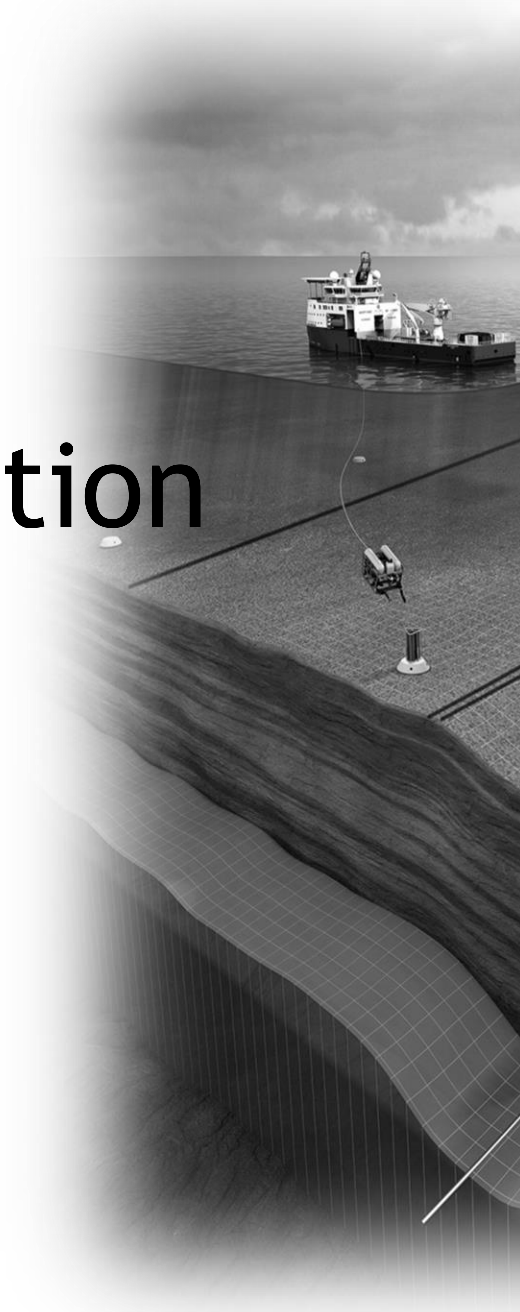
Reference case and infrastructure

- South Morecambe reference case:
  - Start injection 2030 at 9 MTPA (gas phase) for 25 years
  - Reservoir pressure stays below critical pressure of CO_2 throughout this timeframe
- North Morecambe reference case:
  - Start injection 2035 at 9 MTPA (gas phase), build reservoir pressure to dense phase conditions and switch to dense phase injection for combined total of 20 years injection to fill store
- Stores are pressure independent

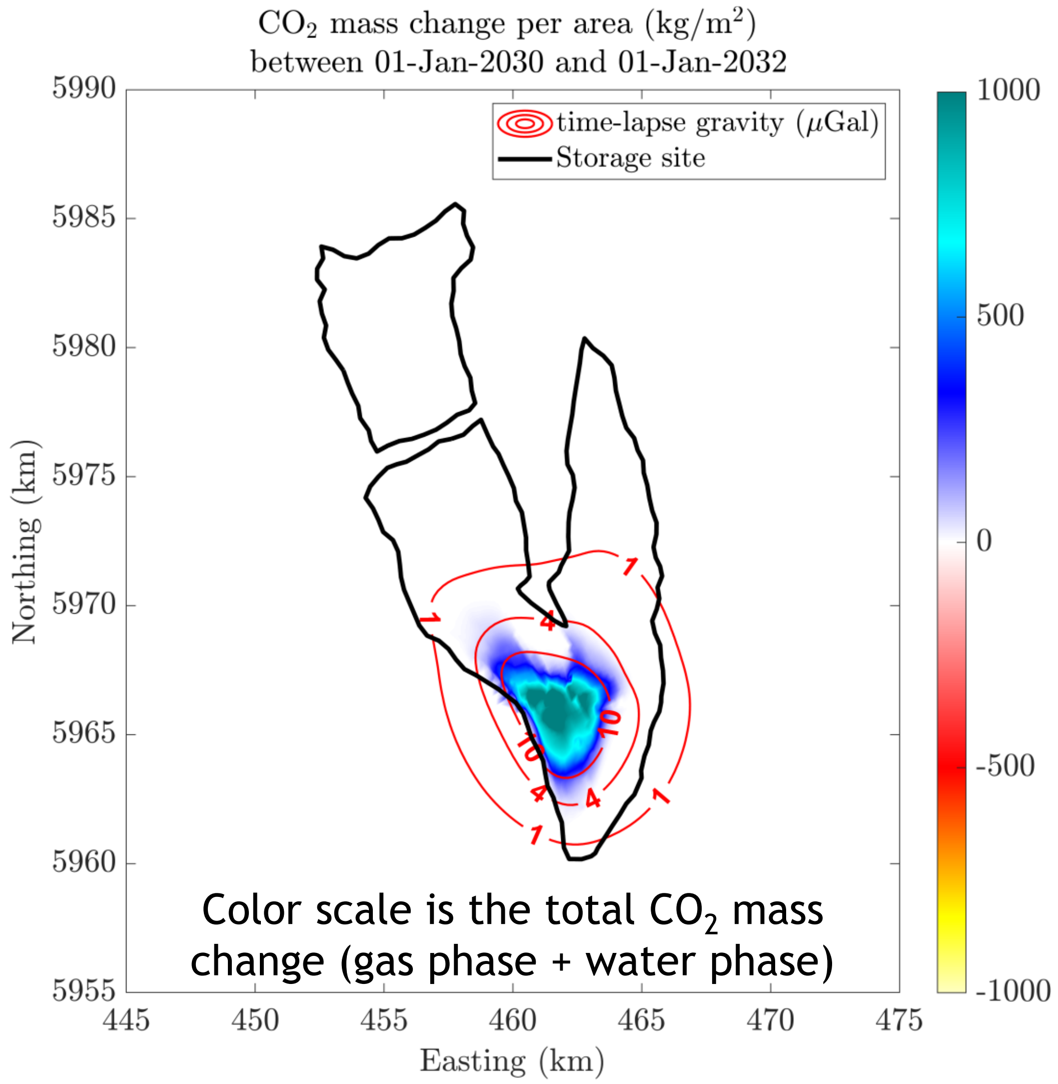


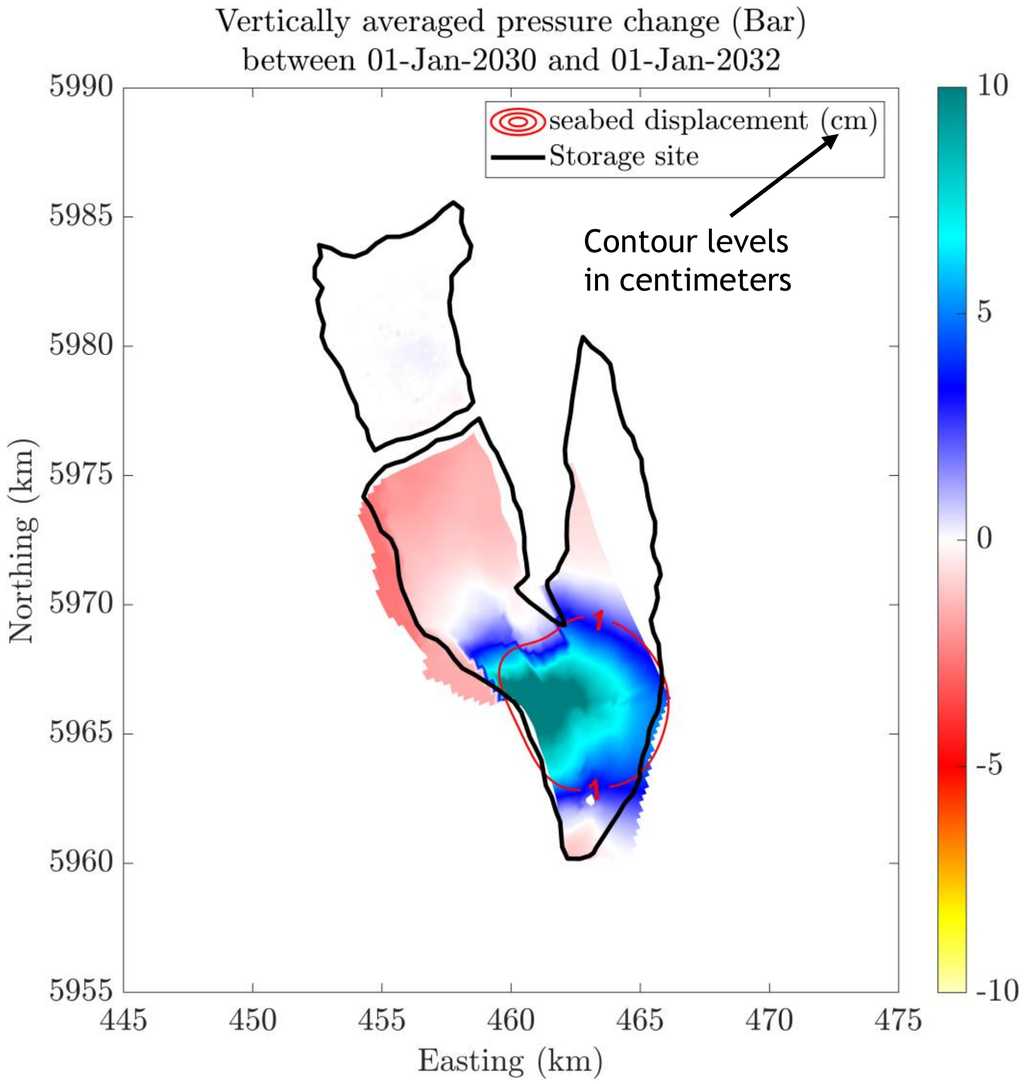


Modeled gravity and seafloor deformation

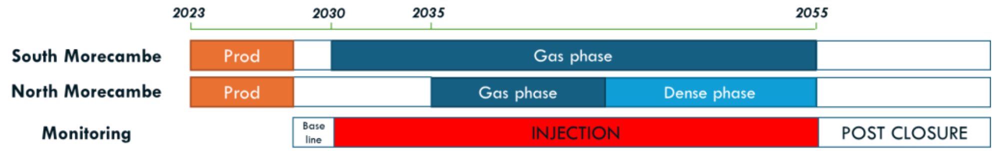


Modeling results (time-lapse 2030 – 2032)

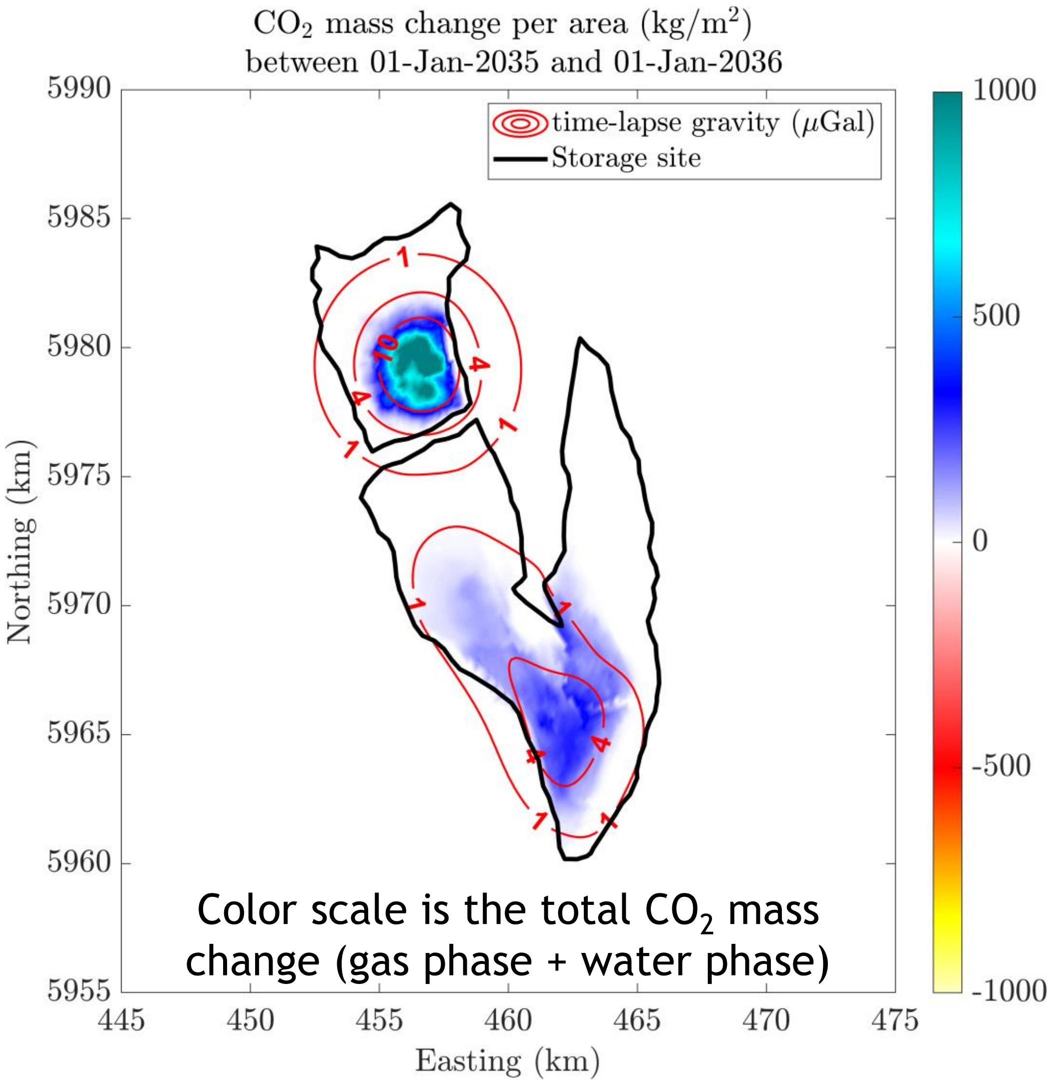


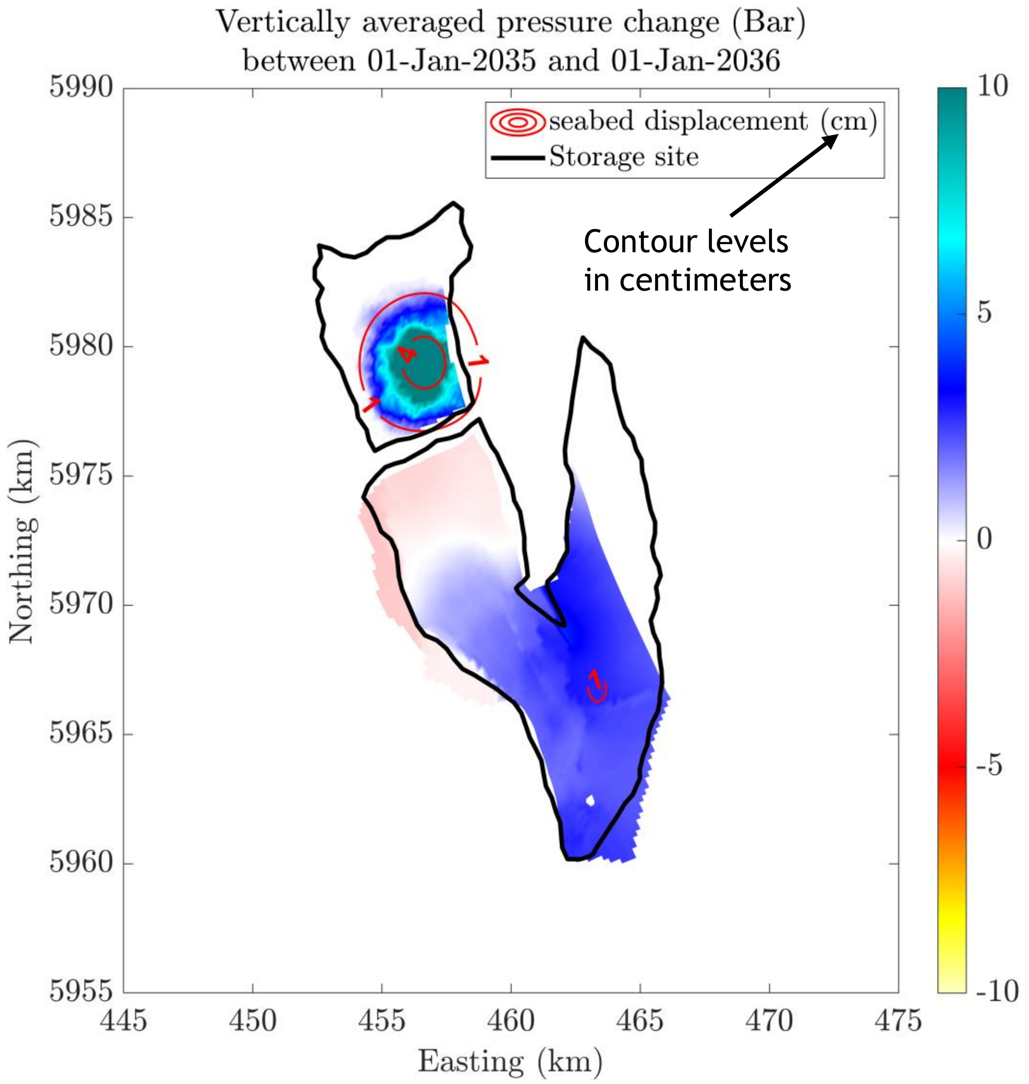


2030 to 2032

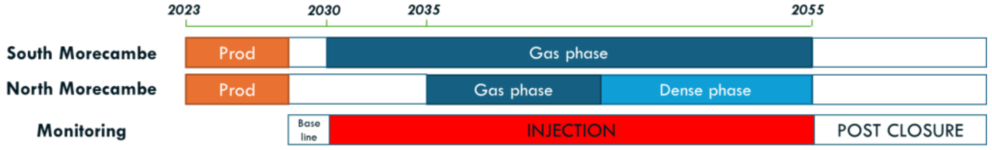


Modeling results (time-lapse 2035 – 2036)

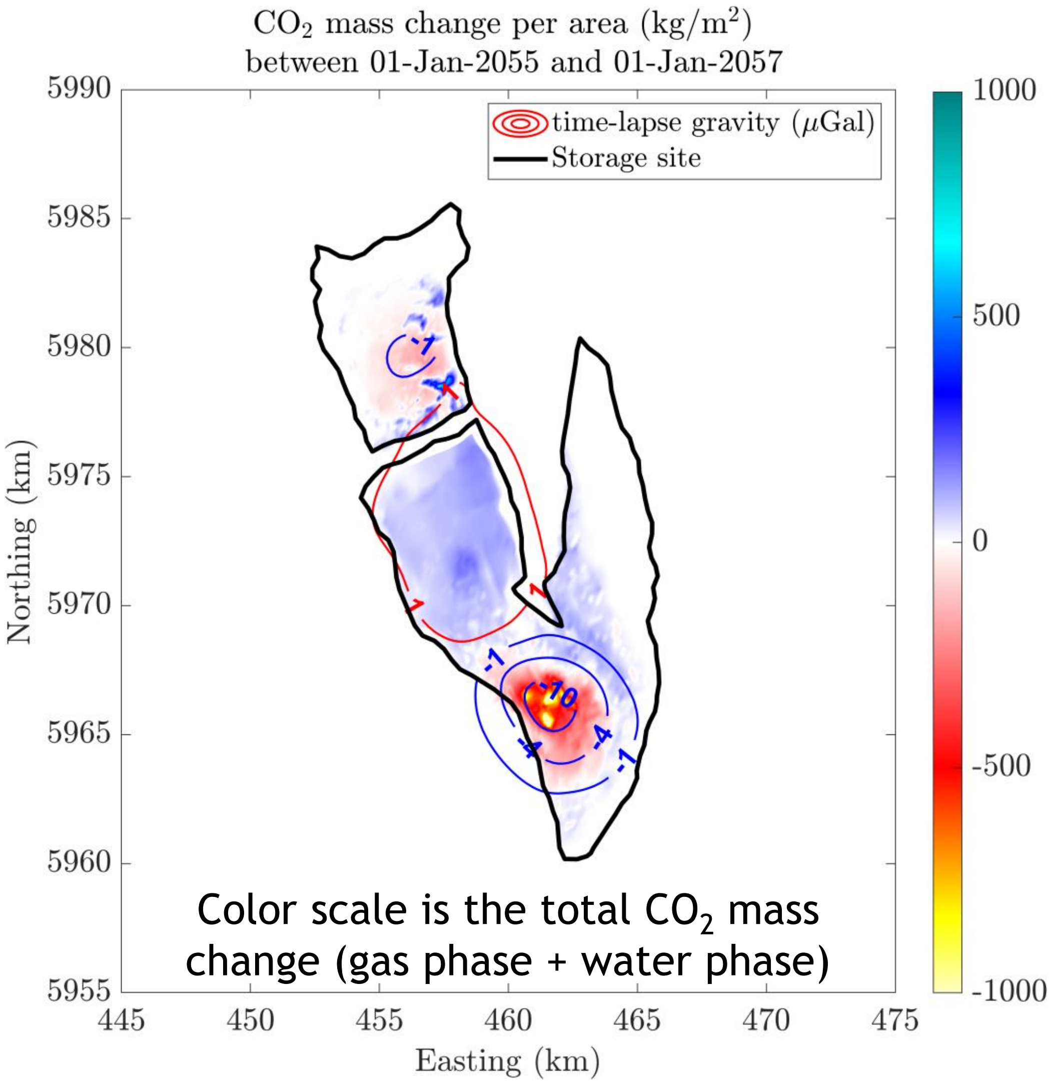




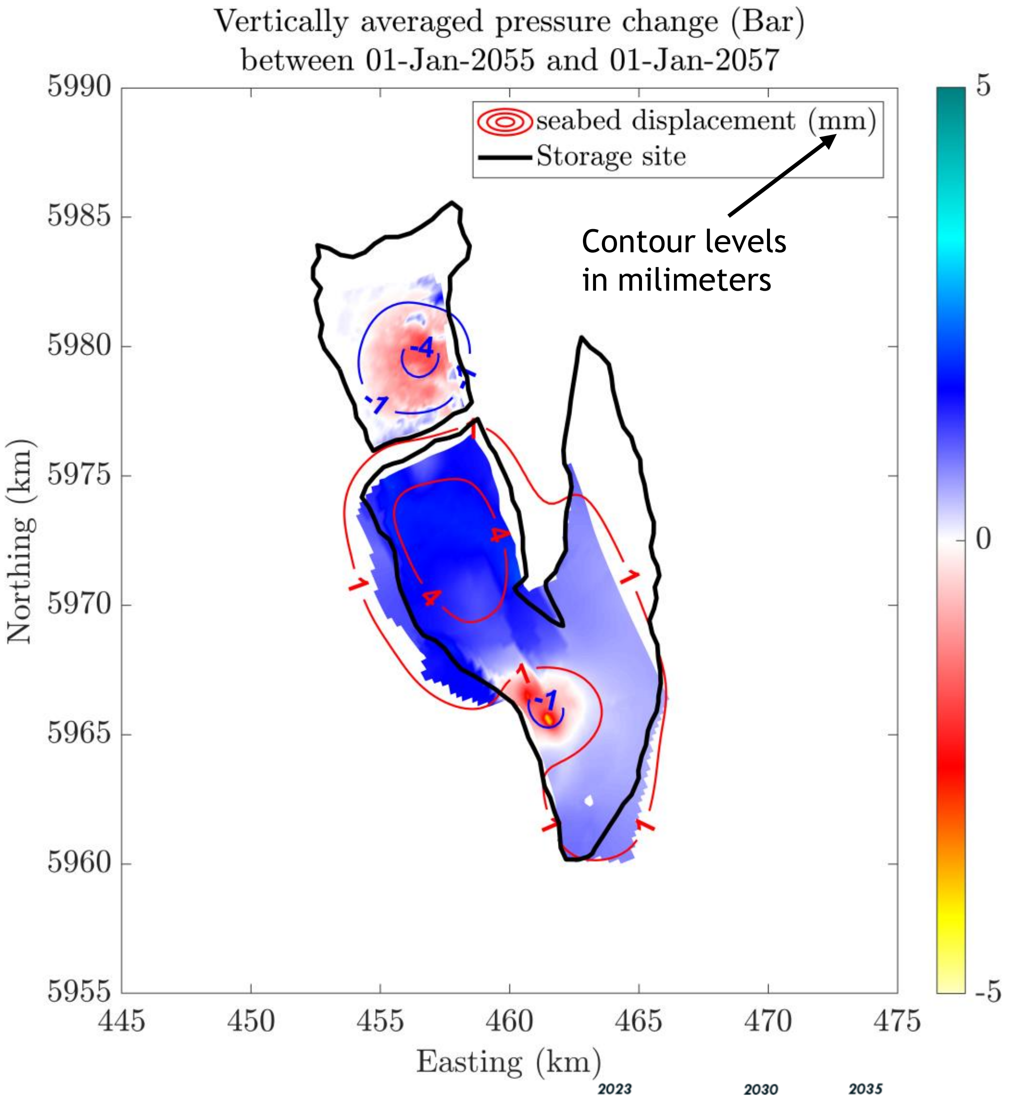
2035 to 2036



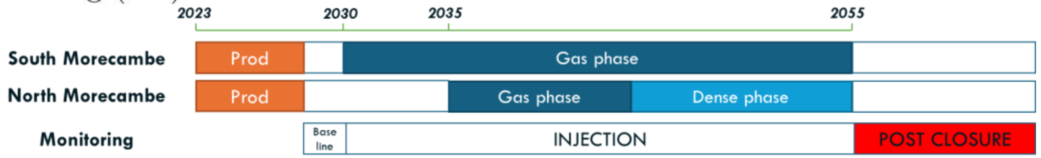
Modeling results (time-lapse 2055 – 2057)



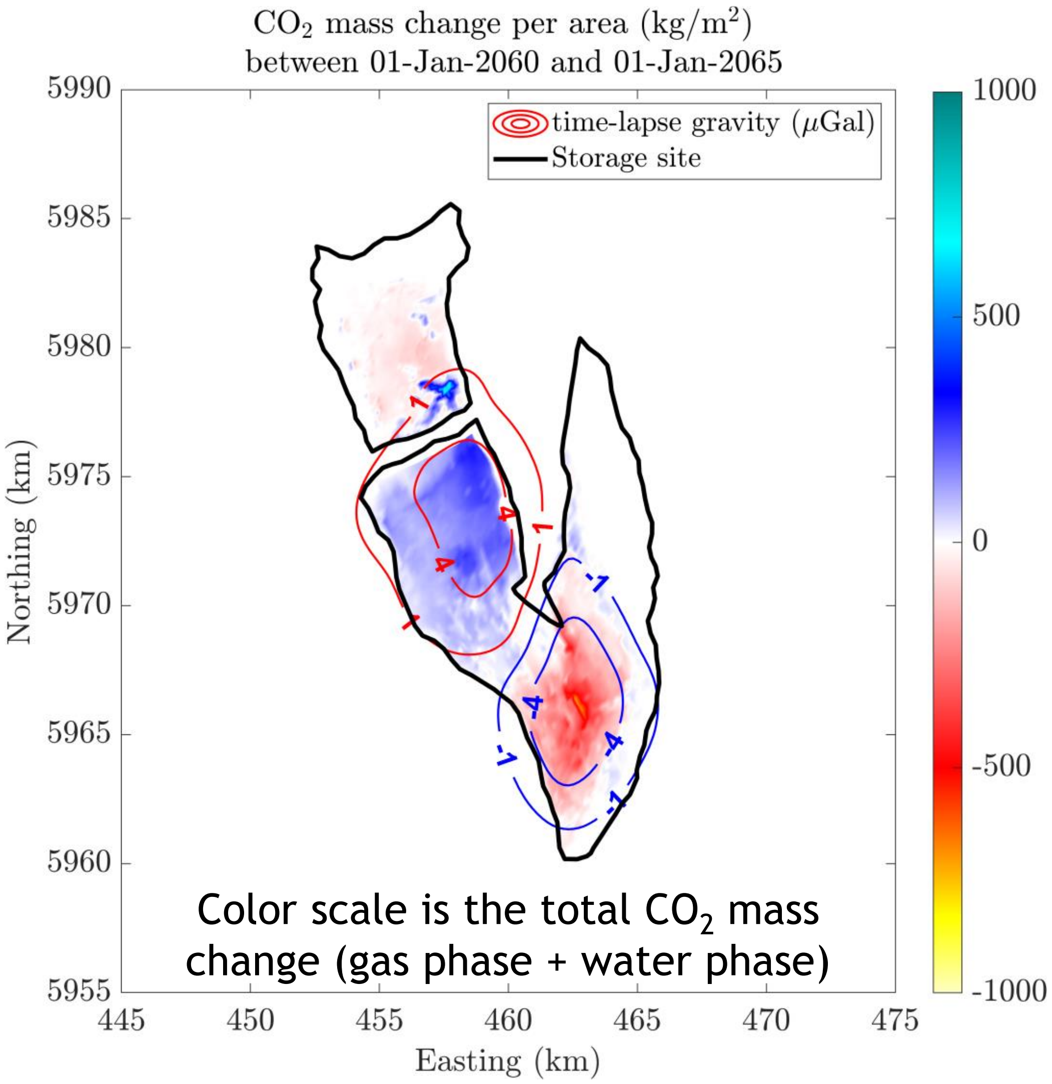
Color scale is the total CO_2 mass change (gas phase + water phase)

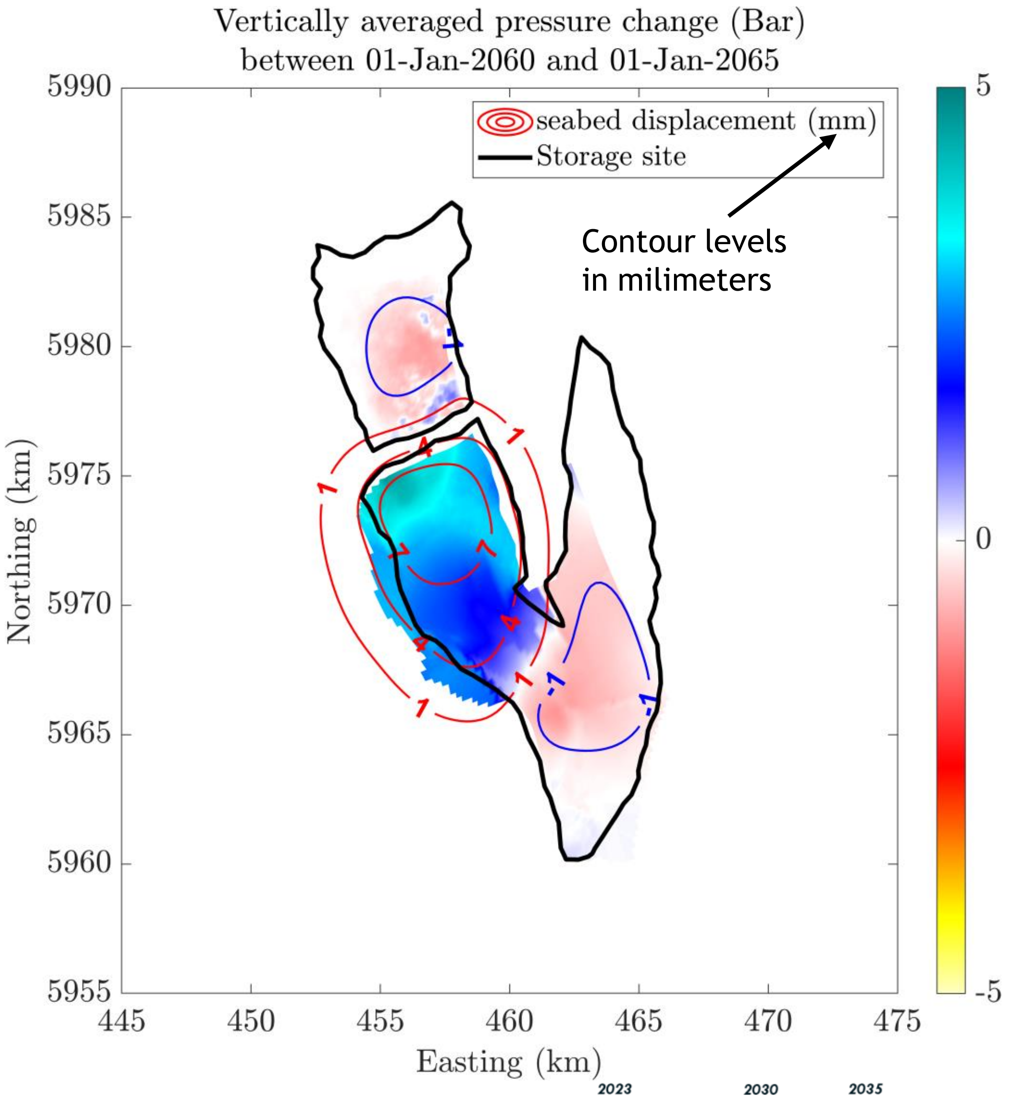


2055 to 2057

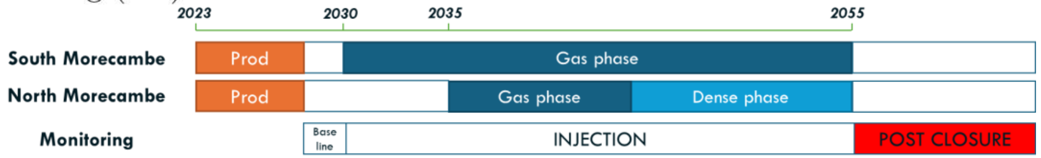


Modeling results (time-lapse 2060 – 2065)

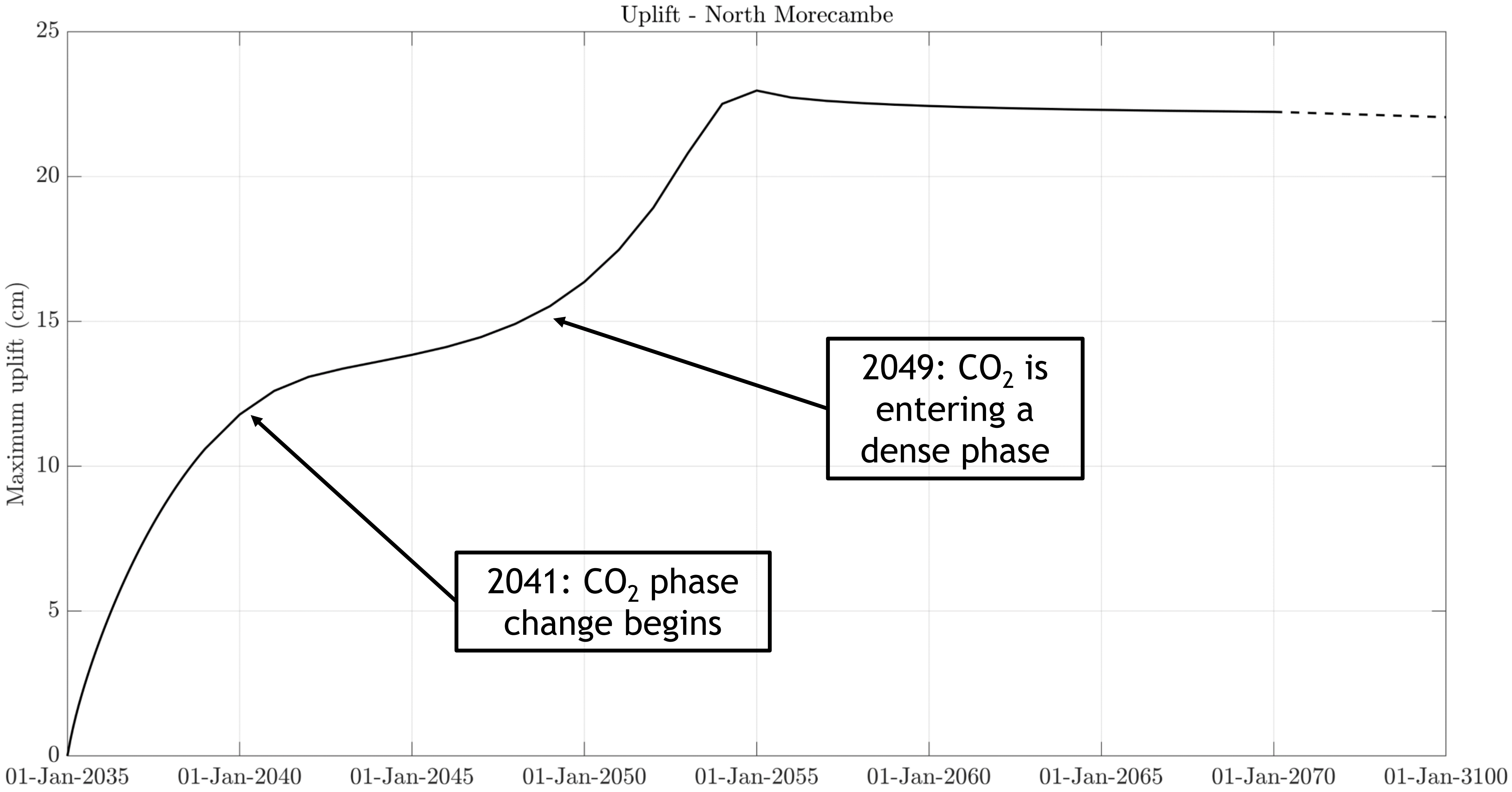




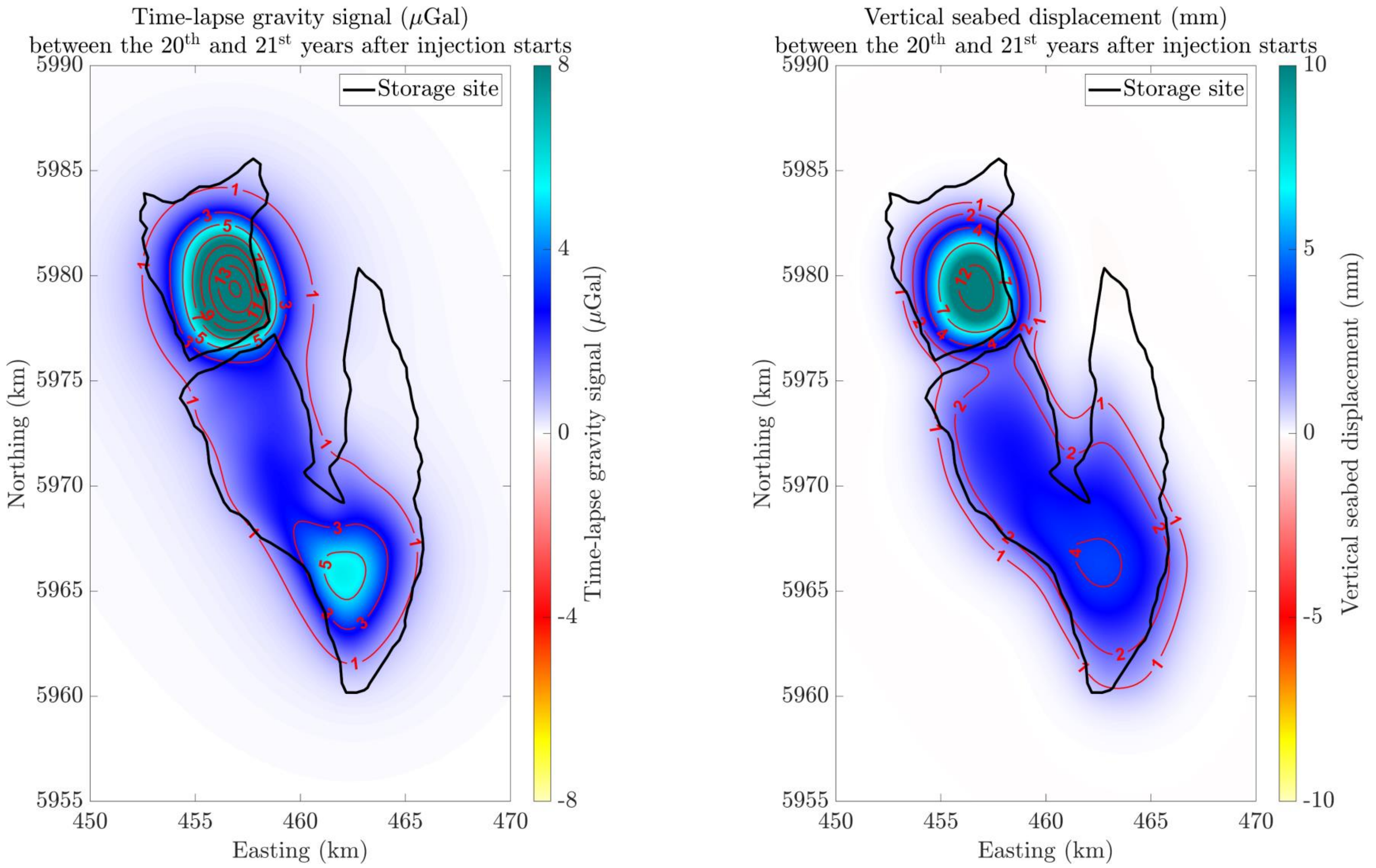
2060 to 2065



Seabed displacement x phase behavior of CO_2

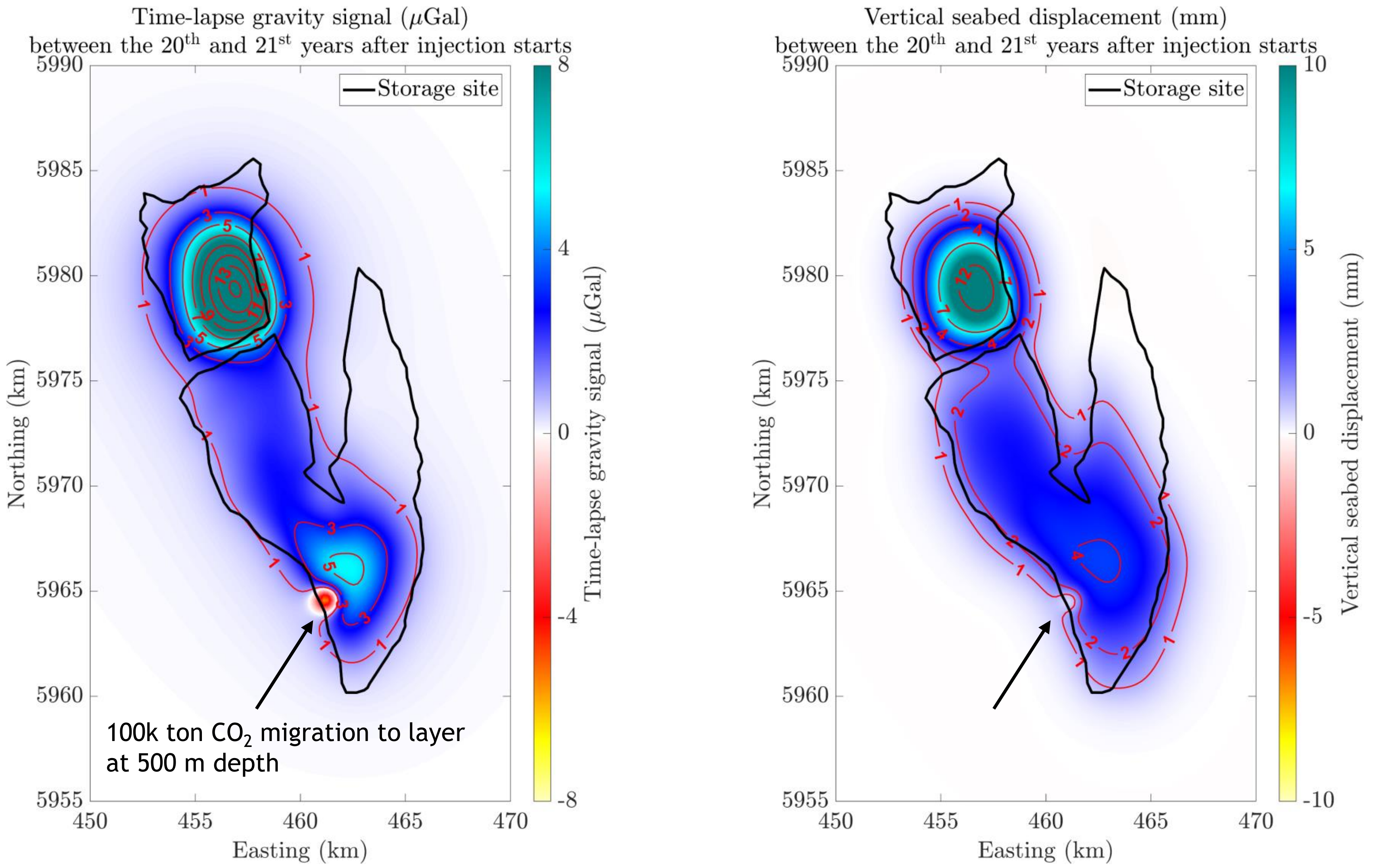


Artificially engineered CO_2 migration to a shallow layer



Baseline scenario

Artificially engineered CO_2 migration to a shallow layer

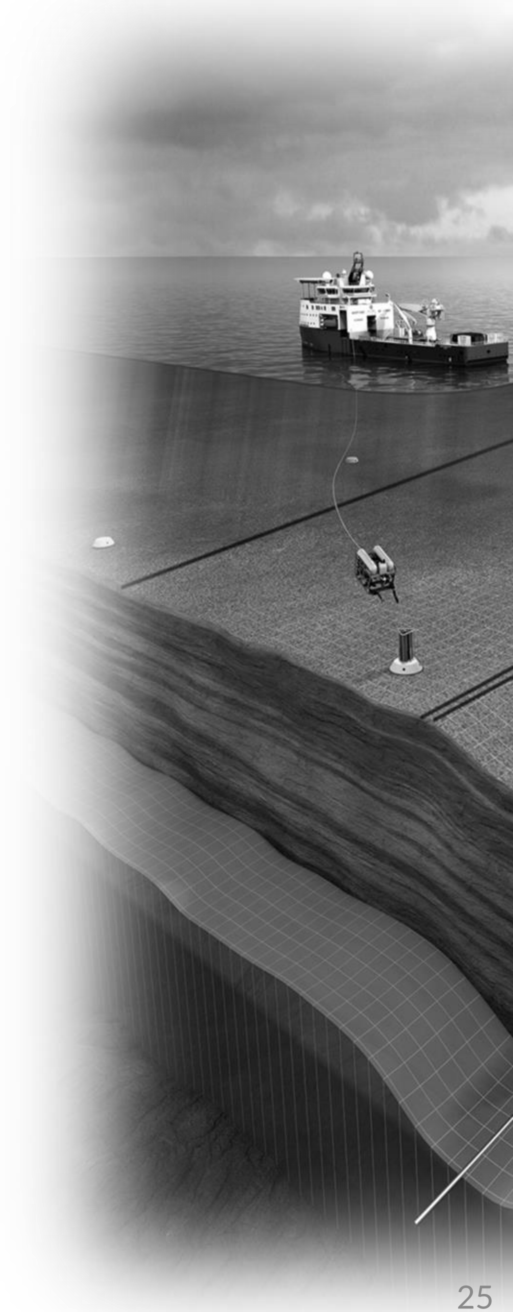


Artifical scenario

Summary

- The feasibility of time-lapse gravity and seabed deformation for MMV at the Morecambe CCS site was investigated
- The reservoir behaviour has been represented by dynamic flow models provided by Spirit Energy
- Forward modeling indicates well-detectable time-lapse gravity and seabed uplift signals in under one-year intervals during the injection phase
- Alternative Scenareos evaluated so far have demonstrated the potential for pathway/secondary containment monitoring:
- The findings suggest that:
  - Time-lapse gravity is a suitable method to map the CO2 saturation front within the storage site
  - Seabed uplift signals can inform on the pressure evolution during injection and CO2 behavior
  - gWatch is a justifiable technology for plume monitoring using measurements of 4D gravity and seabed deformation
- Way forward:
  - Evaluate survey design and define spatial and temporal sampling requirements

Outlook and conclusions



Outlook

Autonomous surveys with unmanned surface vessel operating eROVs for data acquisition on the seabed and in the water column

Operational in 2025

- Minimize our carbon footprint
- Minimize HSE exposure
- Reduce the cost of subsea survey and inspection services

Conclusions

- 4D gravity and seafloor deformation monitoring used for decades in gas fields in Norway
- For CO_2 storage in depleted gas reservoirs, timely measurements is shown to contribute to ensuring conformance, containment, and contingency monitoring
- Can be a key element of future monitoring strategies due to
  - Increased cost sensitivity
  - Colocation challenges (e.g., wind farms)
  - Environmental regulations

Thanks