Seafloor uplift and gravity monitoring of CO_2 storage

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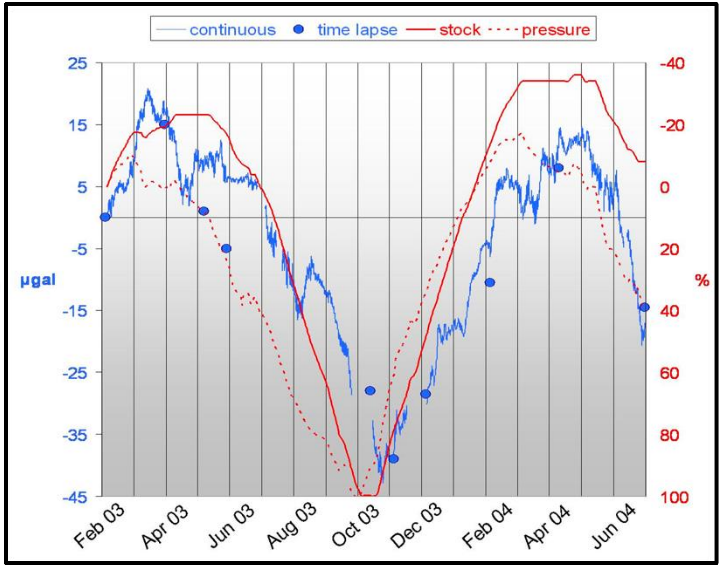
MMV technology showcase
Aberdeen 8th June 2026
North Sea Transition Authority

QUAD GEOMETRICS

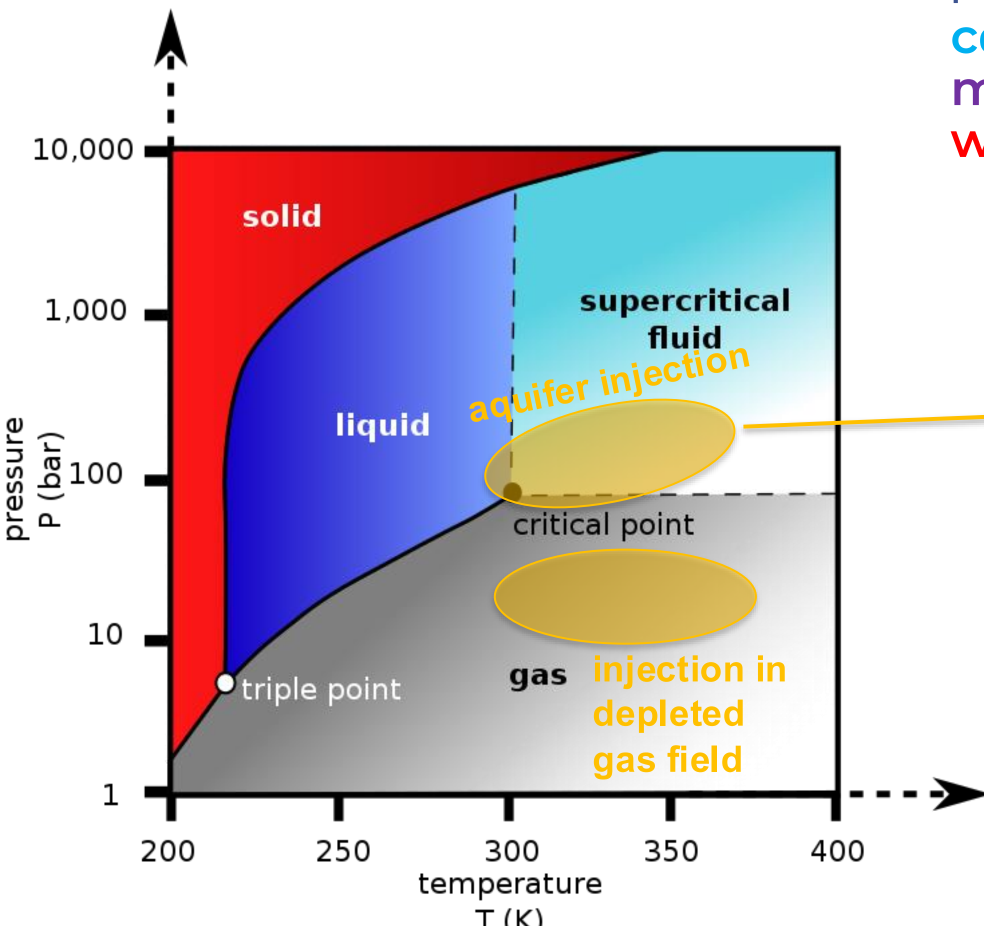
Gravity monitoring applications

- **Geothermal**
  - a.o. New Zealand, Japan, Philippines and Indonesia since the 1960's
- **Volcanoes**
  - >10 countries since the early 2000's
  - A correct forecast of an eruption has been made
- **Groundwater**
  - a.o. southwestern USA
- **Hydrocarbon production**
  - Production from reservoirs with gas, Norway since ~2000
- **Gas storage**
  - Izaute, France 2003-2004
- **CO_2 storage**
  - Sleipner, North Sea 2002-
- ***Technologies are mature***
- ***Methods are still improving***



Bate: 4D reservoir volumetrics: a case study over the Izaute gas storage facility. First Break 2005.

Gravity monitoring of CO_2 storage

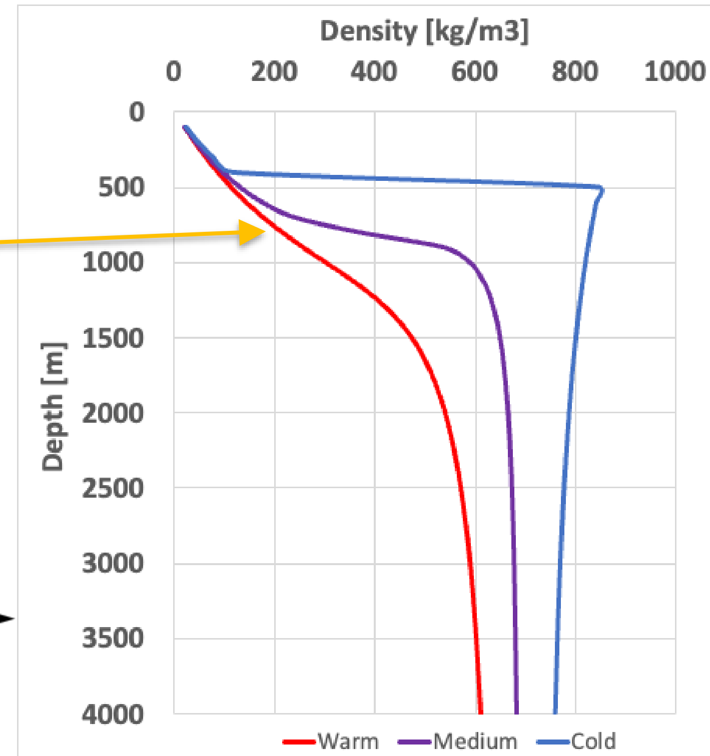


Density of CO_2 vs. depth for hydrostatic pressure and three geothermal gradients:

cold: 0 °C + 25 K/km

medium: 15 °C + 27.5 K/km

warm: 30 °C + 30 K/km



Gravity monitoring of CO_2 storage

CO_2 injected in aquifer:

- displaces water

$$\Delta g = G\frac{\Delta m}{r^2} = G\frac{\Delta m_{CO2}}{r^2}\underbrace{\left(1-\frac{\rho_W}{\rho_{CO2}}\right)}_{CO_2\ factor}$$

- increases water pressure and density

$$\Delta g = G\frac{\Delta m}{r^2} = G\frac{\Delta\rho_W\cdot h}{r^2} = G\frac{\Delta p\cdot c_W\cdot\rho_W\cdot h}{r^2}$$

- pore expansion

$$\Delta g = G\frac{\Delta m}{r^2} = G\frac{\Delta\varphi\cdot\rho_W\cdot h}{r^2} = G\frac{\varphi\cdot\Delta p\cdot c_r\cdot h}{r^2}$$

$$\Delta z = \gamma\frac{\Delta h}{r^2} = \gamma\frac{\Delta p\cdot c_r\cdot h}{r^2}$$

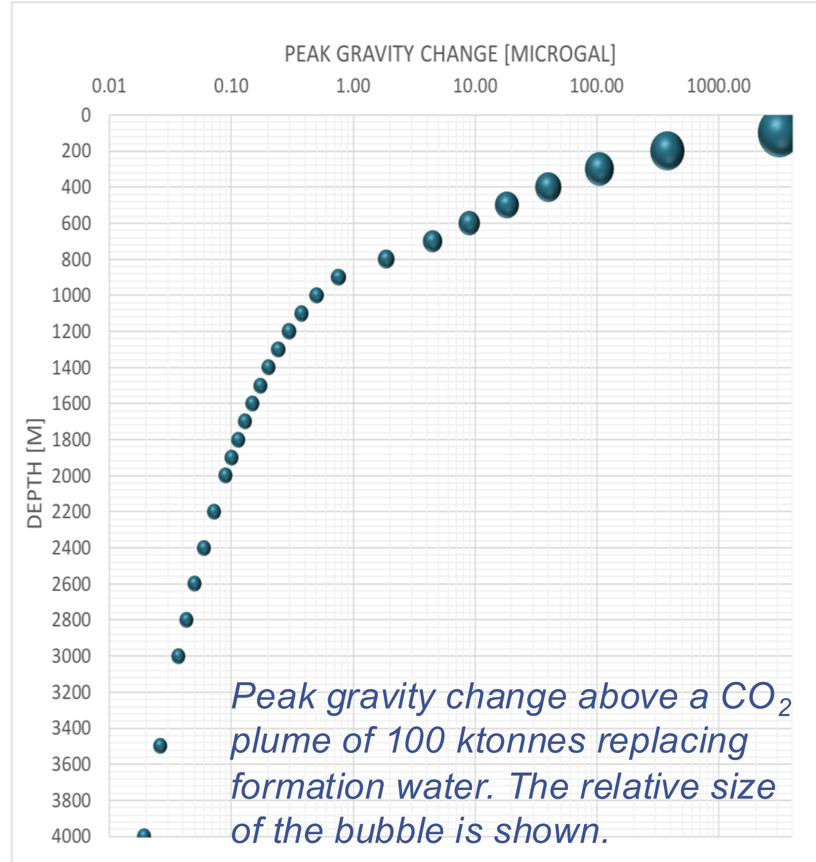
CO_2 injected in depleted gas field:

- Increases mass = injected mass of CO_2

$$\Delta g = G\frac{\Delta m}{r^2} = G\frac{m_{CO2}}{r^2}$$

- pore expansion

$$\Delta z = \gamma\frac{\Delta h}{r^2} = \gamma\frac{\Delta p\cdot c_r\cdot h}{r^2}$$

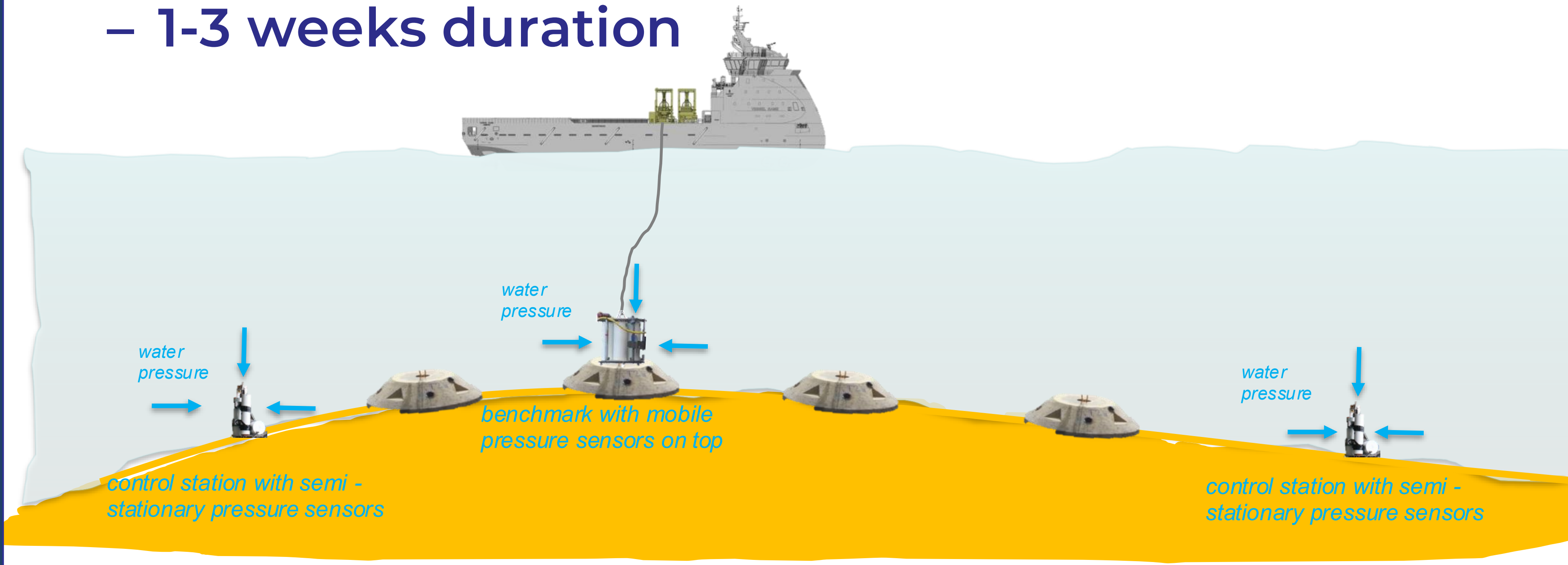


Peak gravity change above a CO_2 plume of 100 ktonnes replacing formation water. The relative size of the bubble is shown.

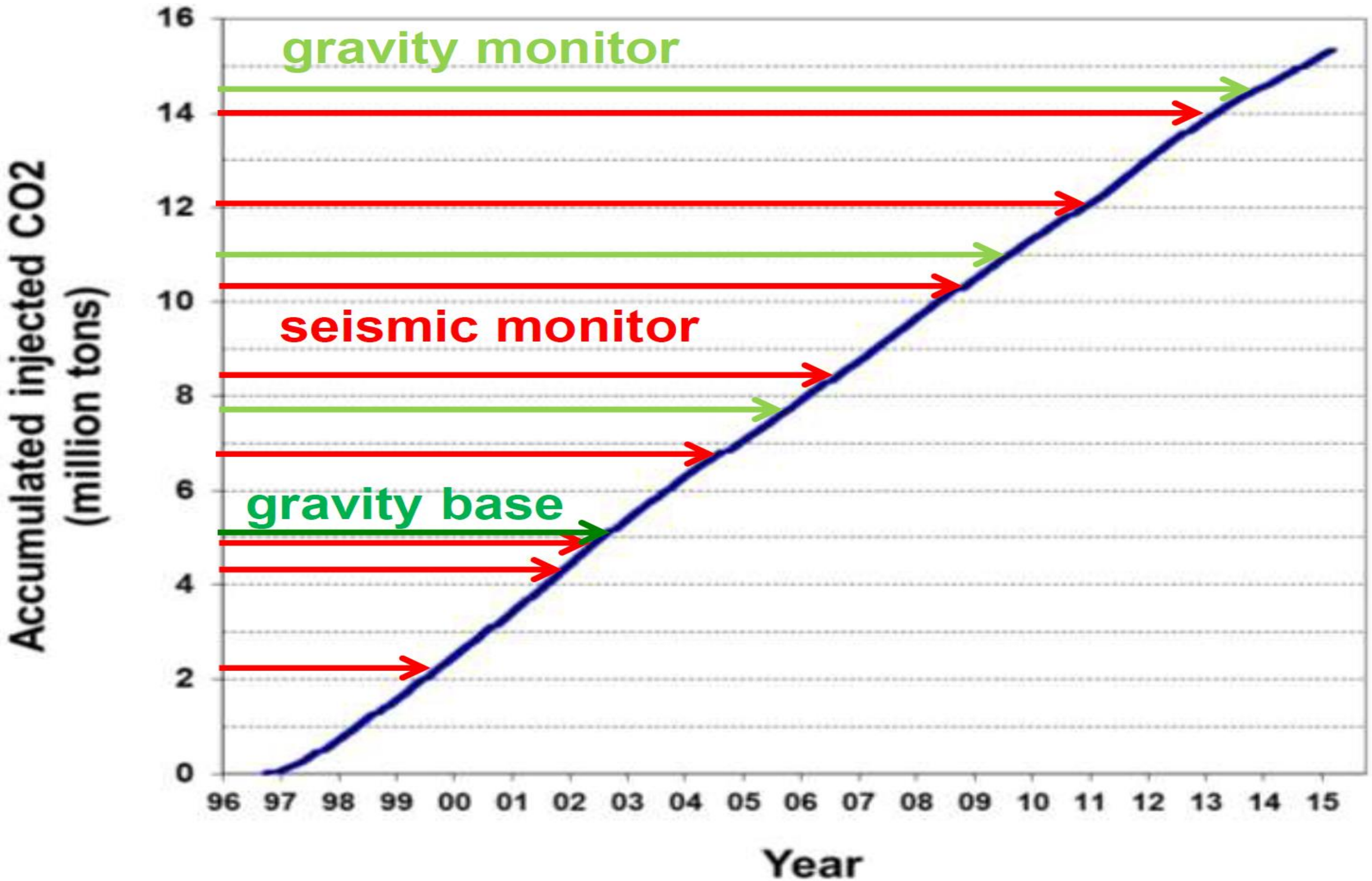
Eiken: Gravity – surface and borehole. In: Geophysics and Geosequestration 2019.

Seafloor surveys for gravity and heave

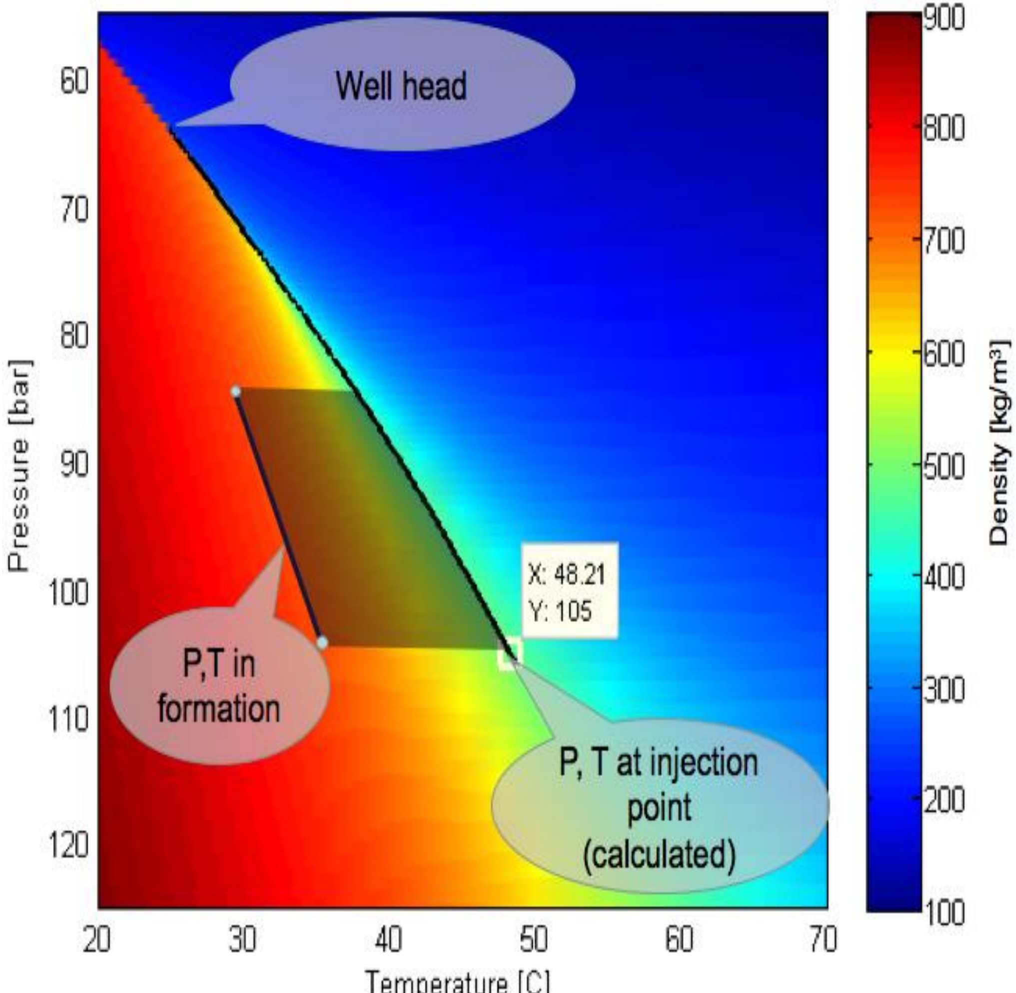
- Permanent seafloor benchmarks
- Campaign surveys
  - 1-3 weeks duration



Sleipner geophysical monitor data

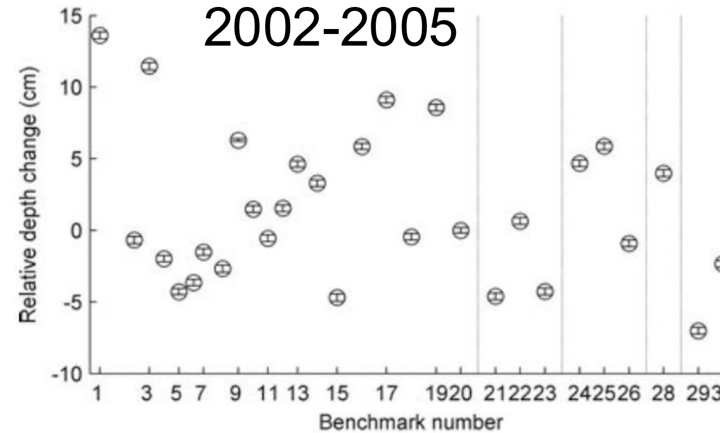


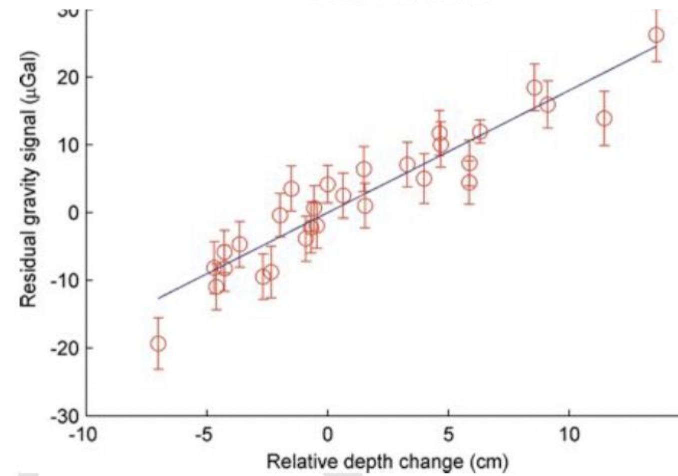
Density of CO_2 – at Sleipner



Eiken: Twenty Years of Monitoring CO_2 Injection at Sleipner. In: Geophysics and Geosequestration 2019.

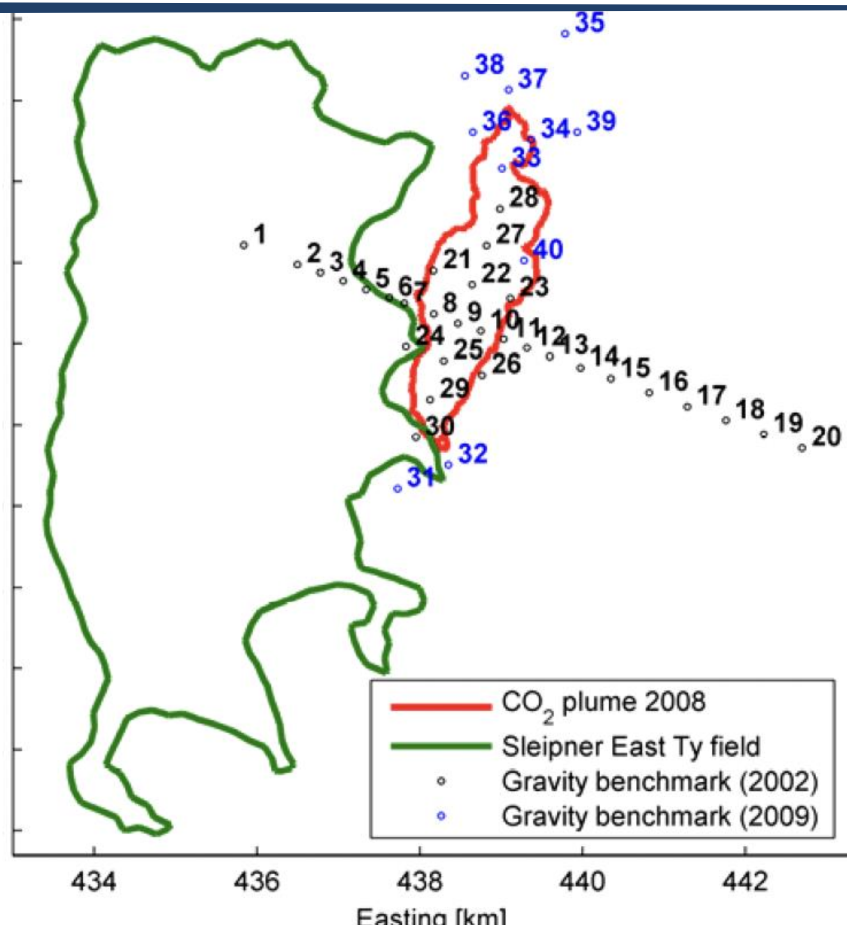
Sleipner seafloor gravity benchmarks

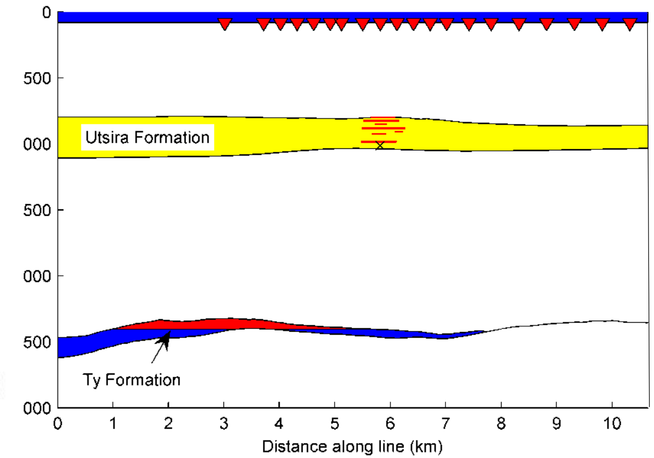




Alnes et al.: Monitoring gas production and CO_2 injection at the Sleipner field using time-lapse gravimetry. Geophysics 2008.

Sleipner gravity stations

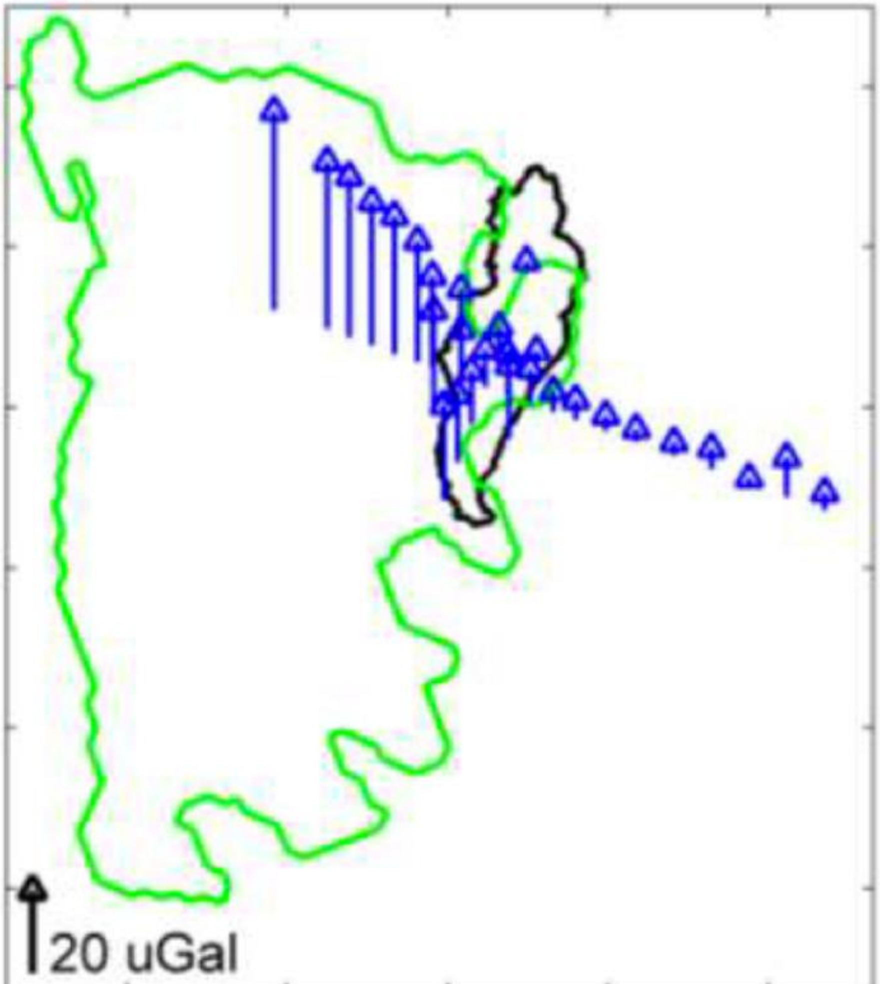




Alnes et al.: Monitoring gas production and CO_2 injection at the Sleipner field using time-lapse gravimetry. Geophysics 2008.

Alnes et al.: Results from Sleipner gravity monitoring: updated density and temperature distribution of the CO_2 plume. Energy Procedia 2011.

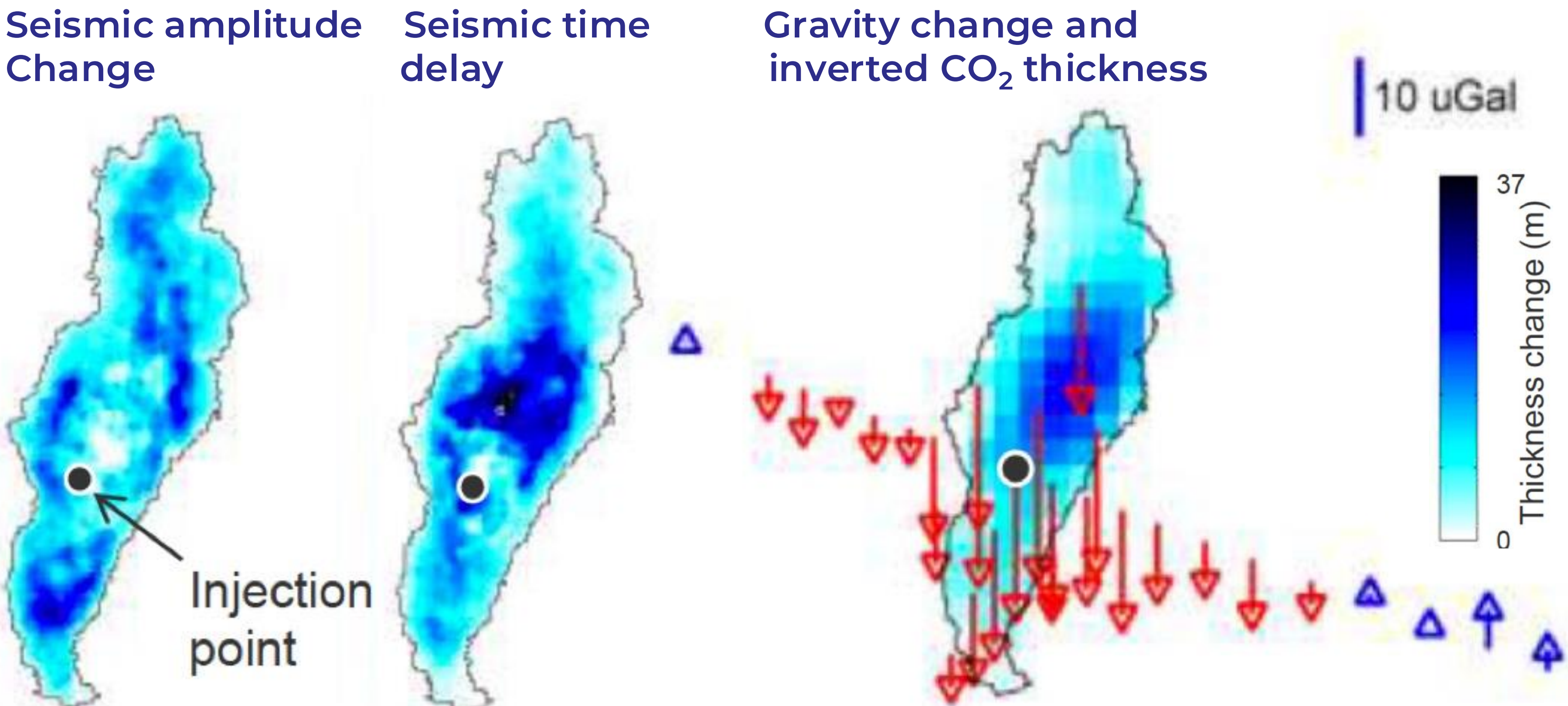
Gravity change caused by deep gas reservoir



Alnes: Gravity surveys over time at Sleipner.
IEAGHG Monitoring Network Meeting 2015.

Gravity changes caused by injected CO_2

2013 – 2002



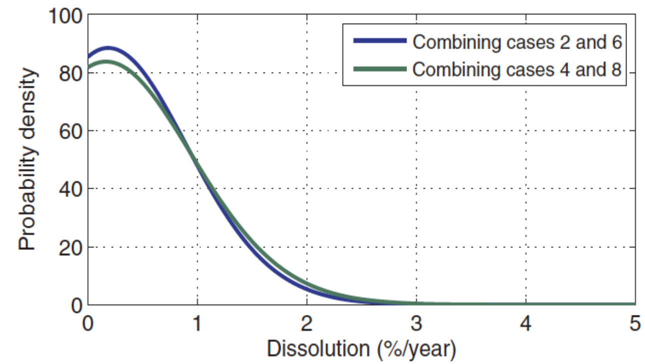
Alnes: Gravity surveys over time at Sleipner. IEAGHG Monitoring Network Meeting 2015

Is mass missing? Has CO_2 been dissolved?

Interpretation steps:

1. Separation of CO_2 and gas signals
2. CO_2 distribution from 4D seismic
3. CO_2 density from pressure and temperature
4. Is any CO_2 dissolved in the formation water?

Maximum dissolution rate:
1.8% per year



Alnes et al.: Results from Sleipner gravity monitoring: updated density and temperature distribution of the CO_2 plume. Energy Procedia 2011

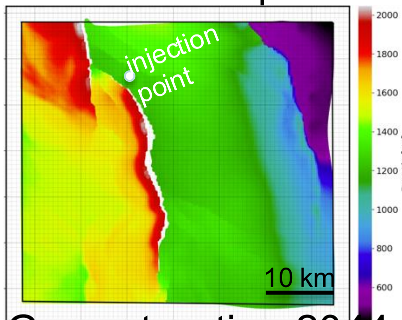
Hauge and Kolbjørnsen: Bayesian inversion of gravimetric data and assessment of CO_2 dissolution in the Utsira Formation. Interpretation 2015

Sleipner CO_2 monitoring learnings

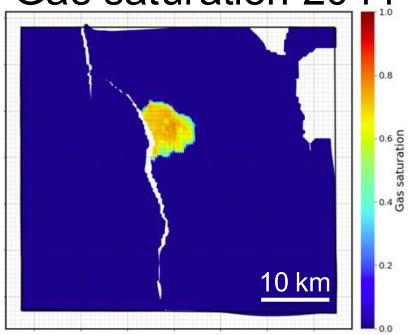
- There are no indications of CO_2 in the overburden
- The CO_2 plume grows and densifies steadily.
- 4D seismic has been a powerful tool
- Gravity provides important additional data.

Smeaheia gravity and uplift modelling

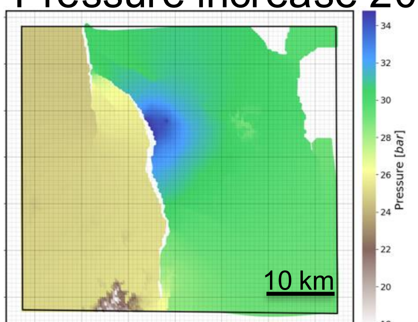
Reservoir depth



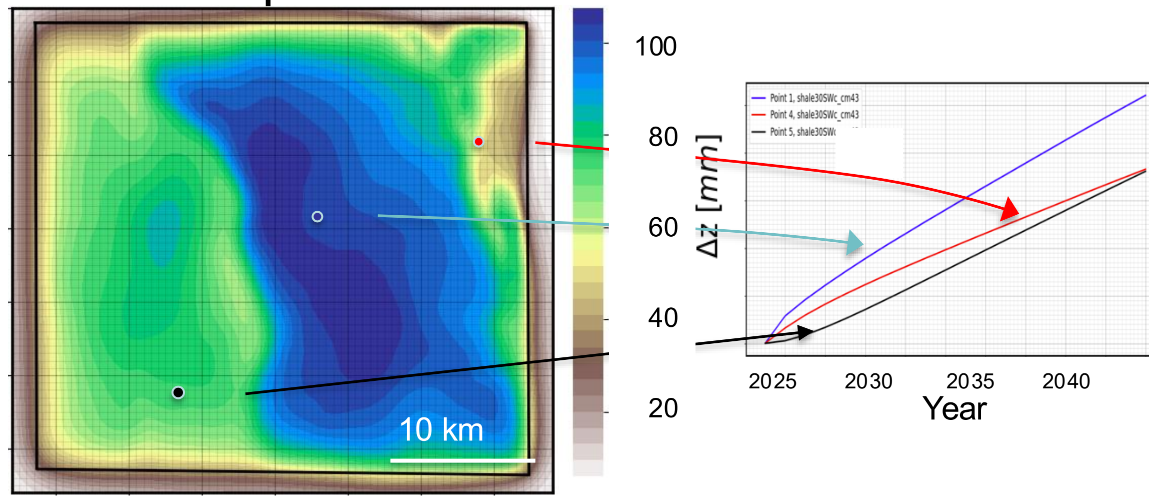
Gas saturation 2044



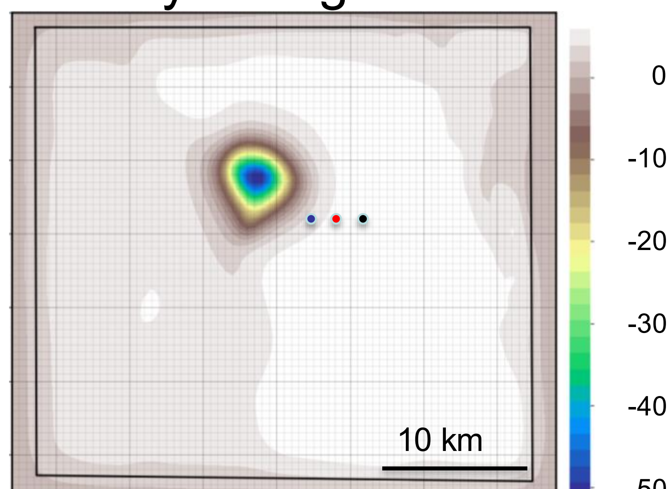
Pressure increase 2025-2044

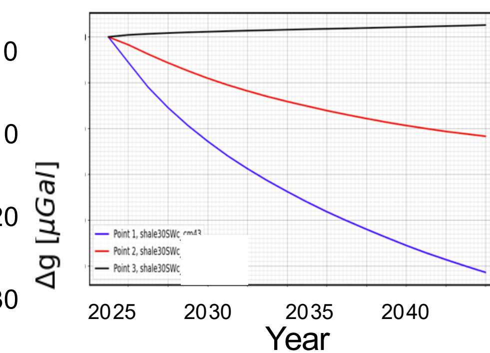


Seafloor uplift 2025-2044



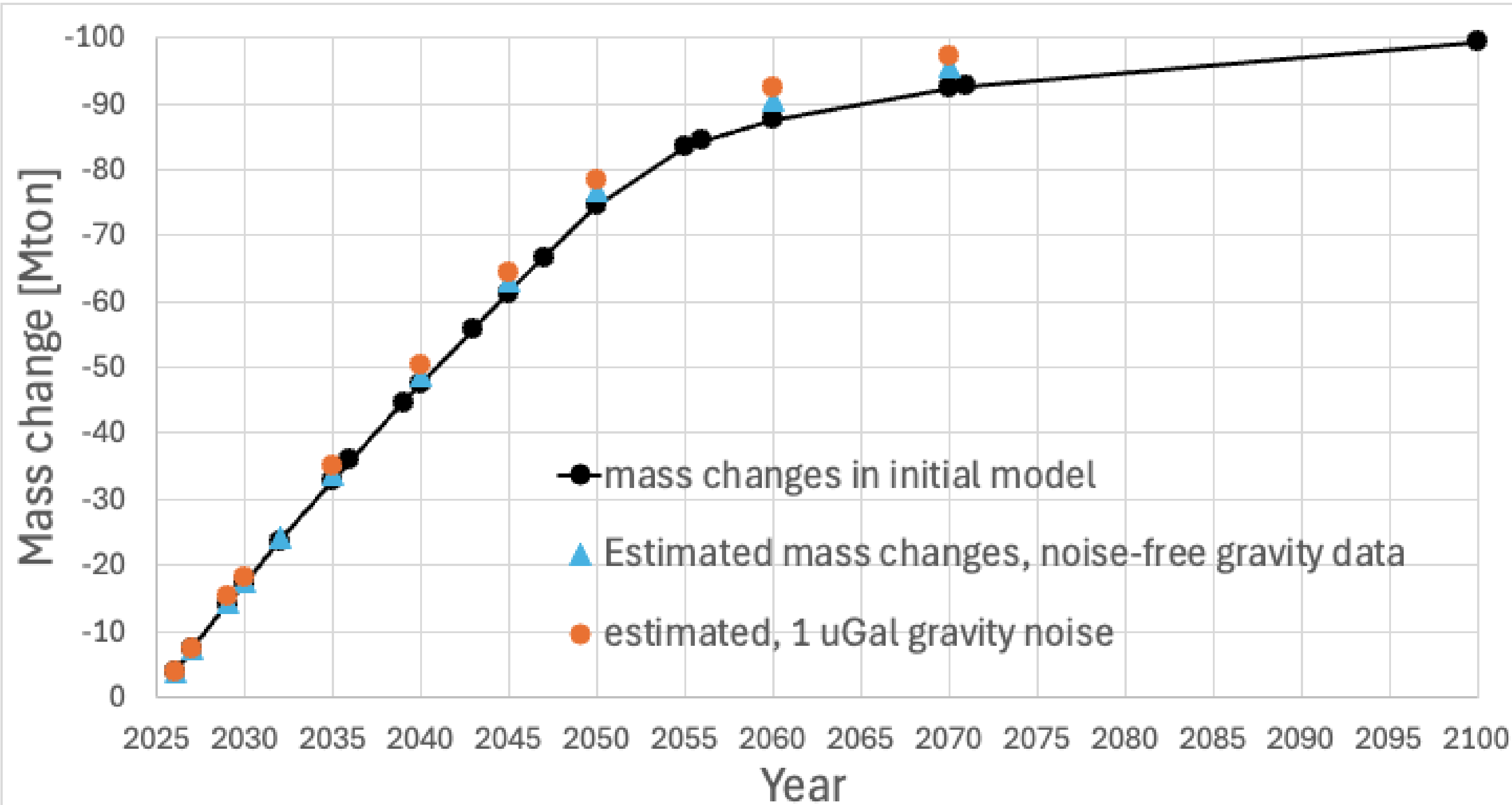
Gravity change 2025-2044





Jordan et al. 2026

Endurance
mass change estimates from gravity



Combining gravity with other data

- Injected mass, including composition
- Downhole pressure and temperature
- Observation well
- 4D seismic
- A flow model which integrates results

Gravity.

It's not just a good idea.

It's the Law.

Value of gravity information

- **Quantitative information on**
  - mass changes
  - derived properties such as:
    - CO_2 temperature
    - rate of dissolution
- **Leakage detection**
- **Surface uplift can detect pressure anomalies away from injection wells**

Conclusions

- Gravity monitoring can give quantitative information on mass changes and derived properties such as CO_2 temperature and rate of dissolution.
- Discrepancies in mass comparison beyond 6% may indicate dissolution into water, or leakage, and warrant further investigation.
- Uplift can inform on pressure propagation in the aquifer.
- Gravity and uplift data can help understand the physics of CO_2 storage better