# Gravity surveys over time at Sleipner

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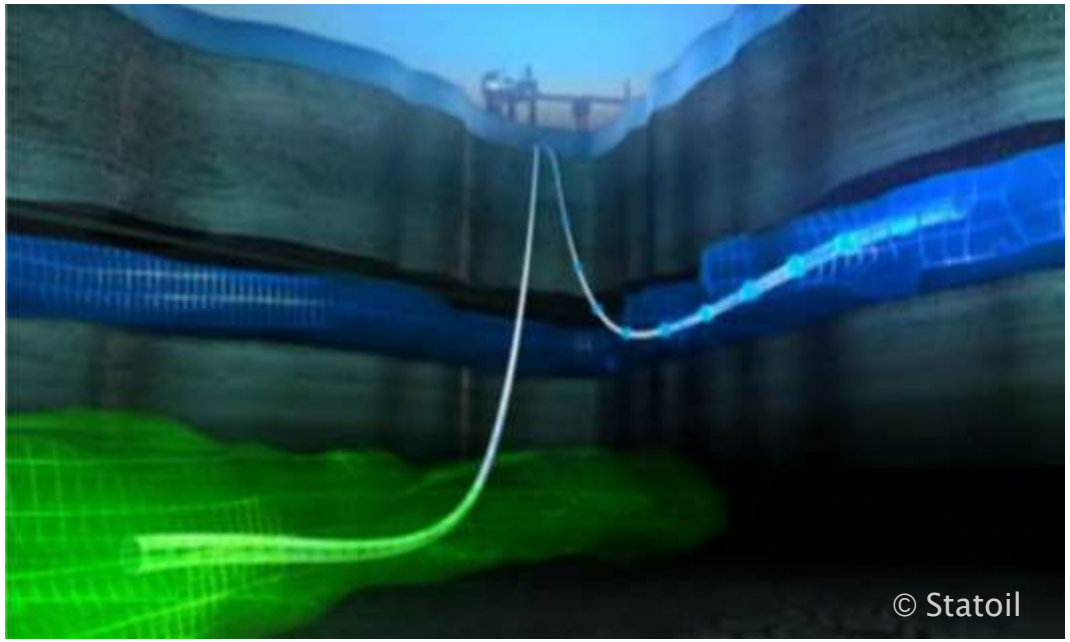
# Outline

- Introduction to Sleipner
- Geophysical monitoring
- Introduction to time-lapse gravity
- Results and interpretation
- Comparison with 4D seismic
- Summary



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# Sleipner $CO_2$ capture and storage

- Sleipner Vest gas contains 9% $CO_2$
- $CO_2$ is captured in amine plant and injected into the shallow Utsira Fm.
- Injection started in 1996, injecting almost 1 mill. ton (MT) $CO_2$ per year
- Sleipner platform is also producing gas from deeper reservoirs




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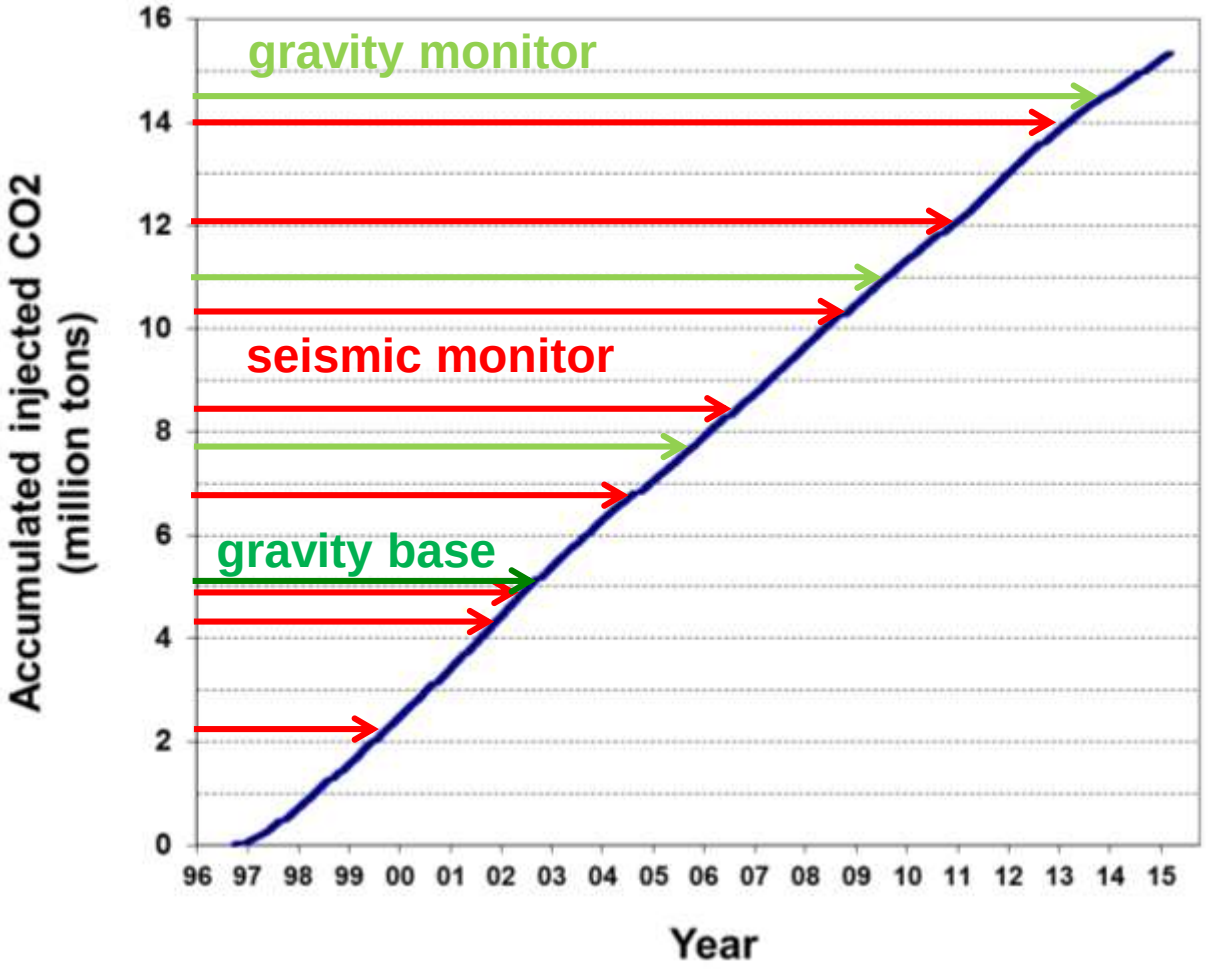
# Geophysical monitoring

- Time-lapse seismic (8 monitor surveys)
  - high resolution
- Time-lapse gravity (3 monitor surveys)
  - quantitative results



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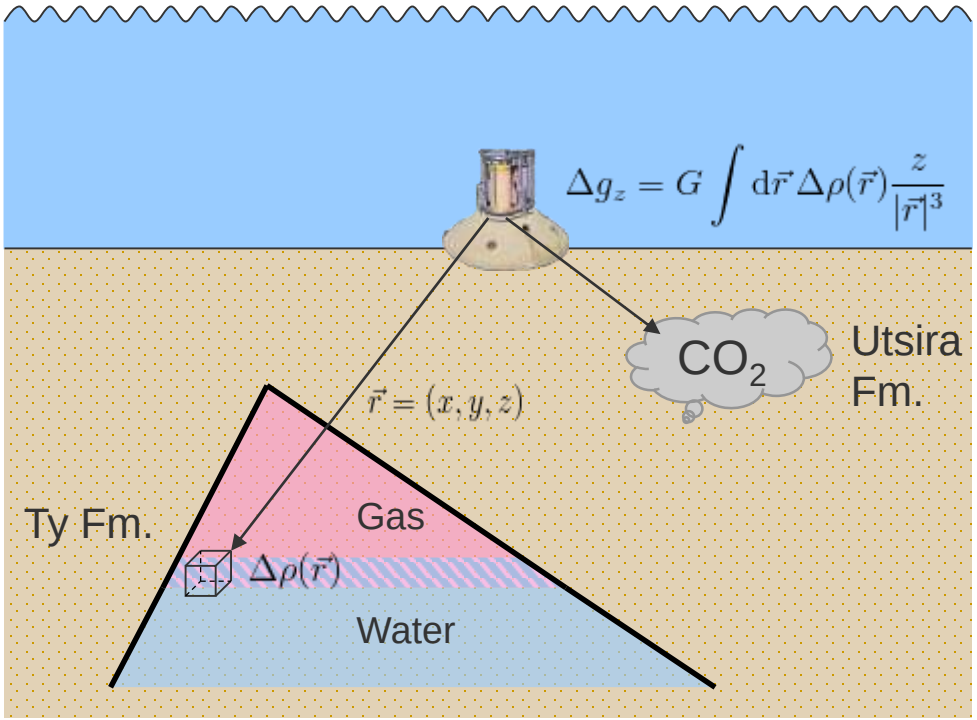
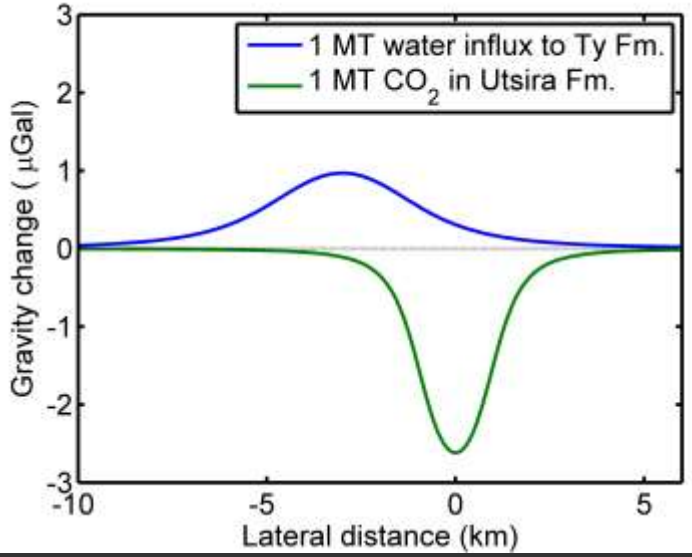
# Theory of gravity

- Seafloor gravity changes if there is subsurface density change, for instance
  - $CO_2$ replaces brine
  - Depletion of gas reservoirs
  - Water influx to gas reservoirs
- Amplitude depends on
  - density contrast
  - burial depth
- Typical values (in μGal = $10^{-8}$ m/s$^2$)
  - 1 MT of $CO_2$ at 800m depth ~ **-2** μGal
  - 1 MT water influx at 2400m depth ~ **+1** μGal
  - standard gravity g ~ 980 000 000 μGal



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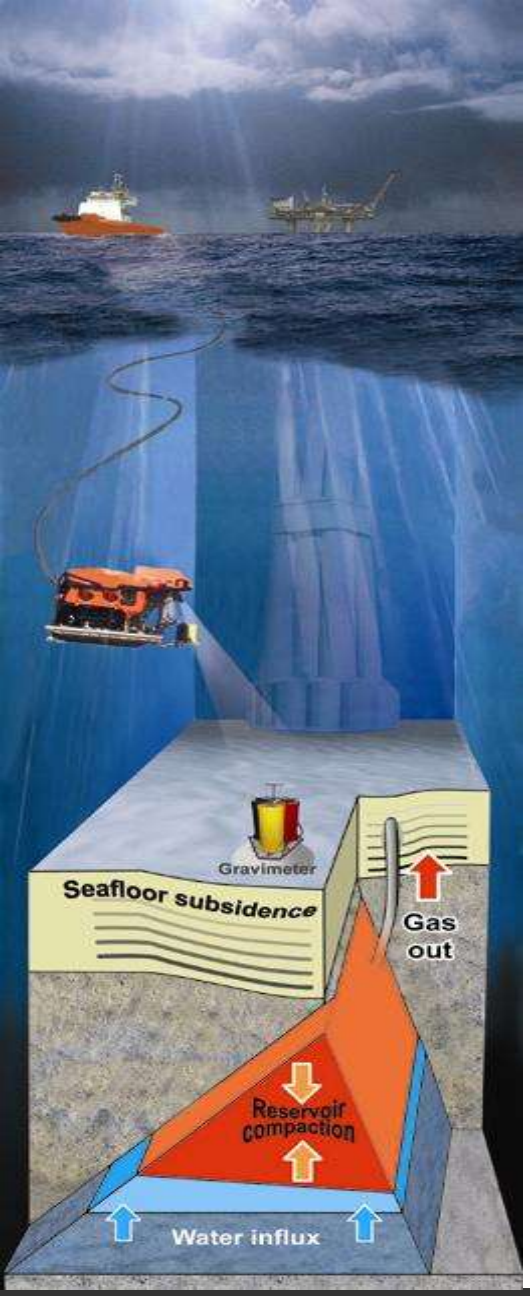


# Methodology

- Permanently deployed concrete benchmarks on the seafloor
- Mobile instrument carried by ROV, measuring 10-20 minutes at each site
- Measure changes in the gravity field at the seafloor using relative gravimeters (2-3 µGal accuracy)
- Measure vertical movement of benchmarks using water pressure (2-3 mm accuracy)
- The method has so far been used successfully for monitoring several gas reservoirs offshore Norway.



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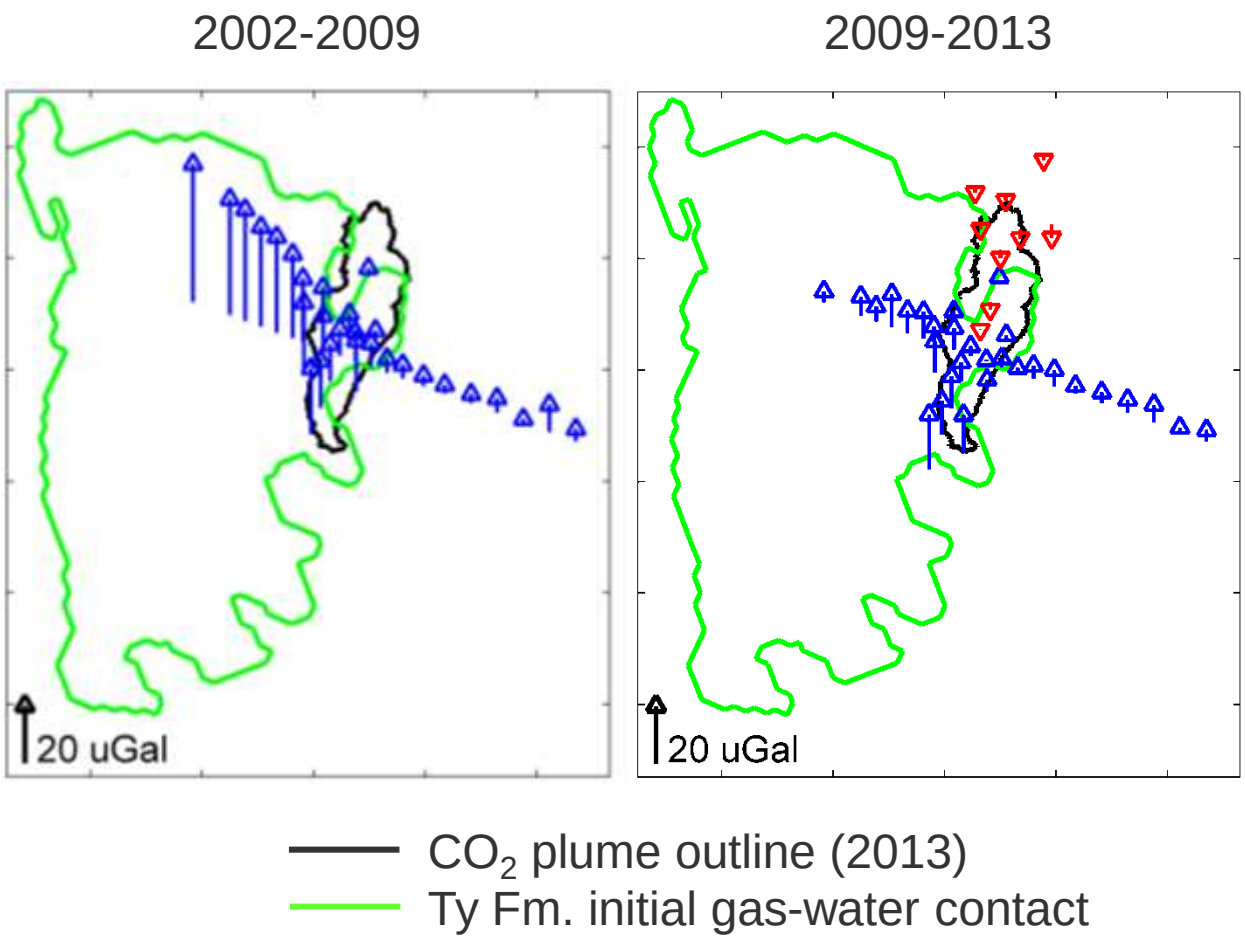
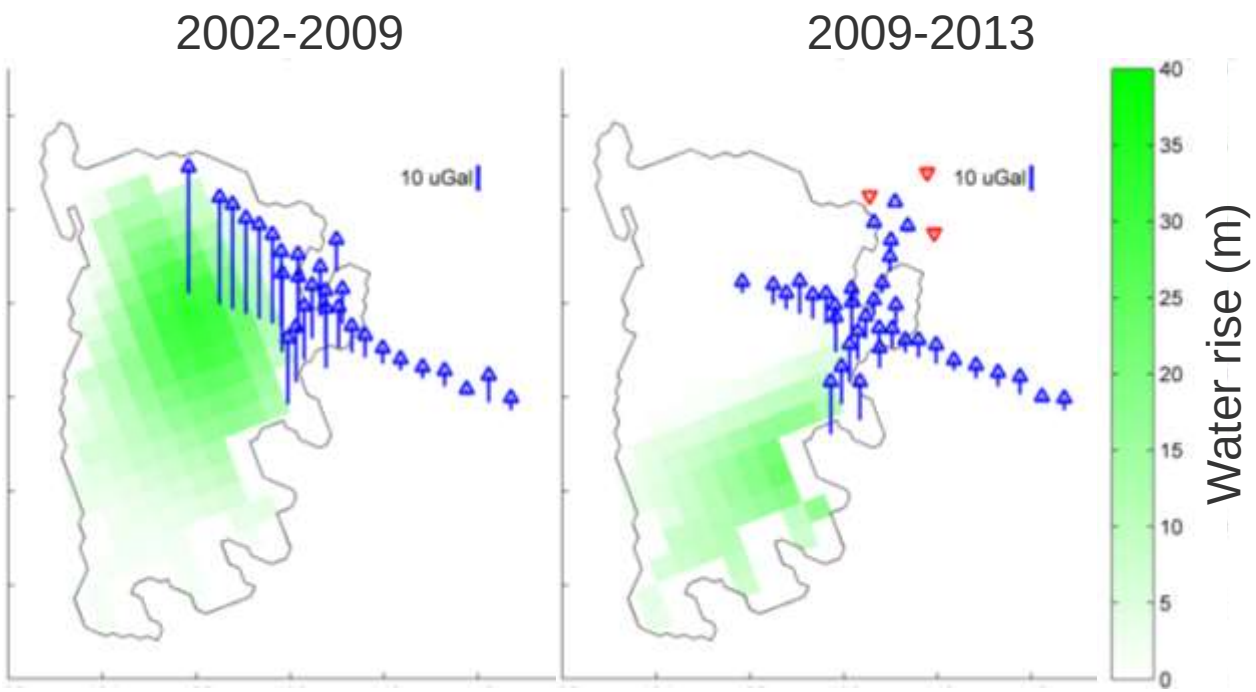
# Measured gravity change

- Arrows show measured gravity change due to
  - CO2 injection to Utsira Fm.
  - Water influx to Ty Fm.
- Water influx to Ty Fm. is dominating the measured signal



# Inversion of Ty signal – constrained by initial gas column

- The arrows show the gravity change after removing the contribution from $CO_2$
- A constrained inversion yields an estimate of the water level rise in Ty Fm.
- The result is in good agreement with well observations



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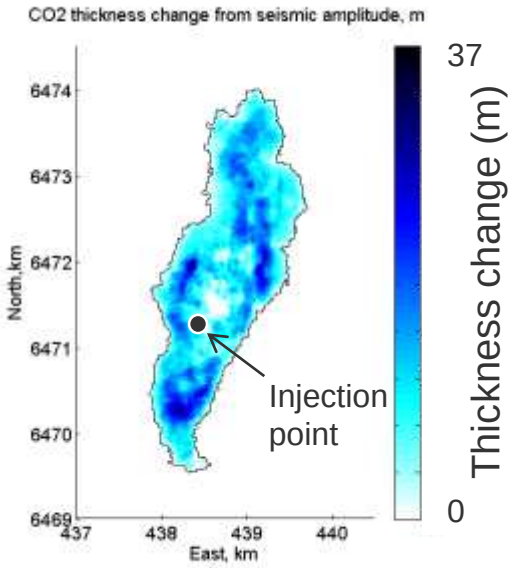
# $CO_2$ thickness change 2002-2013

- How does the $CO_2$ plume develop over time?

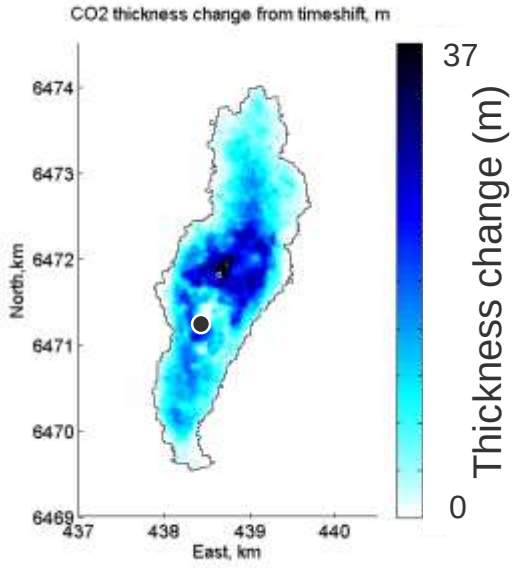
  4D seismic gives two very different pictures!

- After removing the signal from water influx to the Ty Fm., the gravity signal from $CO_2$ is visible
- Inversion of gravity data indicates that the plume is growing mainly in the centre, similar to the 4D timeshift picture.

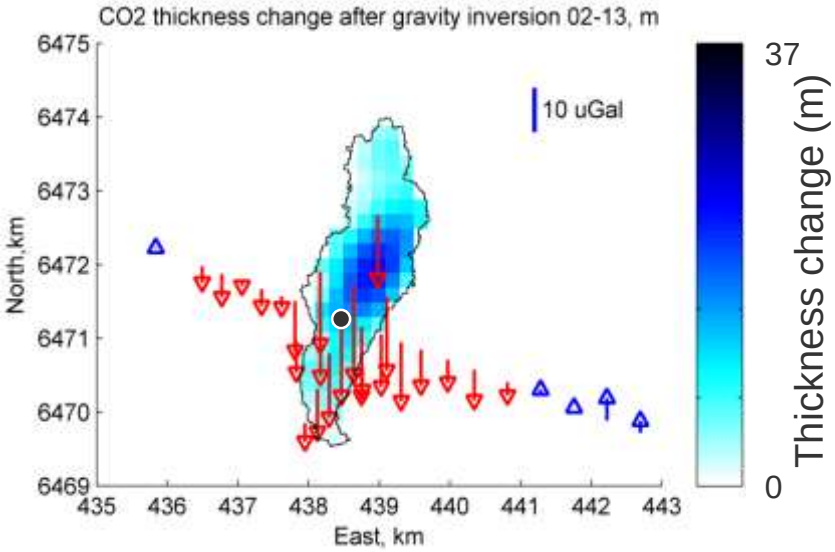
4D seismic amplitudes




4D timeshift




Gravity inversion:



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# Quantitative interpretation

- 9.4 MT $CO_2$ was injected between the gravity surveys in 2002 and 2013
- Inversion of gravity data estimates that 8 ± 2 MT $CO_2$ is stored in the Utsira Fm, if no $CO_2$ is absorbed in brine
- The data also shows that $CO_2$ absorption into brine is happening with a rate of less than 2.7% per year.
- The accuracy is limited by
  - uncertainty in the subtracted signal from water influx to the Ty Fm.
  - lack of gravity stations over the northern part of the plume in the base survey

# Summary

- Time-lapse gravity is useful for quantitative monitoring of subsurface $CO_2$ storage (and even more useful for monitoring water influx to gas fields)
- Current instrument accuracy corresponds to a sensitivity of ± 1 MT $CO_2$ at 800m depth
- Gravity surveys over Sleipner prove that the $CO_2$ is stored in the Utsira Fm. and puts an upper limit on $CO_2$ absorption into brine of 2.7% per year


The views expressed in this presentation reflect Statoil's understanding

Acknowledgement: We would like to thank the Sleipner license partners (ExxonMobil and Total E&P Norge AS) for permission to share this work.



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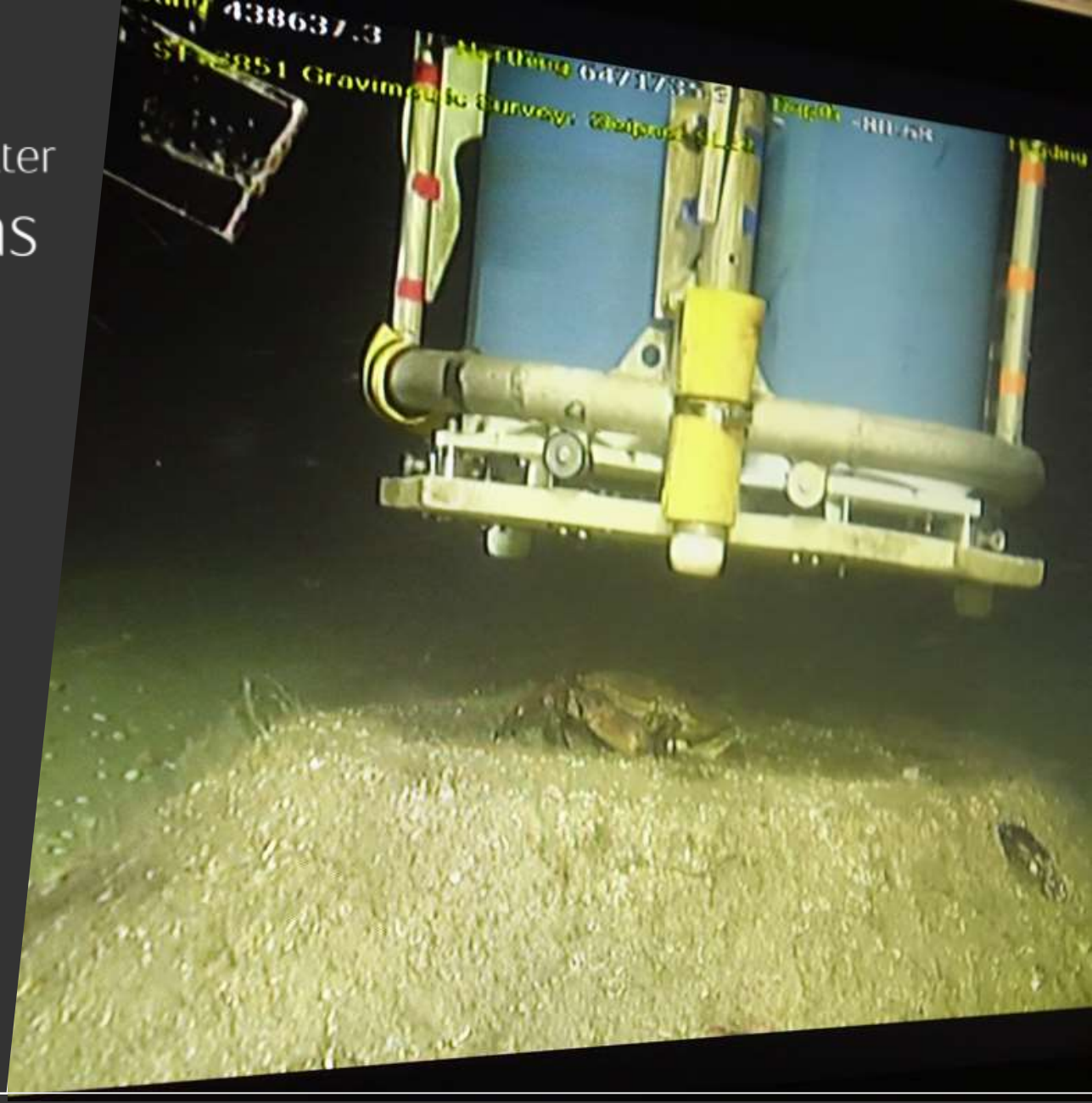
There's never been a better time for good ideas



Gravity surveys over time at Sleipner

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