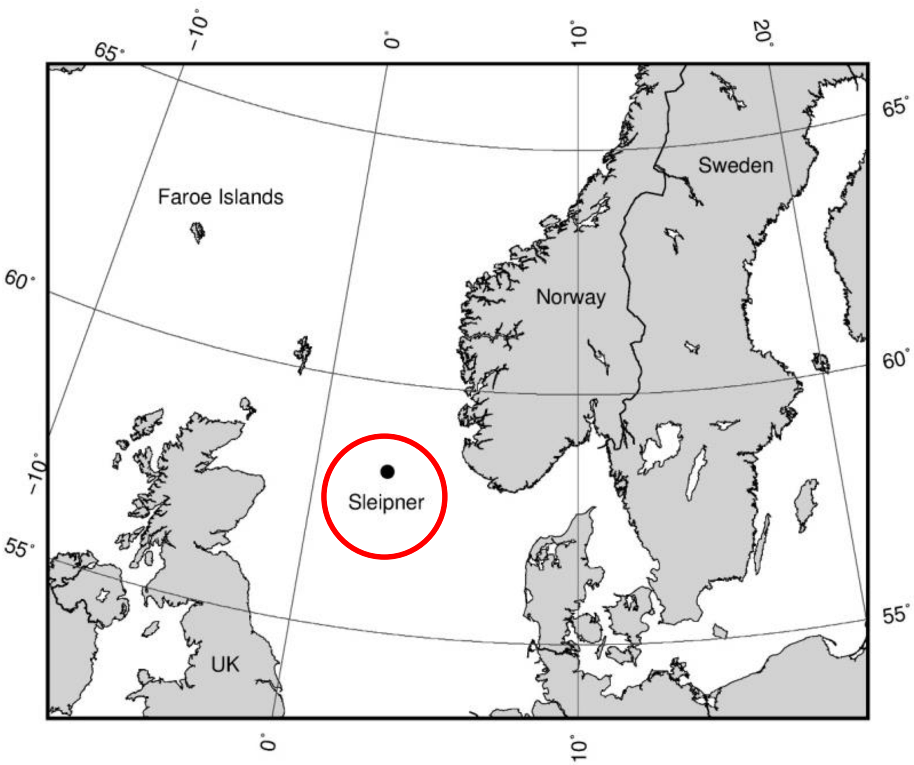
4D seismic - monitoring and modelling

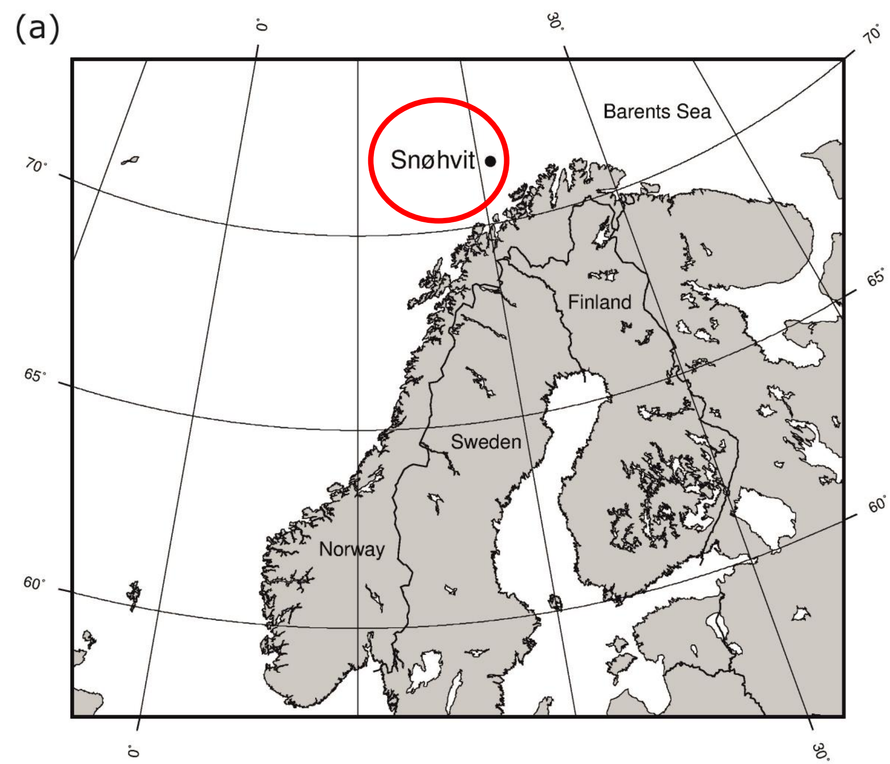
Jim White

(**Gareth Williams, Andy Chadwick,** Laurence Cowton, Anne-Kari Furre, Anders Kiaer)

BGS monitoring experience

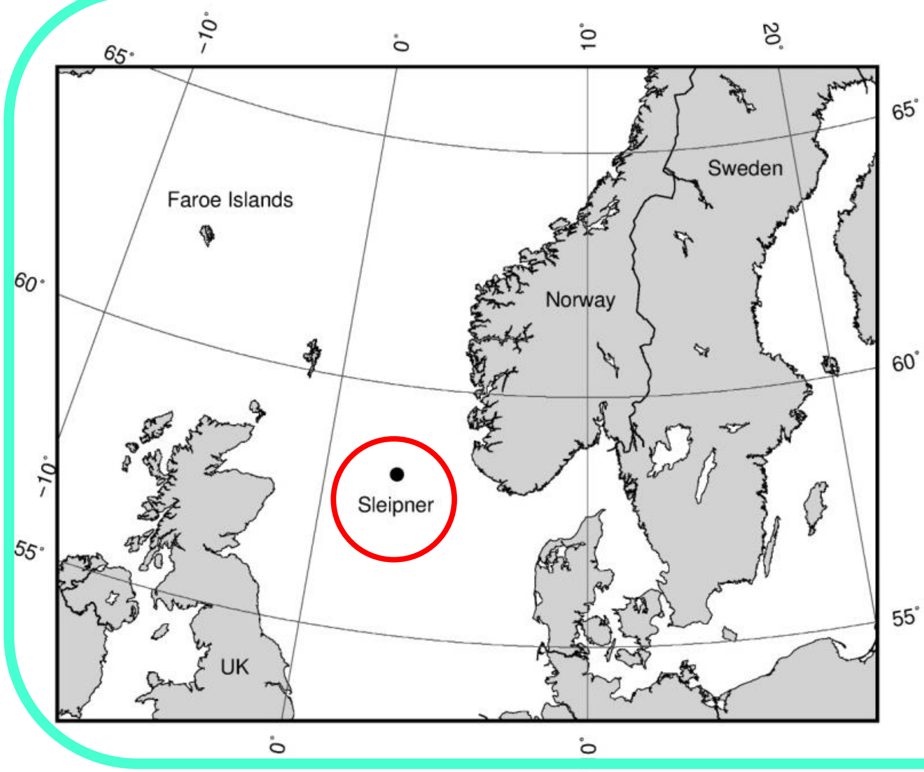


Sleipner

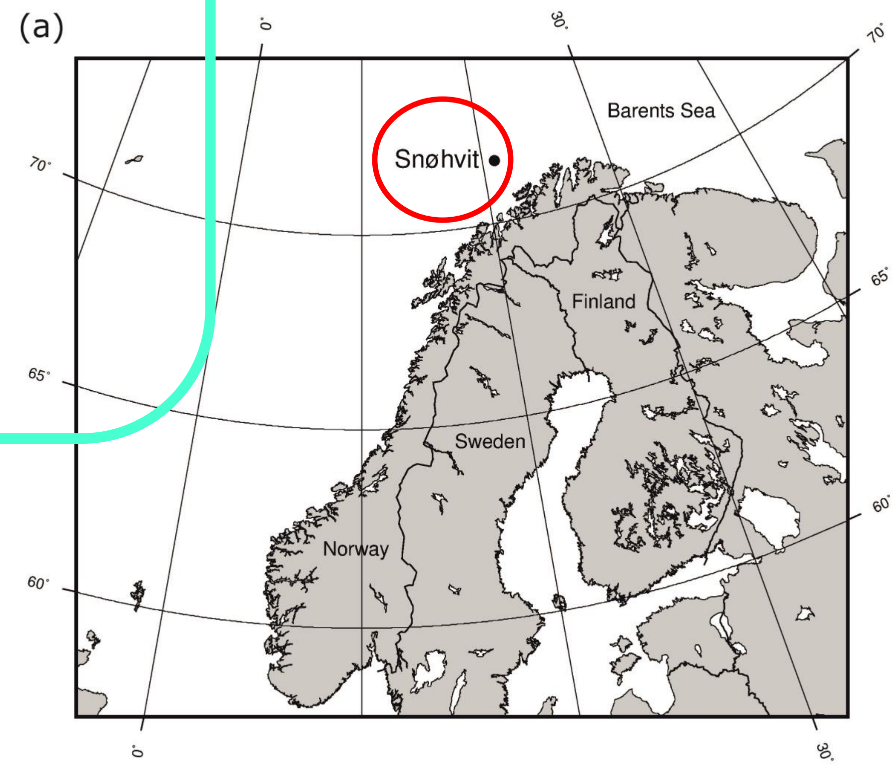


Snøhvit

BGS monitoring experience



Sleipner



Snøhvit

CO_2 Injection at Sleipner

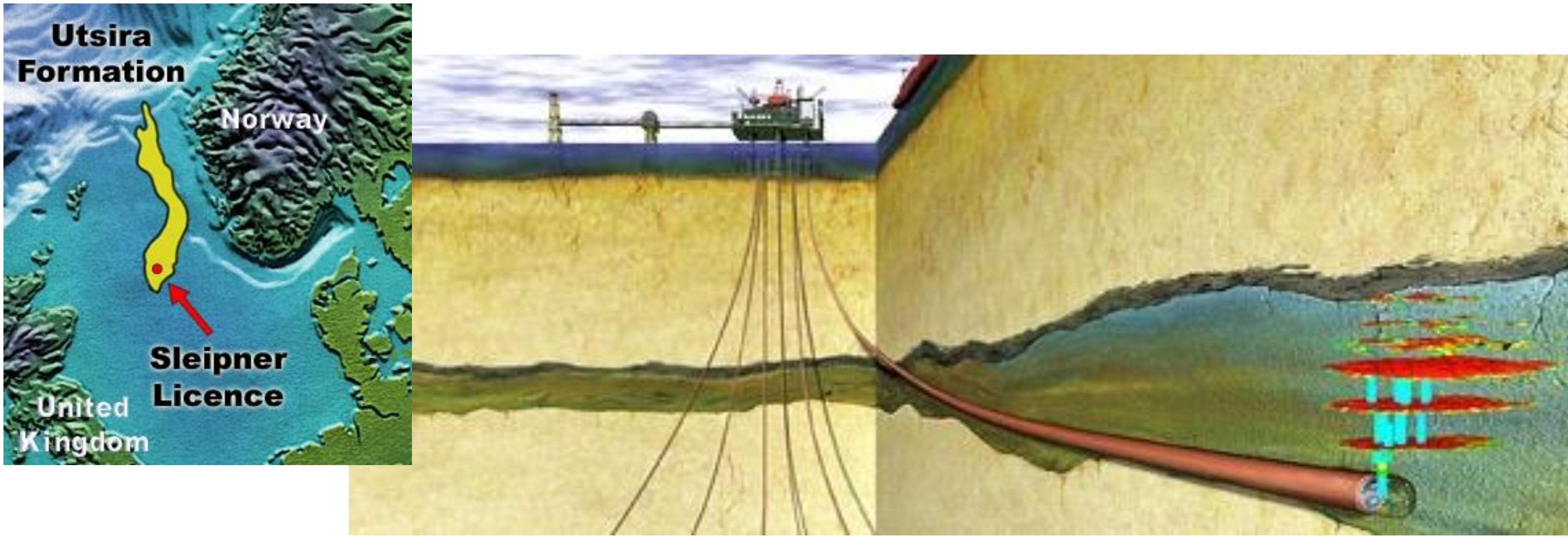
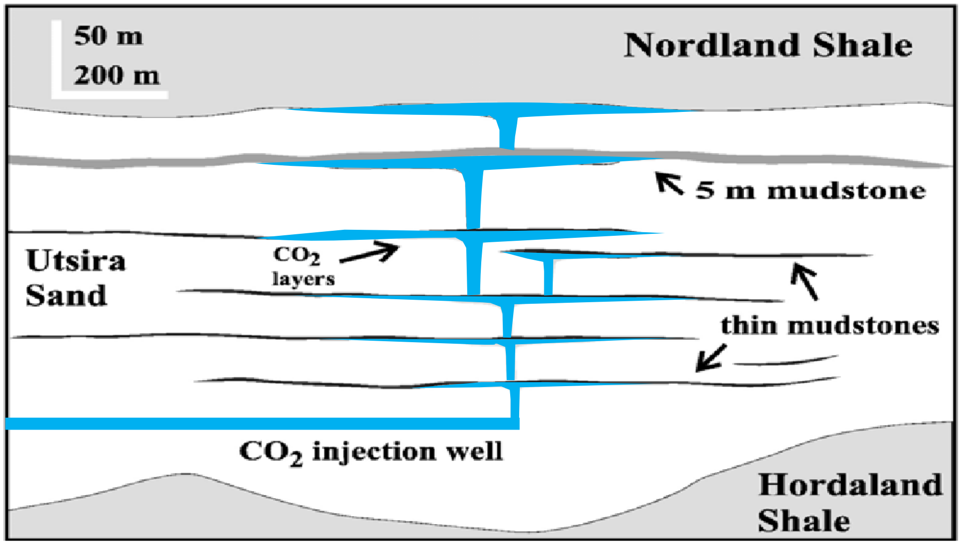


Image © Statoil

- CO_2 injection commenced in 1996.
- ~1 Mt of CO_2 injected per annum.
- Time lapse 3D seismic (1994, 99, 2001, 04, 06, 08, 10)
- 2D high resolution seismic (2006)

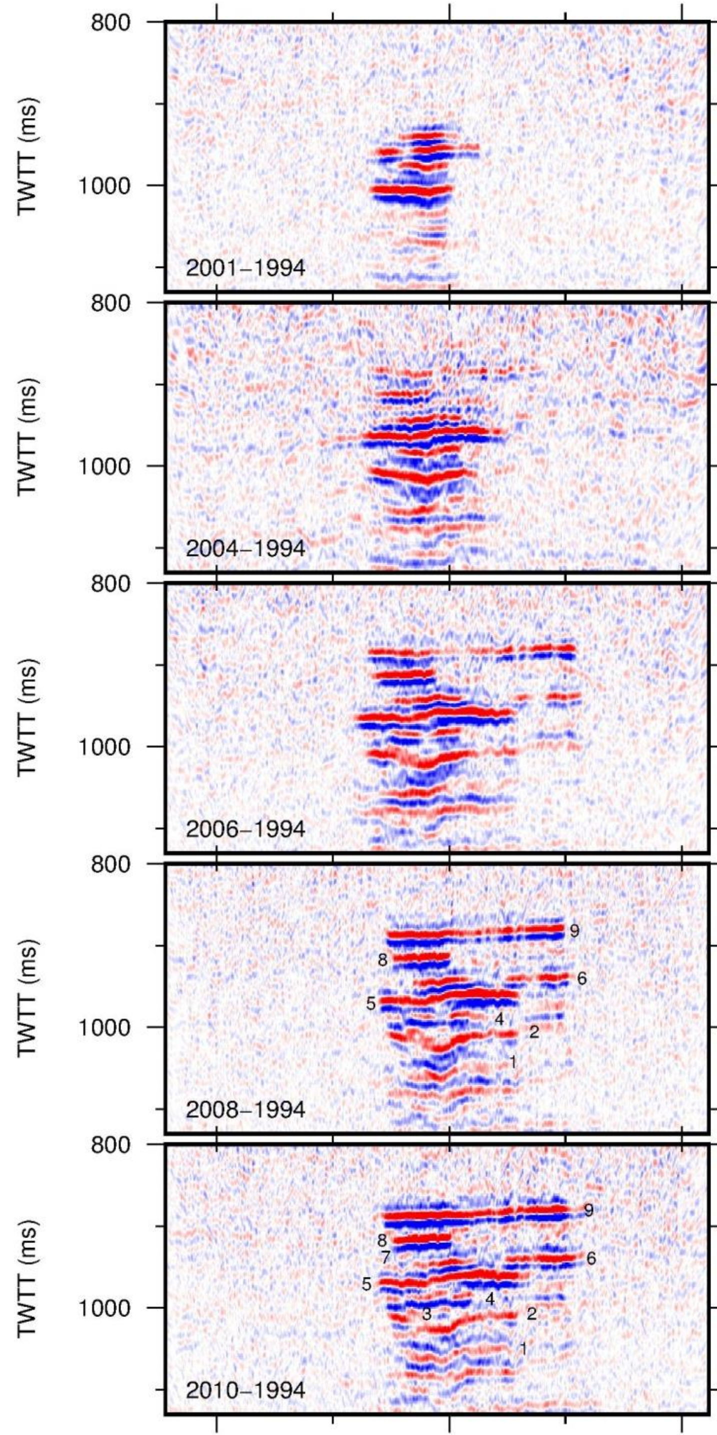
Sleipner – Plume evolution



Semi-permeable mudstones

Interpreted as ~9 distinct reflective CO_2 layers mappable in 3D.

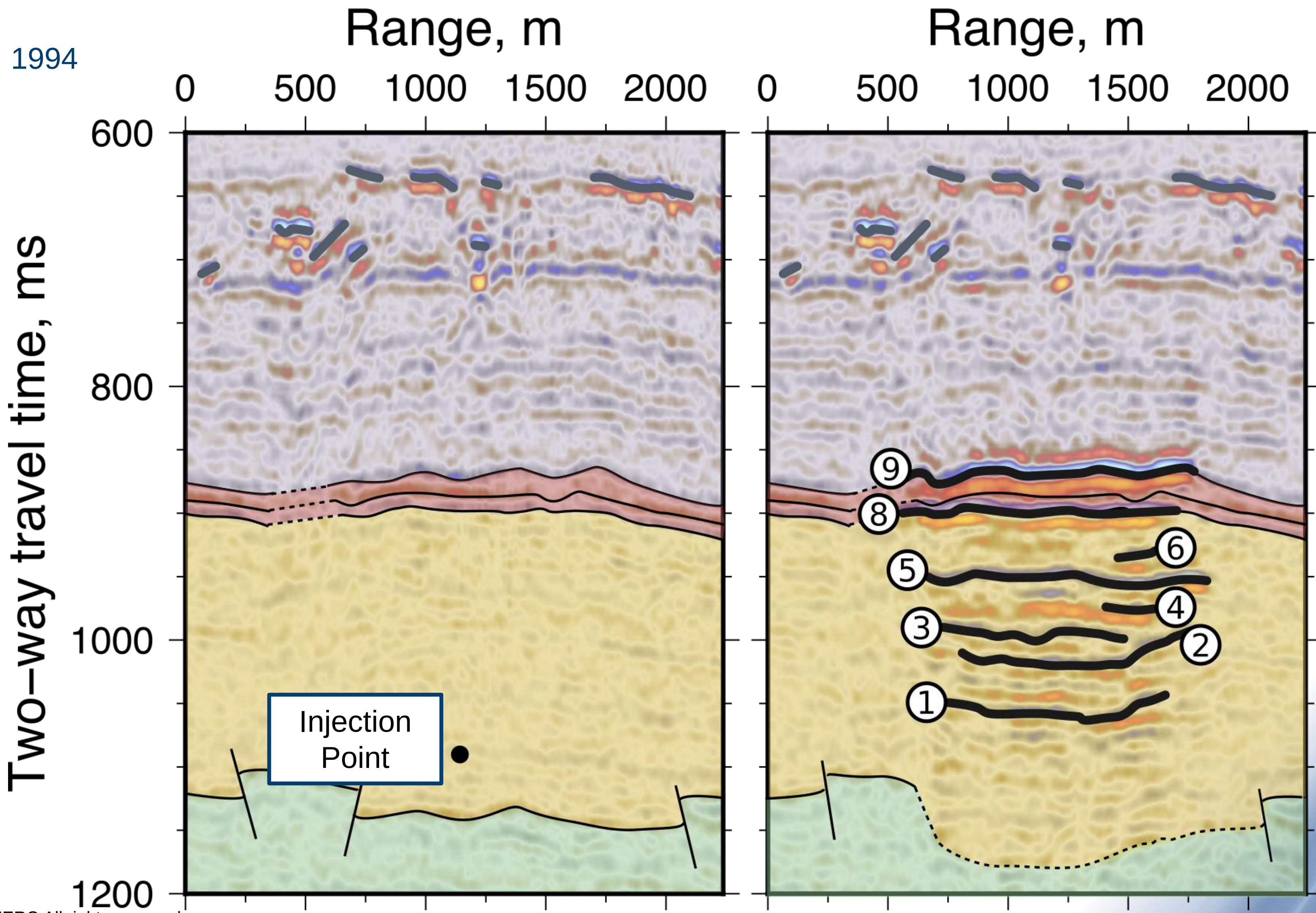
Evolving in a systematic way through time.



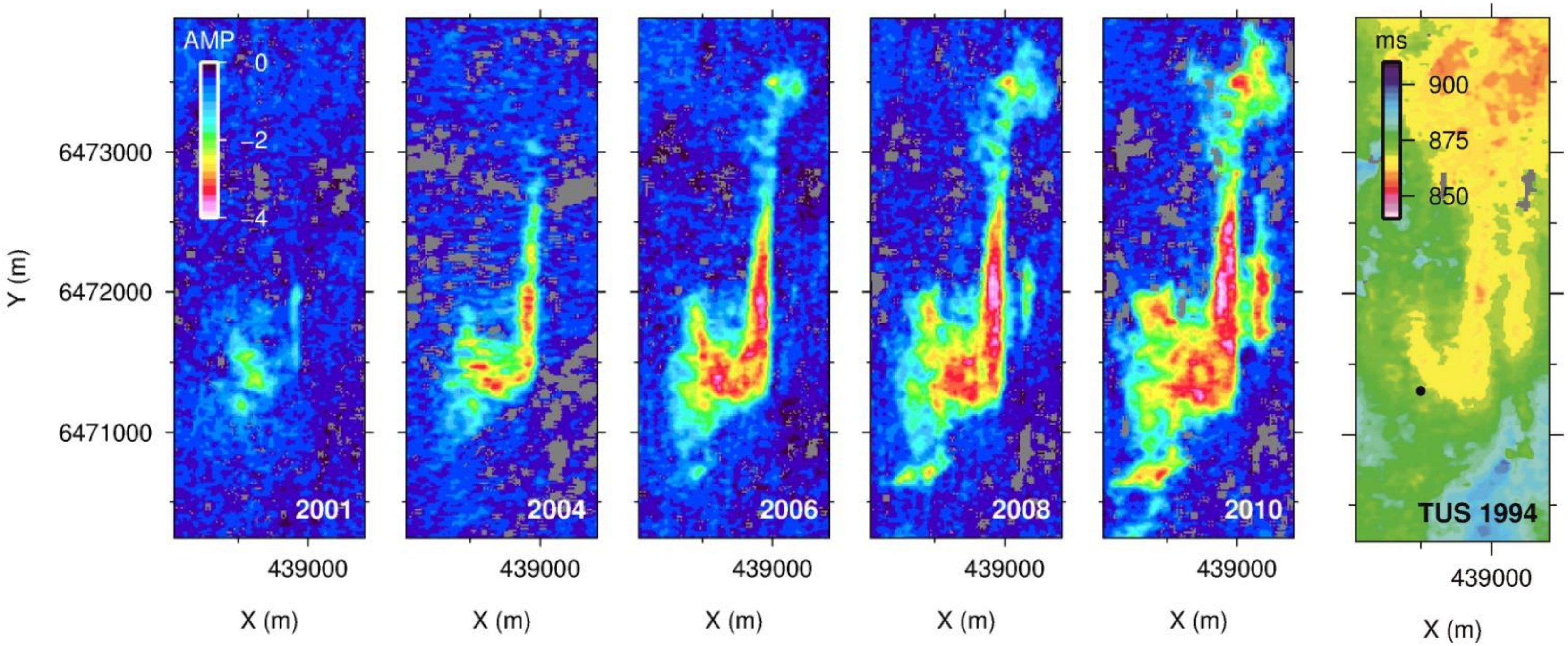
CO_2 distribution – thin layers

1994

2010

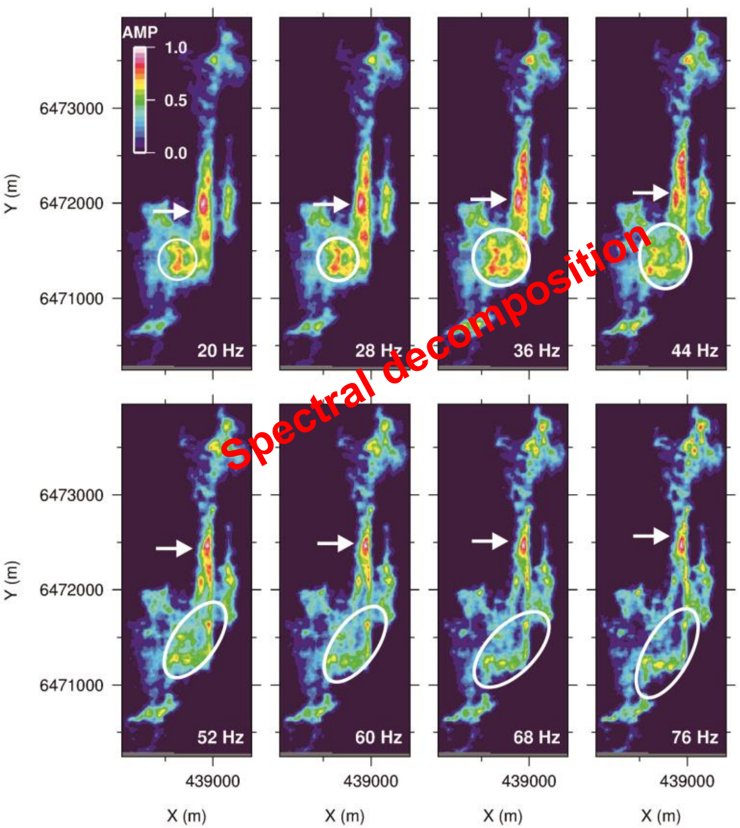


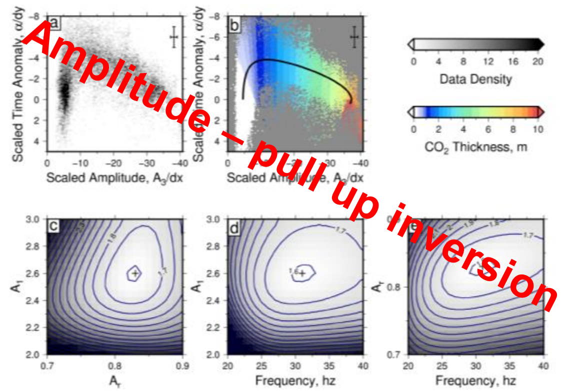
Mapping the extent of the CO_2 distribution – Sleipner top layer

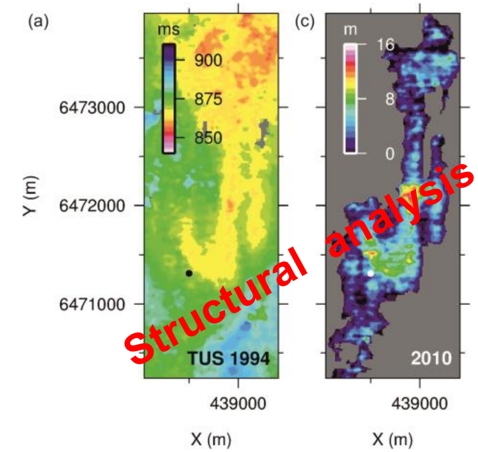


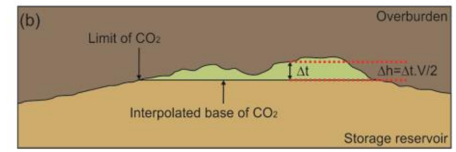
- Map view of the growth of the topmost CO_2 layer with time from the time-lapse seismic vintages in 2001, 2004, 2006, 2008 and 2010.
- Topography of base of caprock suggests buoyancy driven infill.

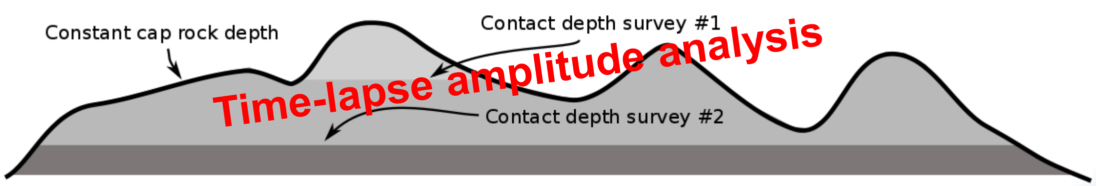
Layer thickness

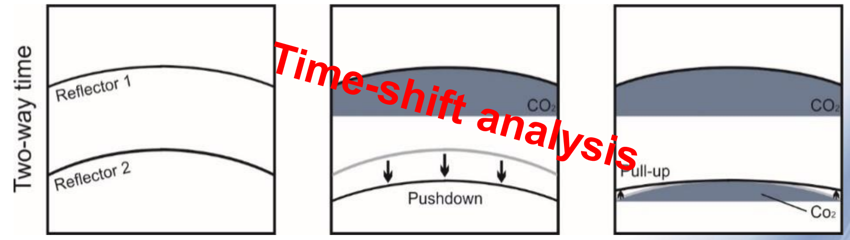






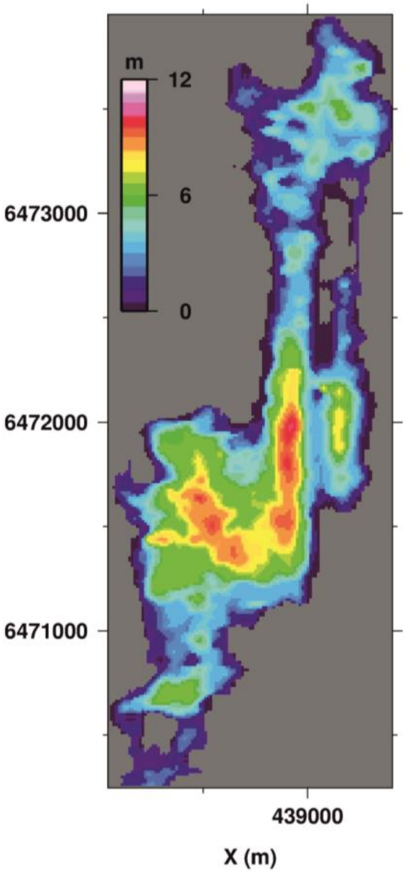






White, J.C., Williams, G.A., Chadwick, R.A., Furre A-K., & Kiear, A., 2018, Sleipner: the ongoing challenge to determine the thickness of a thin CO_2 layer, International Journal of greenhouse Gas Control, 69, 81-95.

Volumetrics



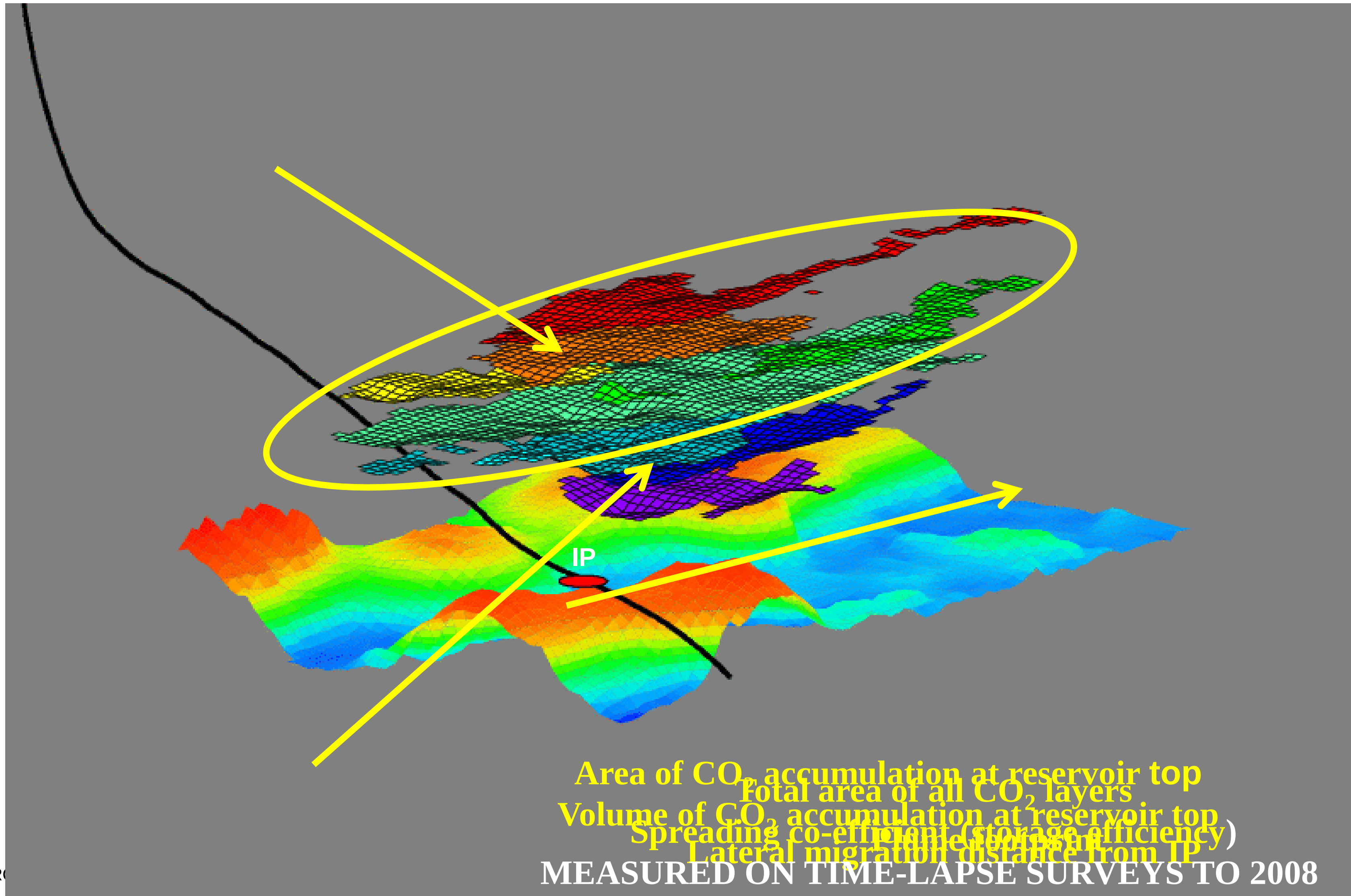
BGS published review of innovative techniques to overcome problem of vertical seismic resolution.

Enables layer thicknesses to be determined by most suitable method.

Spatial extent and thickness of layer allow volumetric calculation of stored CO_2.

	Spectral decomposition 2010TL	Spectral decomposition 2010IP	Time-shifts	Time-lapse amplitudes	Corrected measured temporal spacings	Composite layer
CO_2 volume, x 10^6 m^3	2.39	2.44	1.93	2.65	3.10	2.42
CO_2 mass, mT	1.70	1.75	1.37	1.89	2.22	1.72

Conformance measures



Three main requirements for transfer of responsibility at site closure

1. **No detectable leakage**

2. **Observed behaviour conforms with modelled behaviour**

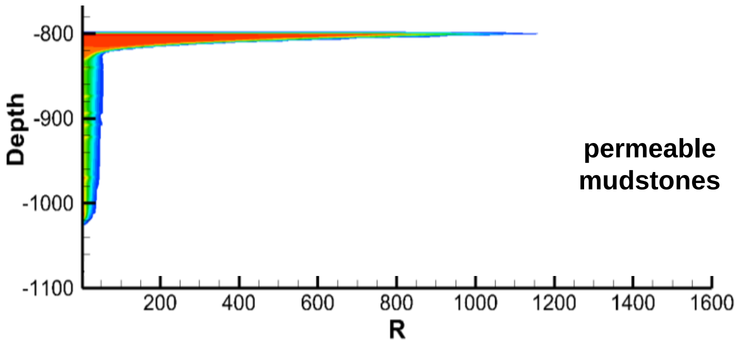
3. **Site is evolving towards long-term stability**

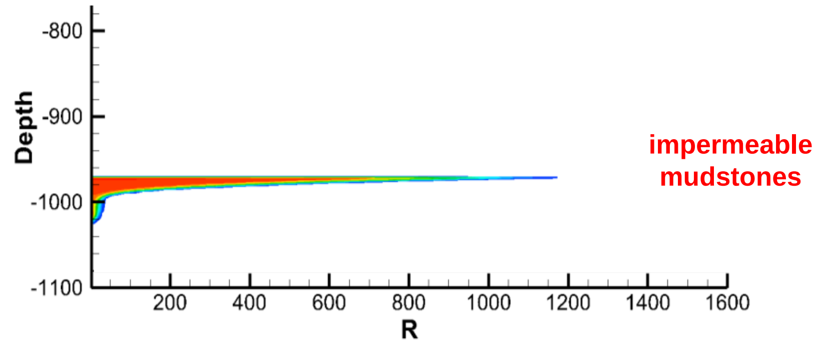
Models with baseline knowledge

Key parameters:

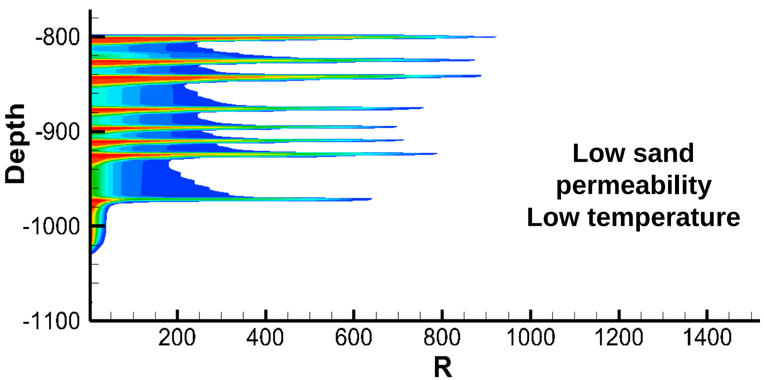
- Properties intra-reservoir mudstones
- Reservoir temperature (CO_2 properties)
- Properties of the reservoir sand

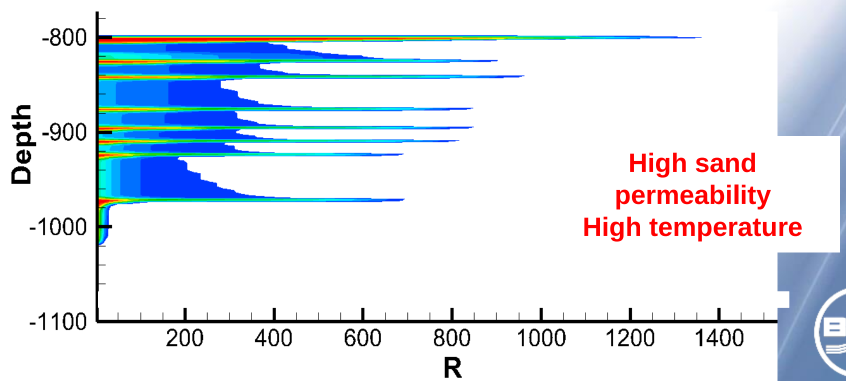
Permeable or impermeable intra-reservoir mudstones give rise to <u>single spreading layer</u>



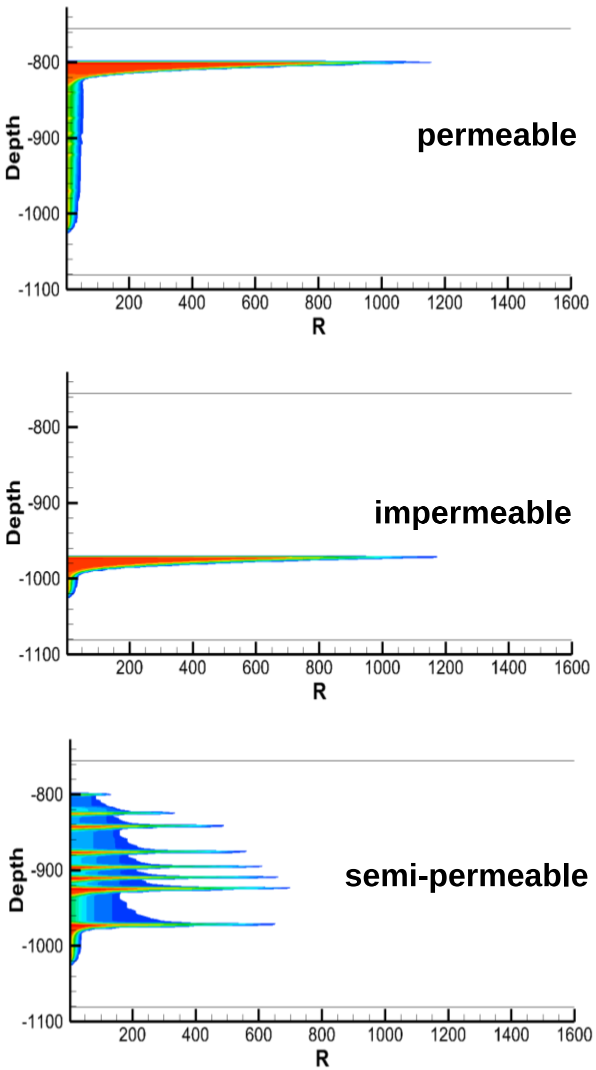


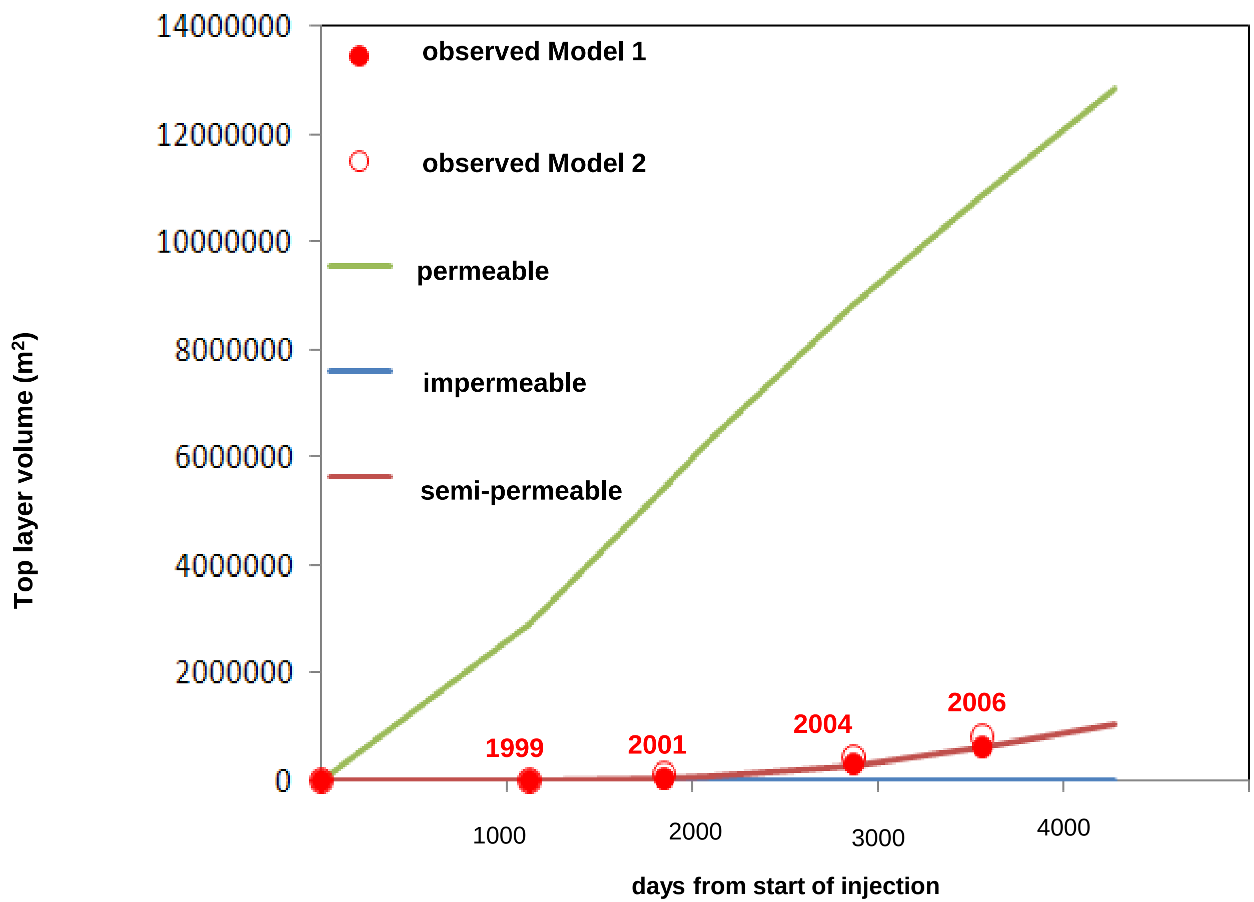
'Semi-permeable' intra-reservoir mudstones give rise to <u>multiple spreading layers</u>





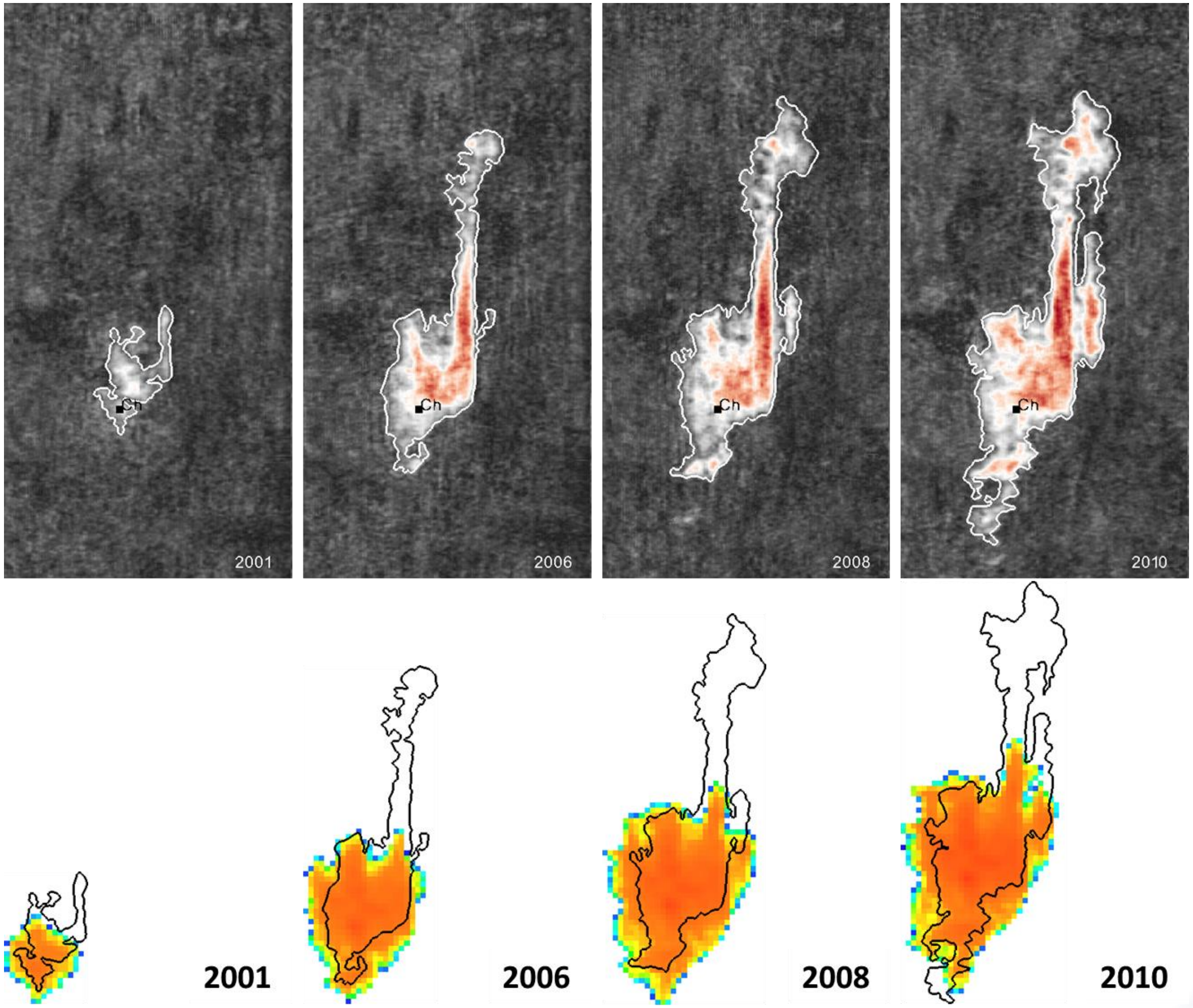
Performance measure: volume of top Utsira reservoir - 1996



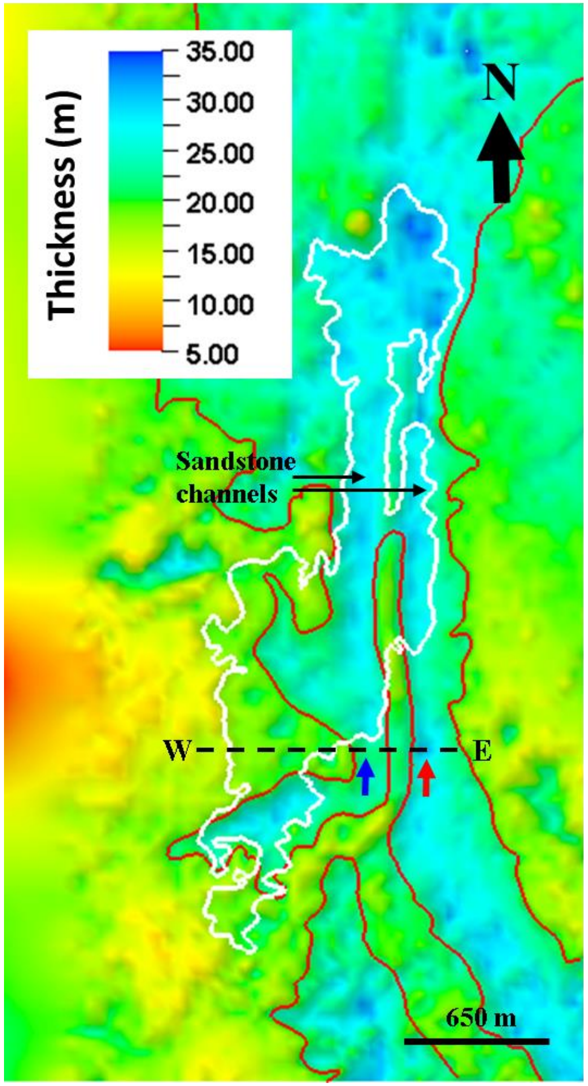


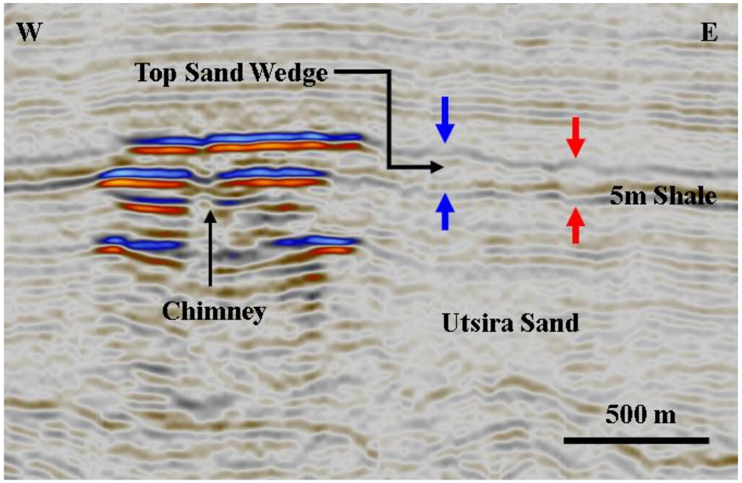
1996 semi-permeable models look promising …..

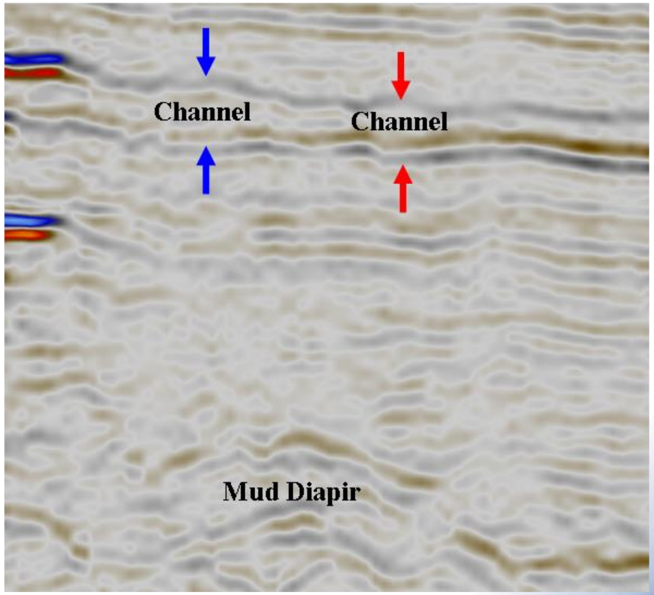
Darcy flow simulation



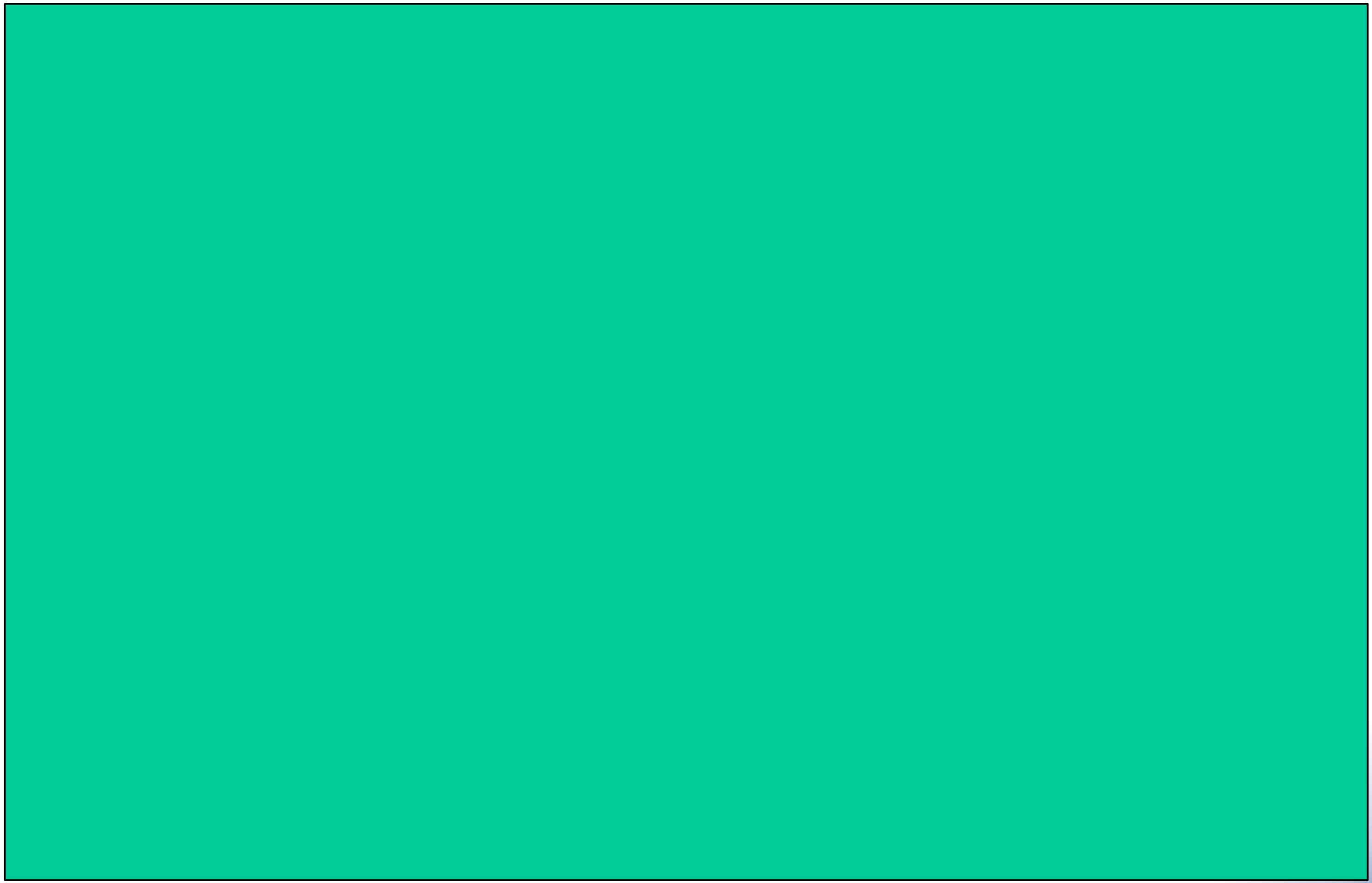
Sleipner – top sand wedge



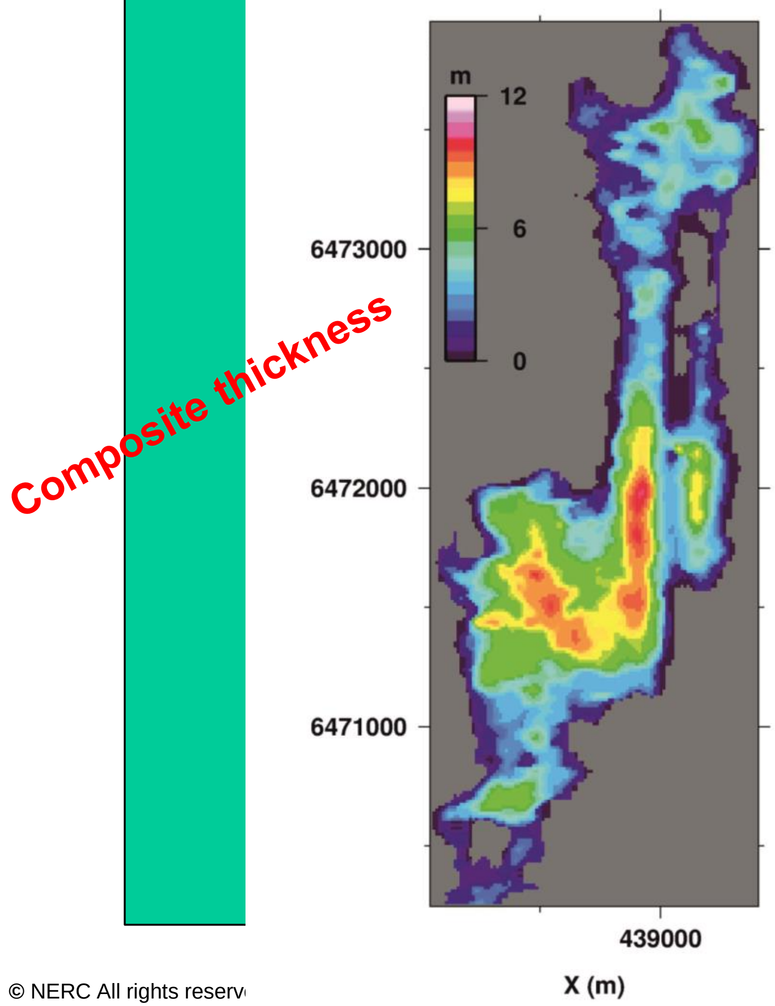




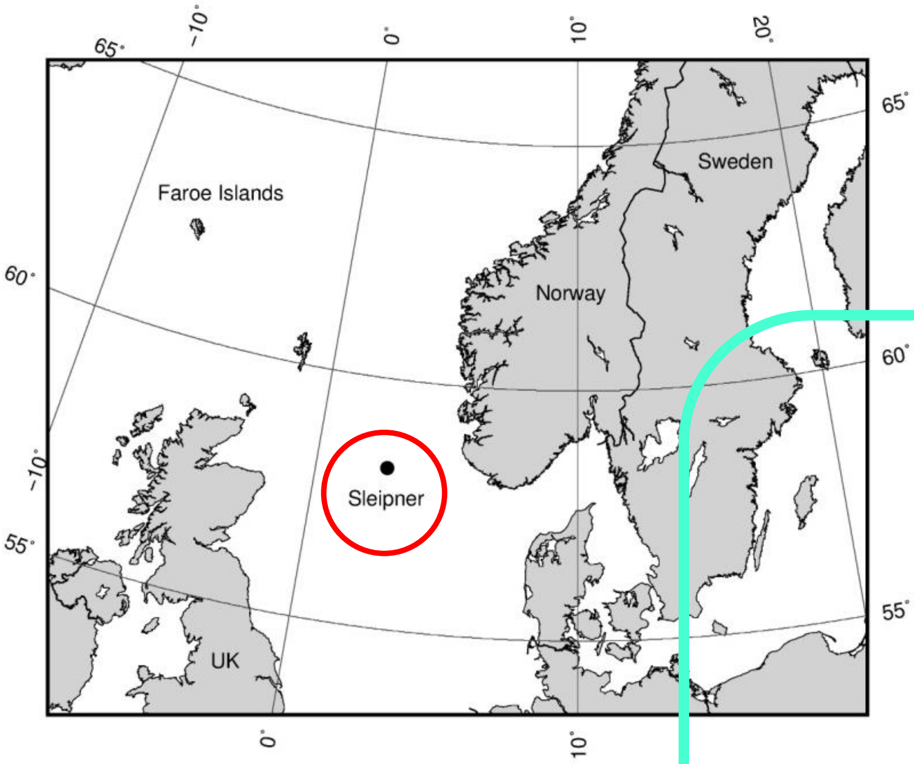
High permeability channel – 3D gravity current



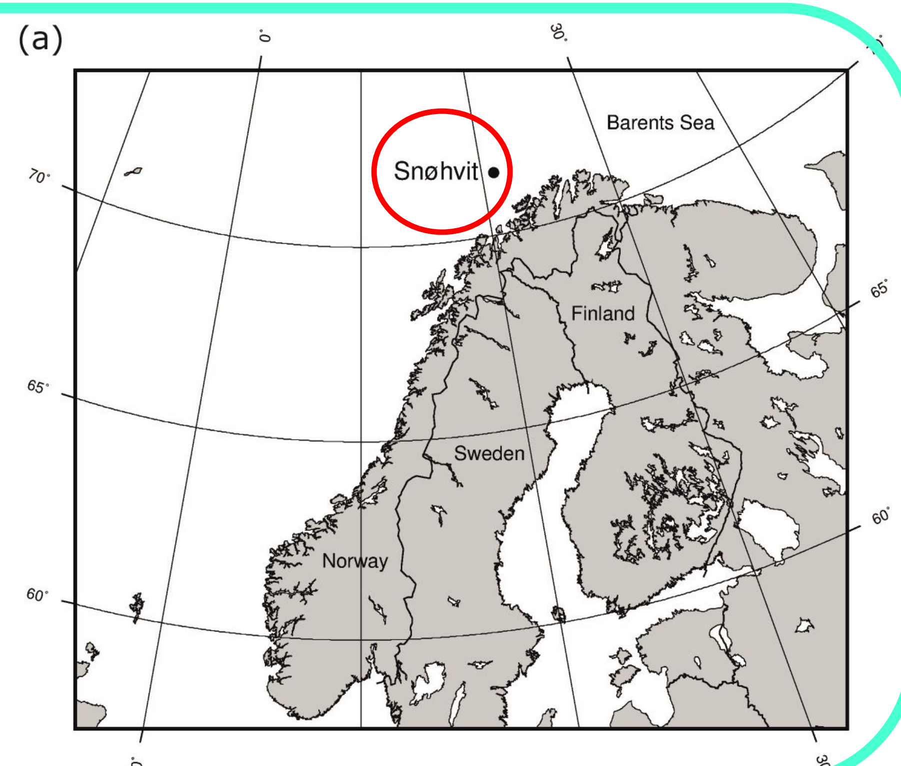
High permeability channel – 3D gravity current



BGS monitoring experience

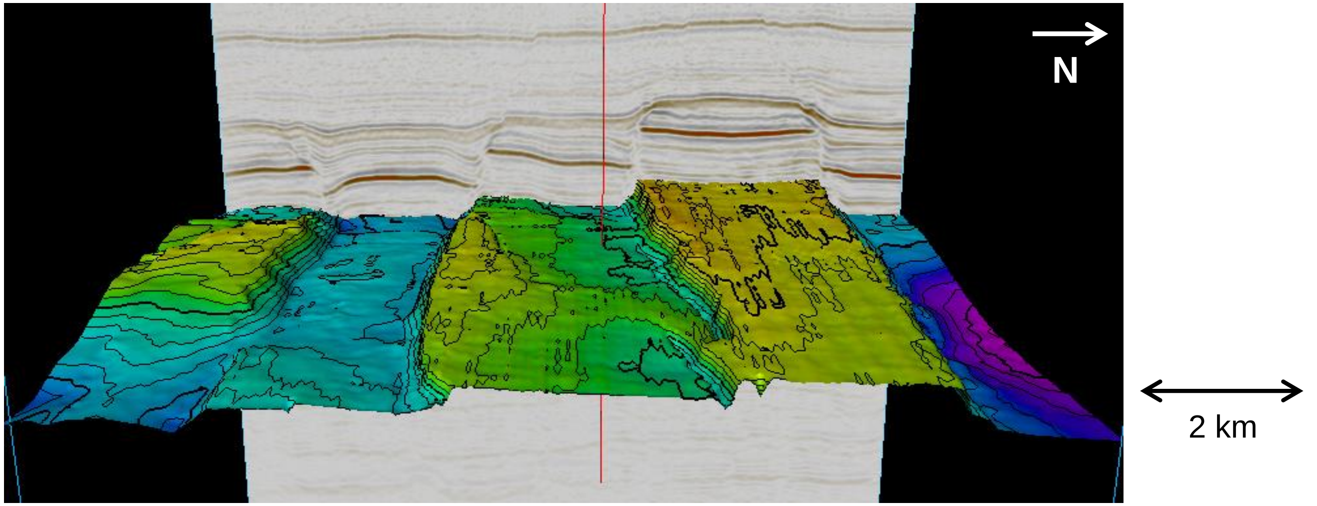


Sleipner



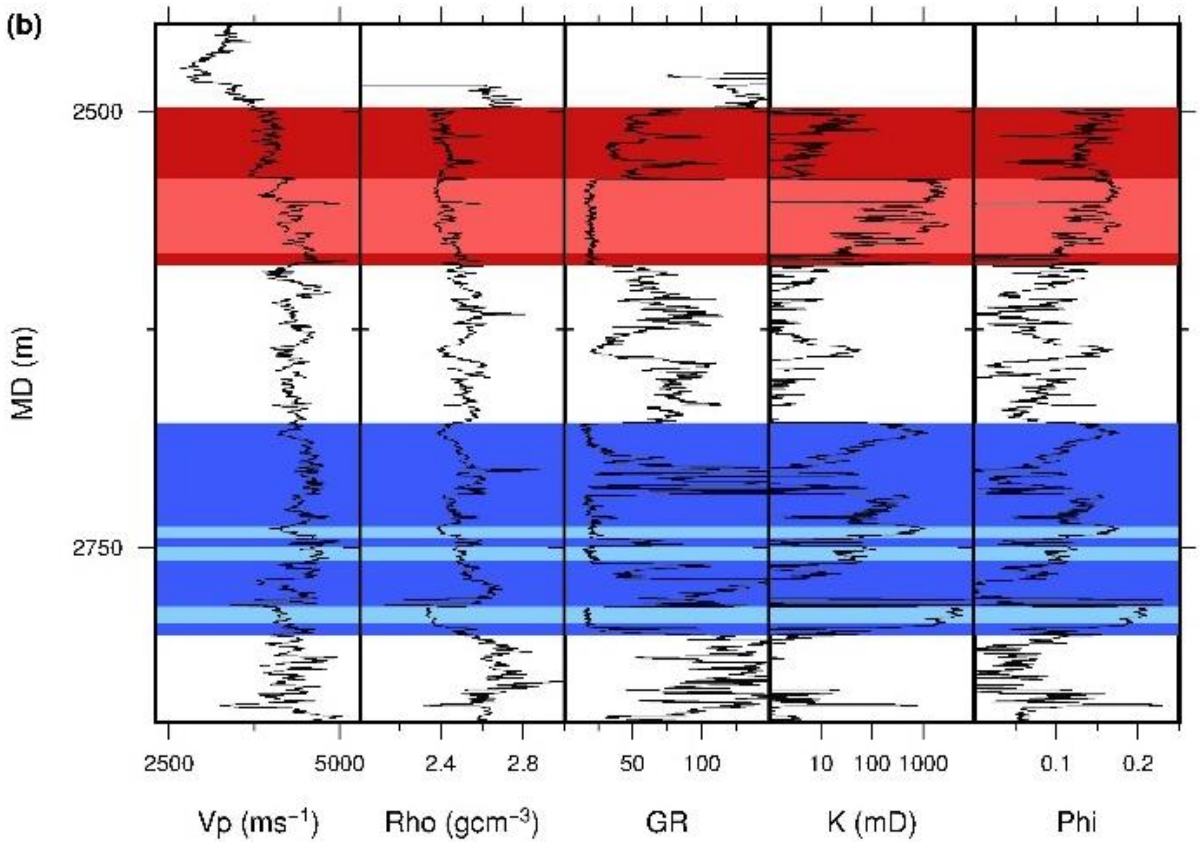
Snøhvit

Injection at Snøhvit

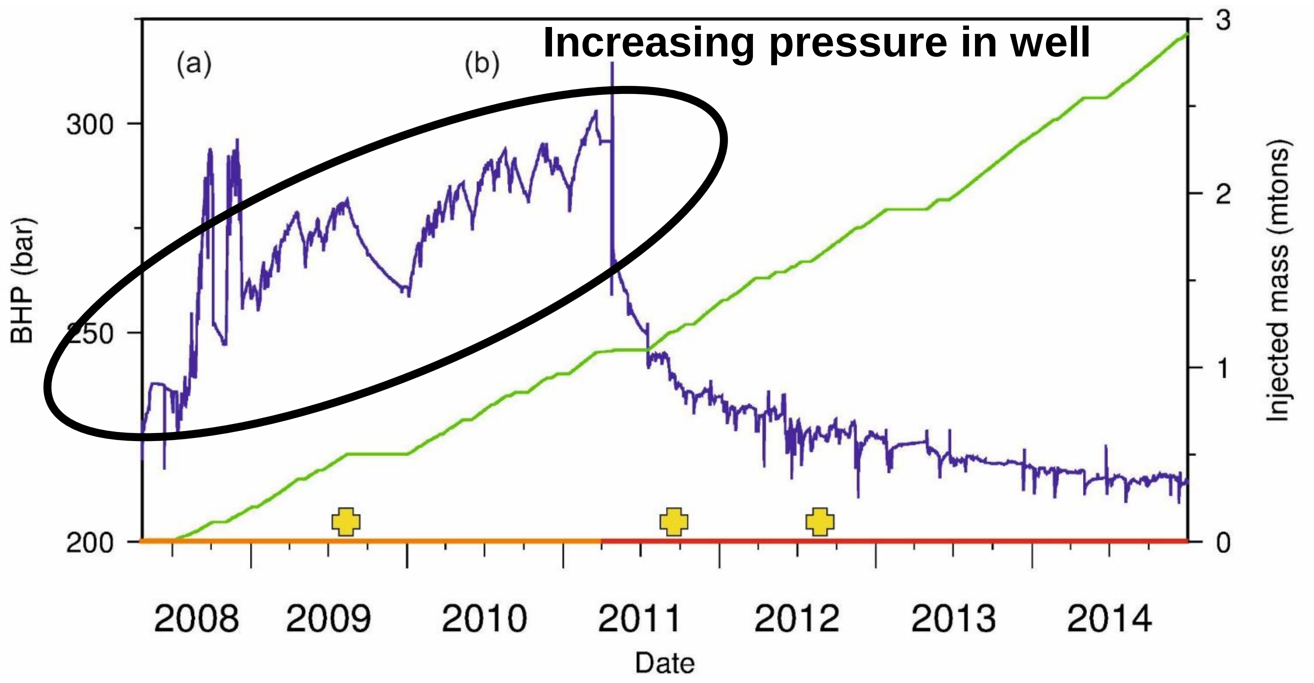


- Two phases of CO_2 injection - into the Tubåen formation and the Sto Formation.
- Reservoirs cut into E-W trending fault blocks.
- Tubåen formation injection - 0.5 Mtons injected over a 16 month period.
- Tubåen approximately 100 m thick, at 2565-2665 m depth below sea surface.
- Stø approximately 85 m thick, from 2450 m
- Time lapse 3D seismic (2003, 2009, 2011, 2012).

Injection perforations

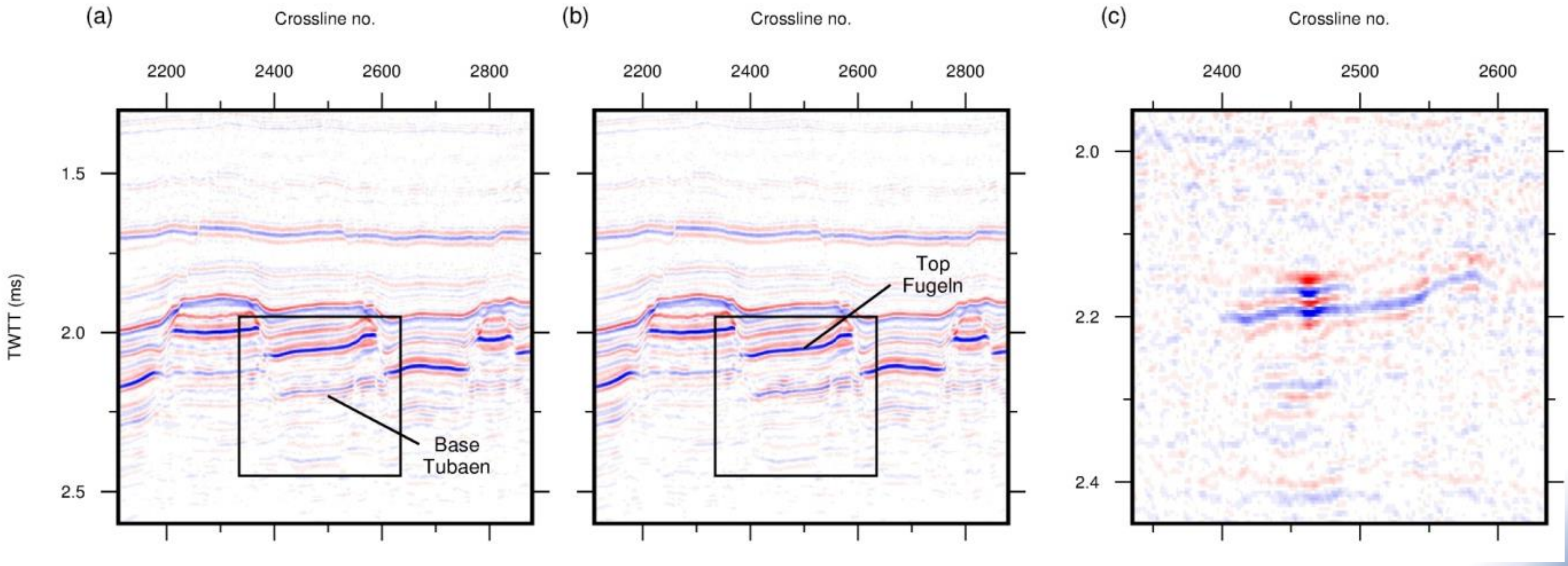


Snøhvit



- Down hole pressure (blue from pressure gauge located at ~1800 m depth)
- Cumulative injection is shown in green
- Seismic survey acquisition dates are marked with a yellow cross
- Change from Tubåen to Stø injection is marked by the change from orange to red on the x-axis

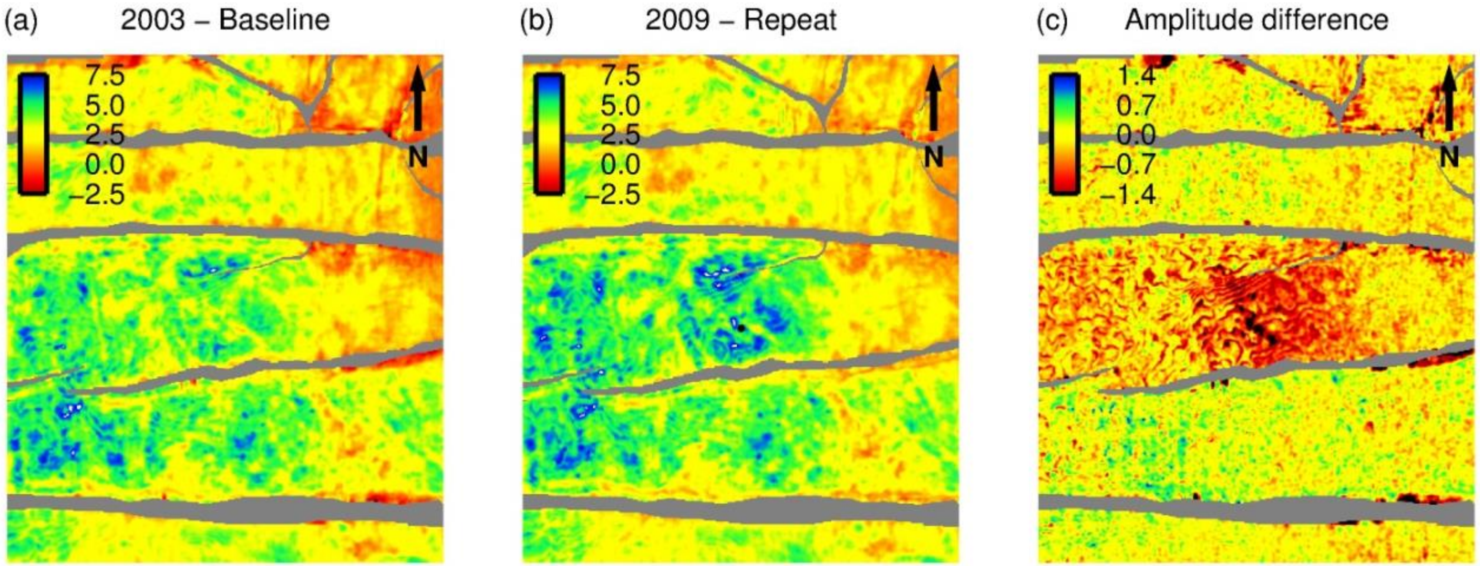
Seismic data



Left - 2003 baseline; Middle - 2009 repeat; Right - time-lapse difference

The time-lapse difference data from the region bounded by the black box.

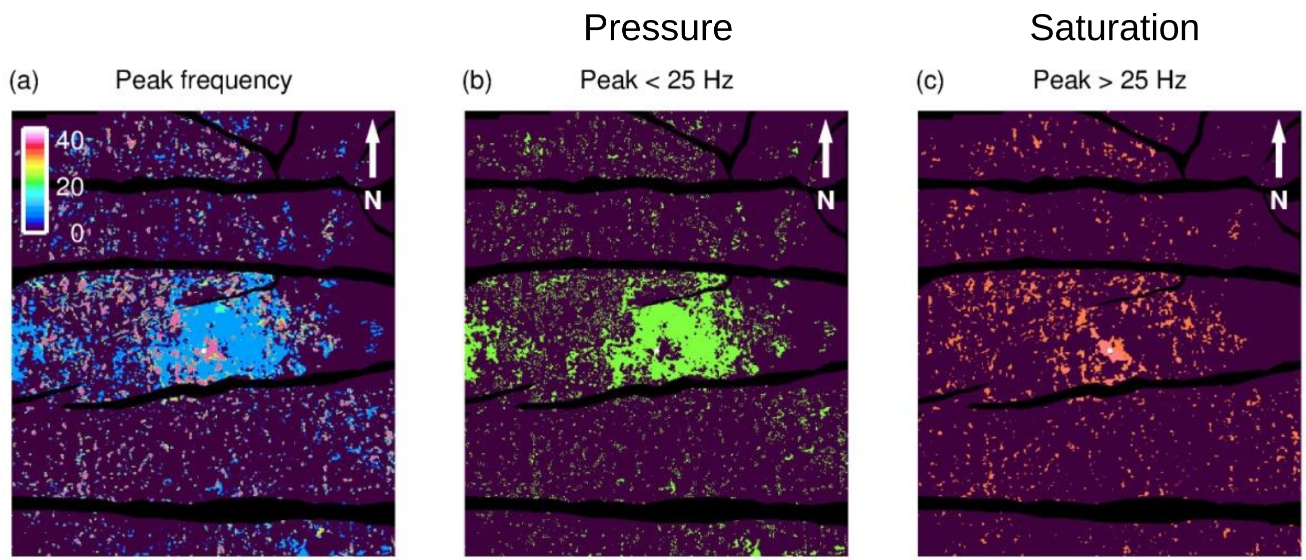
Injection amplitude



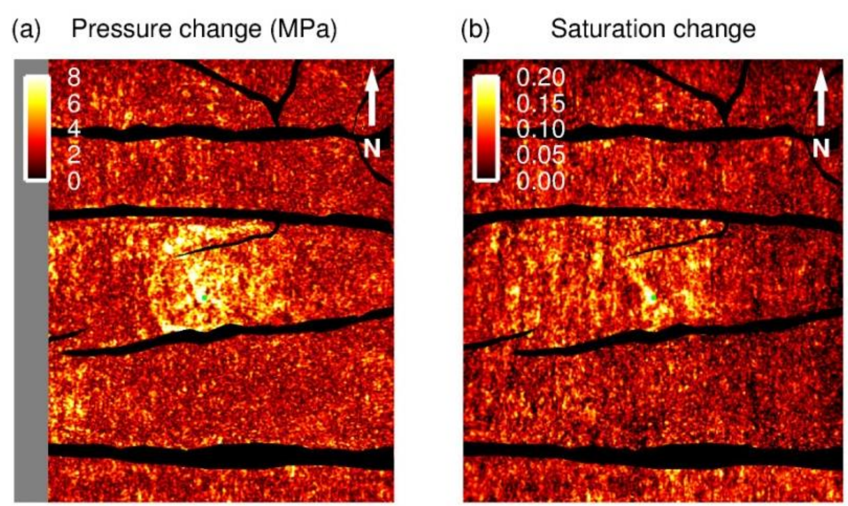
The difference between the grids

Modelling reveals the lateral extent of the anomaly is too big for a fluid substitution (CO_2 replacing brine) effect.

Two methods to define pressure response



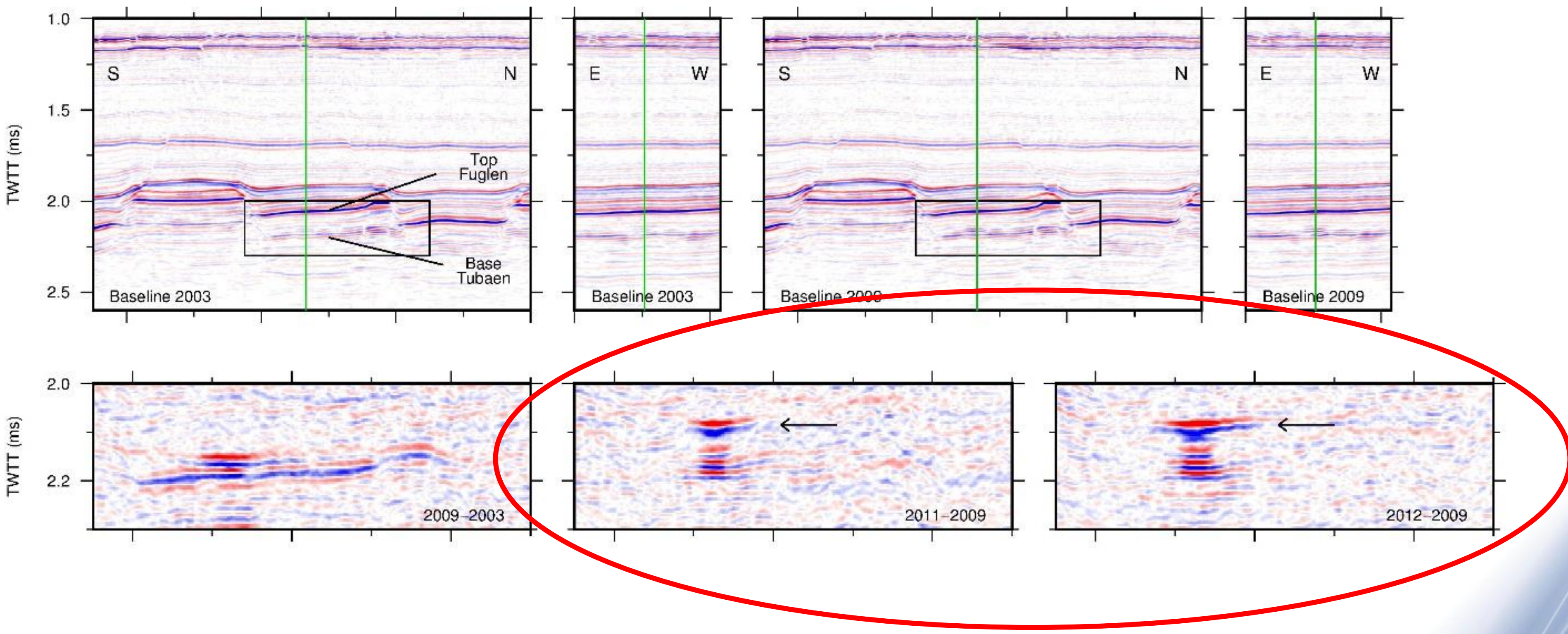
Spectral analysis to derive layer thickness (White et al., 2015).



The inverted pressure and saturation changes from Grude *et al.* (2013).

Results show a striking correlation.

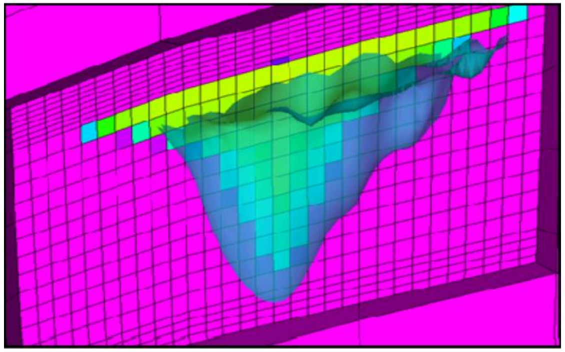
Seismic response



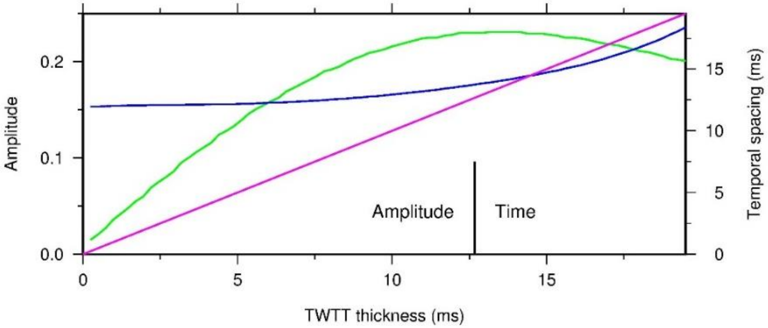
The lateral extent of Stø anomaly more confined.

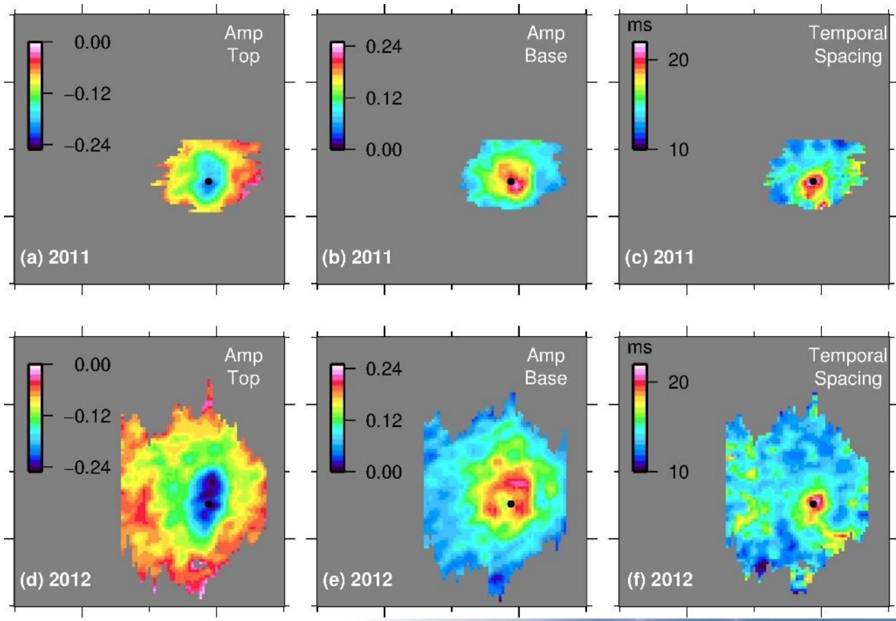
Imaging suggests conical distribution of CO_2.

Modelling and analysis



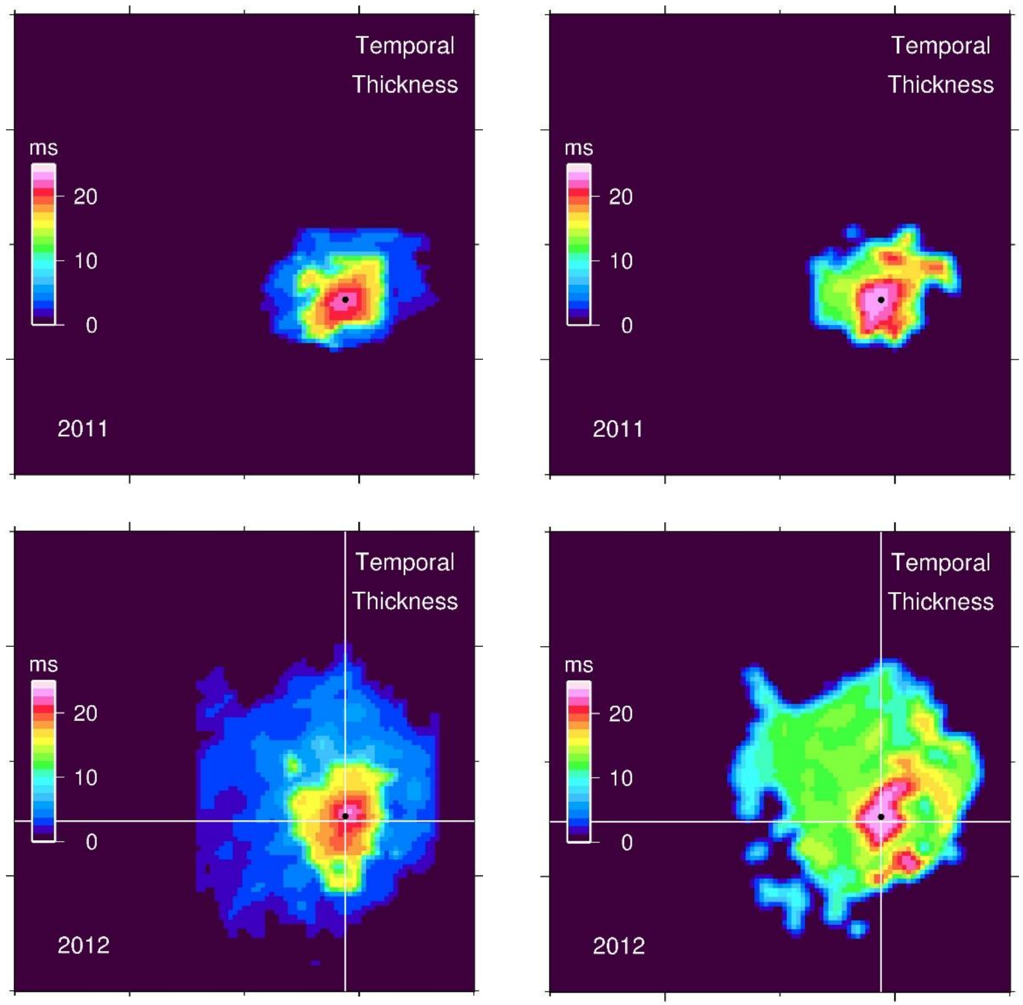
- Reservoir flow modelling (Osdal et al., 2015) and time domain seismic analysis highlight different growth pattern for CO_2 layer.





Thickness estimates

Time-lapse amplitude analysis



Spectral analysis

Conclusions/Questions

- Small volumes of CO_2 can be images with 4D seismic technique.
- Evidence of conformance is provided by geophysical monitoring.
- How can this conformance be quantatively defined?
- What form will the inputs data to the conformance methodology take?

Acknowledgements

- This work was carried out under the ***DiSECCS*** project, funded by the UK EPSRC and the **BIGCCS Centre**, funded by the Norwegian research program FME initiative.
- Additional support was provided by the ***NCCS* Centre**, funded by the Norwegian research program FME initiative.