CCS case study
(strongly inspired by the Sleipner project, offshore Norway)

Special focus: monitoring and ray-based seismic modelling

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Insight Through Modelling

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CCS in a nut shell

CCS: Carbon Capture and Storage

Motivation: possible solution to stabilize global greenhouse gas emissions, decarbonizing industries such as like cement or steel manufacture, ...

Established technique: disposal in deep saline aquifers or depleted gas and oil fields.

Key risks, uncertainties and challenges:

- Site performance: sufficient capacity and injectivity?
- Effective containment: leakage pathways (breached cap rock, transmissive faults, imperfectly sealed wells...)?
- Public perception: concerns about induced seismicity and other potential or anticipated risks, concerns about costs, possible prolongation of using fossil fuels (should one rather invest in renewable energy?).

Summary guided by: English & English, First Break 40, 2022

CO_2 storage is not just like inverse hydrocarbon production!

(Ringrose et al., First Break 40, 2022)

For CCS, none of the properties of supercritical CO_2 as compared to those of liquid CO_2 can be considered as advantageous.

(Report on plant design, Energy Institute London, 2010)

Why seismic modelling?

CO_2 disposal can have a wide range of potentially unwanted effects far beyond the actual injection zone!

=> Monitoring is required!
Key method: seismic surveys

=> Seismic modelling for
- Survey planning
- Survey evaluation
- Interpretation support
- Processing support
- Microseismic monitoring

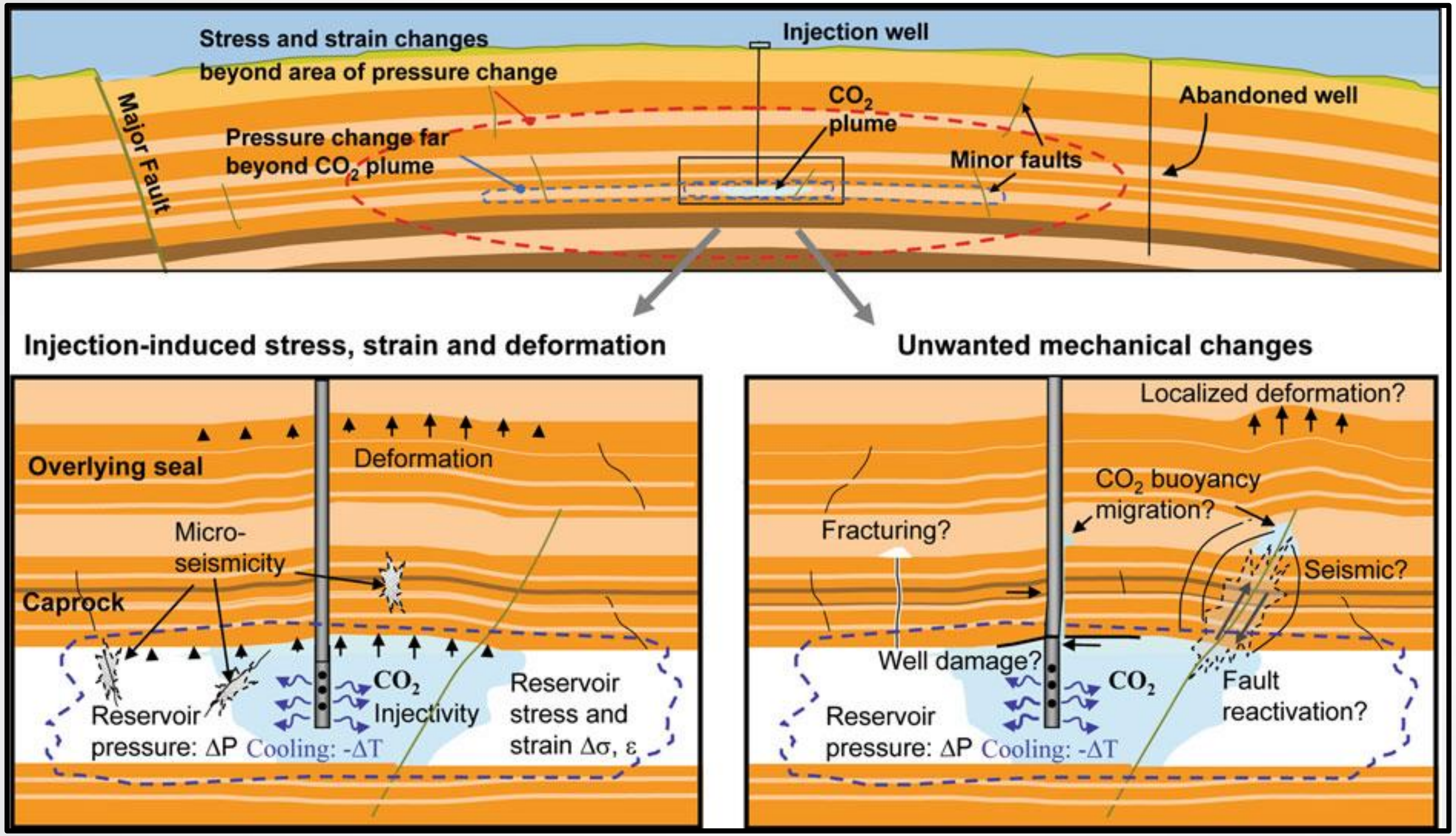
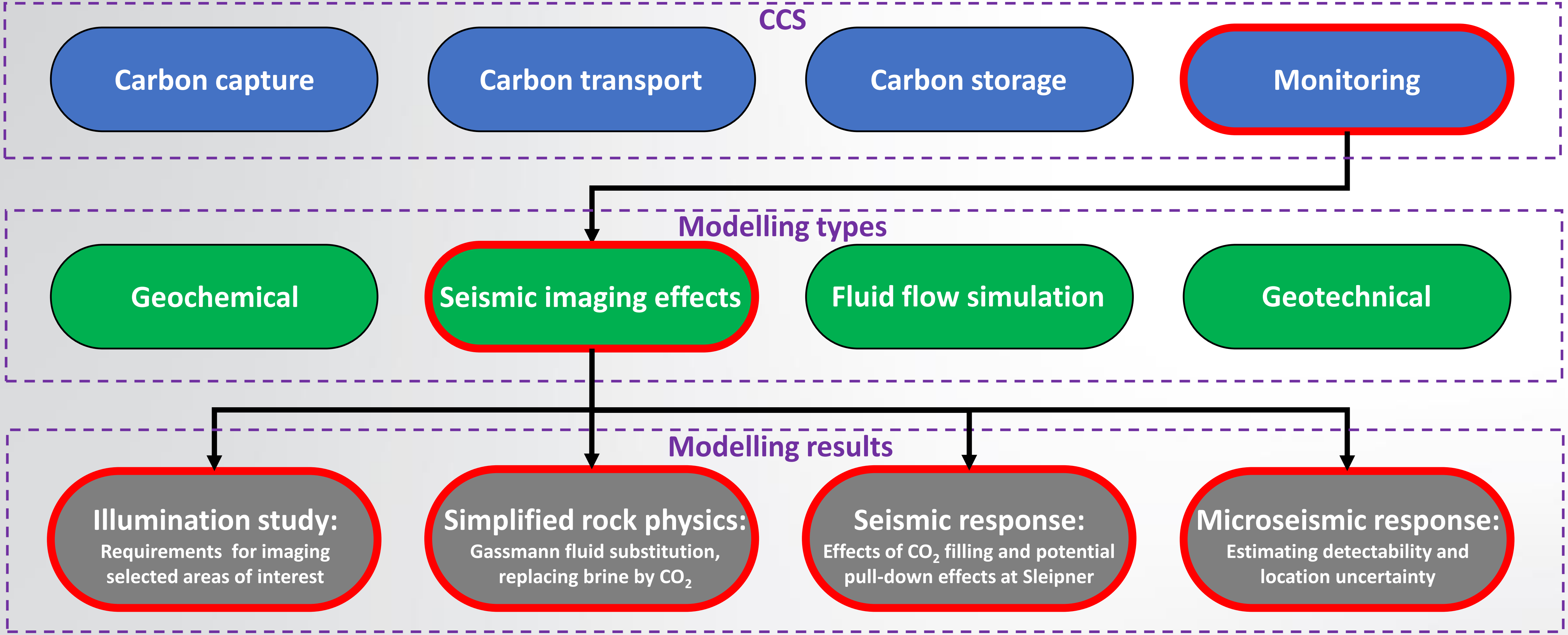


Image source : Rutqvist, Geotech Geol Eng 30, 2012

Outline of the modelling tasks as presented here



Out of a wide range of possible modelling tasks as related to CCS, NORSAR is focussing on seismic monitoring. This presentation is further focussing on the red-framed modelling applications only.

Inspiration from the Sleipner project

- CO_2 injection at **1012 m depth** into the shallow and unconsolidated Utsira formation. The sand-rich succession is 200-300 m thick and has a **net-to-gross ratio of 95%**. It is interbedded with thin (typically about 1 m) shale stringers. **Porosities are 35-40%**, permeability is > 1000 mD for the sand layers and 0.001 mD for the seals.
- The dedicated injection well is highly deviated (2.4 km laterally at 1 km depth). Bottom hole pressure is not known but assumed to be only marginally above hydrostatic. Bottom hole temperature of CO_2 is estimated at about 48°C (i.e., about 13°C higher than the native reservoir temperature). **CO_2 is at supercritical state but very close to the critical point**.
- The injected CO_2 flows in **nine distinct high saturation layers no more than a few meters thick**, capped by the thin intra-sand shales above (which are partly but not fully sealing). CO_2 is buoyantly rising upward and plume shape mainly resembles the top reservoir topography.
- The baseline seismic survey was done in 1994, the 6th repeat 3D survey (as studied here) was carried out in 2010.

Monitoring objectives at Sleipner:

- CO_2 storage performance
- Time-lapse tracking of CO_2 migration (potential vertical leakage to the seabed, cap rock integrity, lateral movement to well bores or outside the license area)
- Predicting future behaviour

Information collected from: Eiken et al., Energy Procedia 4, 2011; Arts et al., Energy 29, 2004; and others.

Sleipner data used

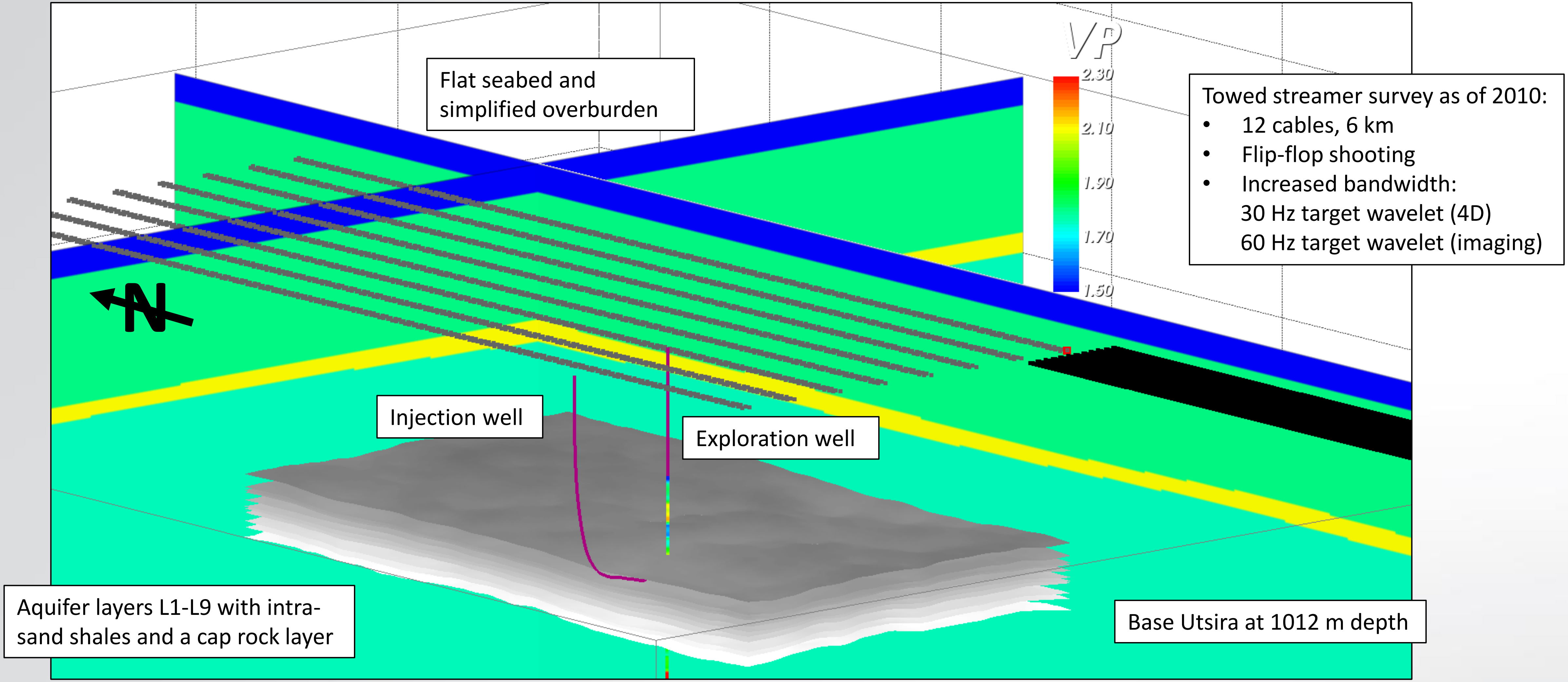
This synthetic case study is inspired by the Sleipner project and is using published data from https://co2datashare.org/organization (a courtesy of Equinor ASA and partners):

- Aquifer interfaces (3.2 km x 5.9 km) for building a reservoir model suitable for seismic forward modelling. There are nine sandstone layers in the model (Utsira L1 to L9 from deep to shallow). L1 to L8 are vertically separated by thin shale layers of about 1 m thickness. L8 and L9 are separated by a shale layer of about 7 m thickness (the “thick shale unit”), separating the Utsira formation (L1 –L8) from the “sand wedge” (L9). The cap rock layer is represented as a 50 m thick shale layer (even though the actual shale is much thicker).
- Plume outlines as of 2010 for each of the layers L1-L9 for defining CO_2 distribution in the model (i.e., this study compares the pre-injection situation in 1994 with the inferred 2010 plume extension).
- The location polygon of the main feeder channel “the chimney”, for introducing a vertical zone of potential CO_2 saturation in the model. In seismic data, the main feeder channel can be interpreted for all layers up to L8.
- Well log data of 15/9-13 for guiding physical property setting in the base model and parts of the overburden.
- Velocity maps for guidance on the velocity drop due to CO_2 saturation between the base survey 1994 and the 2013 monitor survey.

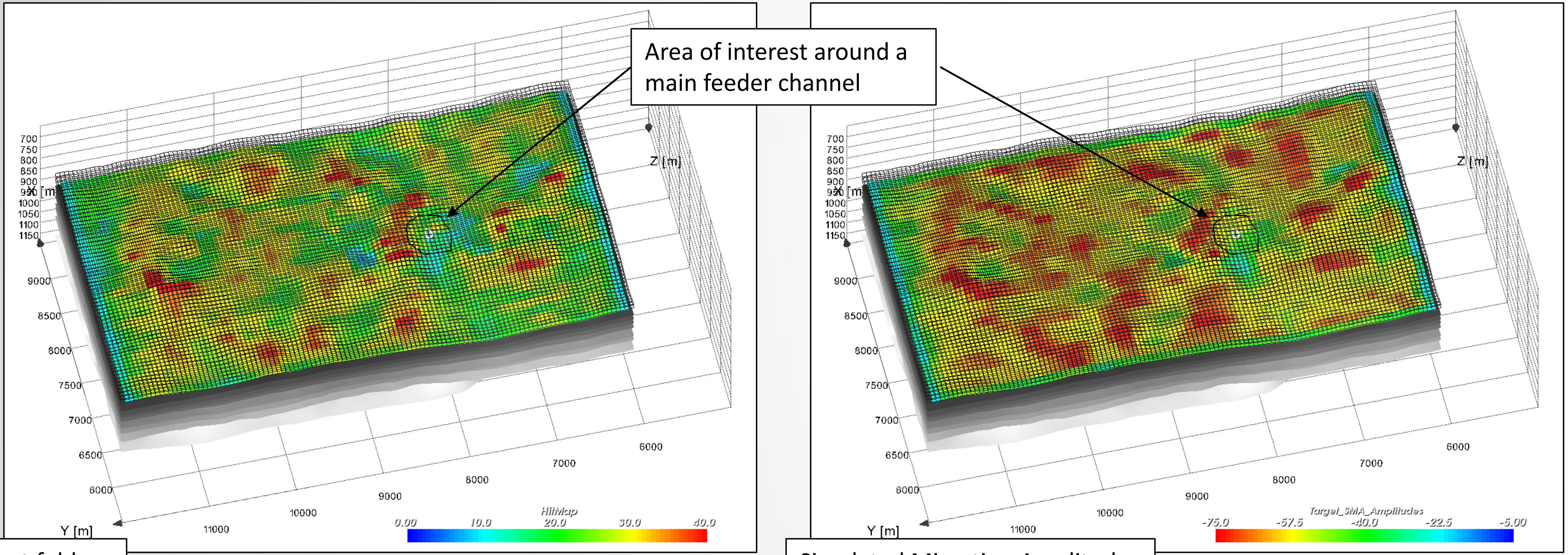
All other information was either collected from other sources or freely added:

- Overburden was kept simple and can be modified for additional tests
- P/T conditions were kept simple and according to some indications in literature

General model setup



Illumination study on Top Utsira (does the pre-injection survey fit the purpose?)

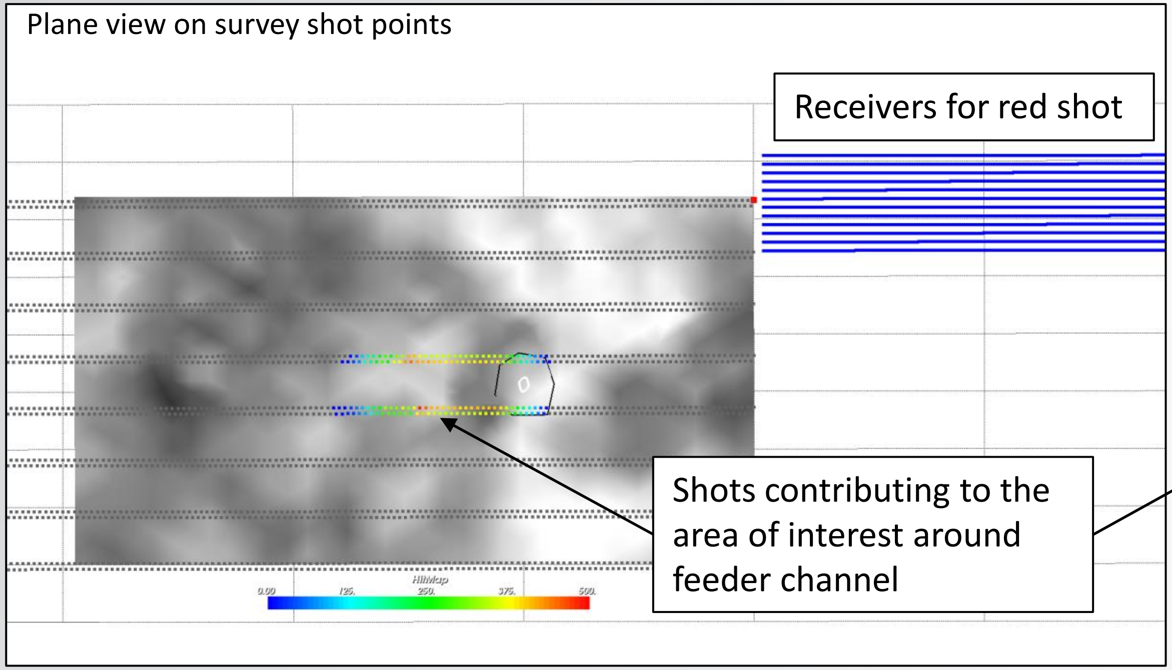


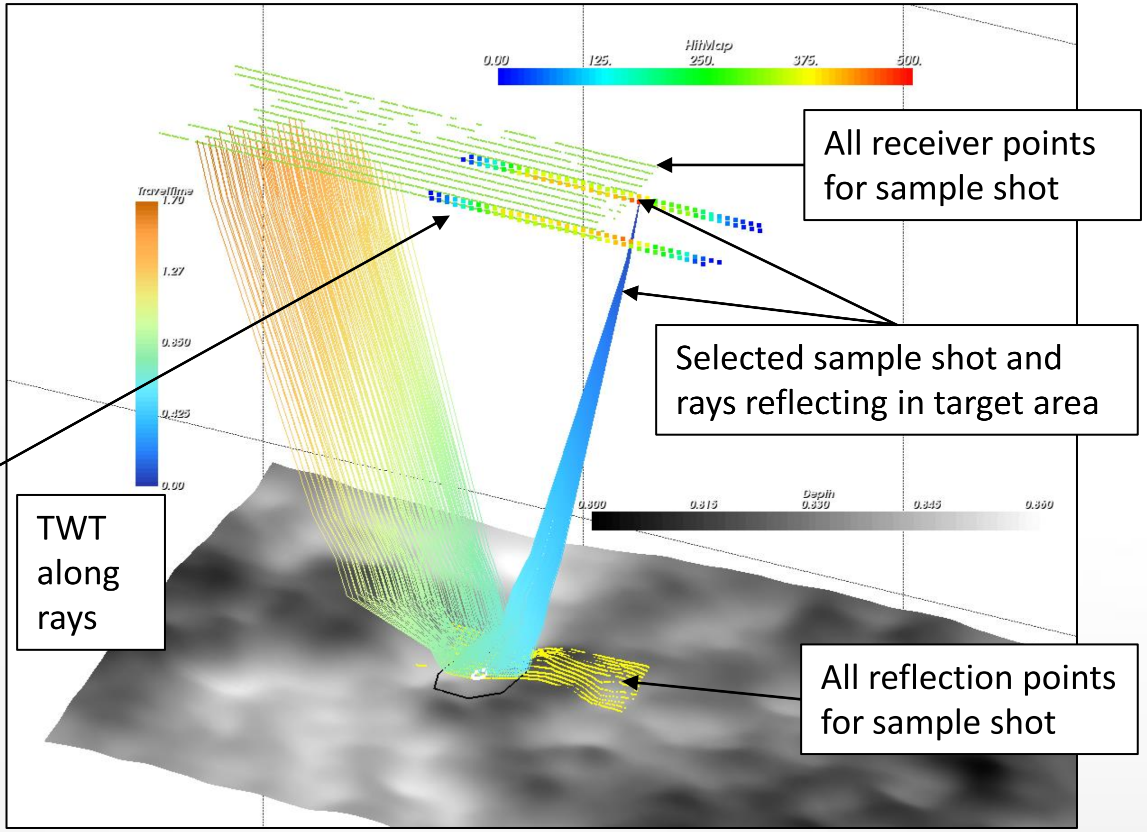
Target fold

Simulated Migration Amplitude

General observations from classic ray tracing and for the given (simplified overburden model): listening time < 2 s, no specific requirements for migration aperture, 3 km maximal usable offset, incident angles up to 85° (critical angles depending on property setting). There is reasonable fold all over the target.

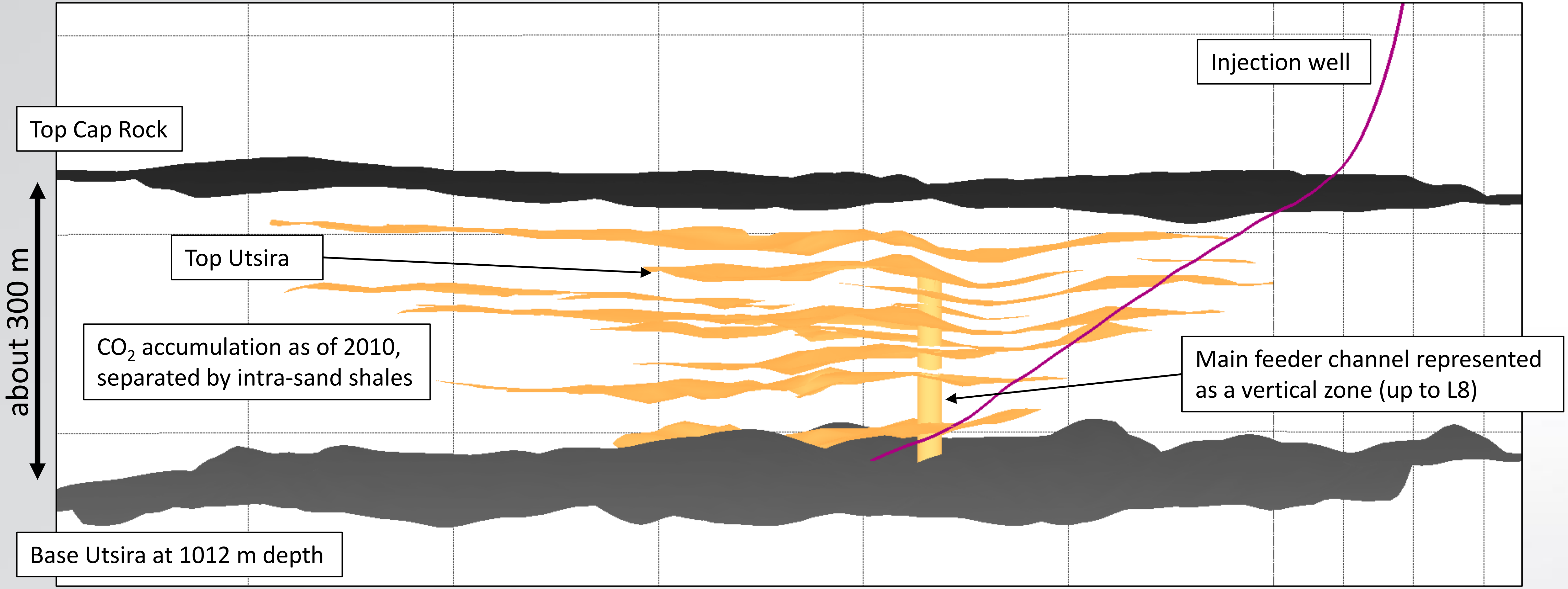
Illuminating the main feeder channel (interpretation/processing support)





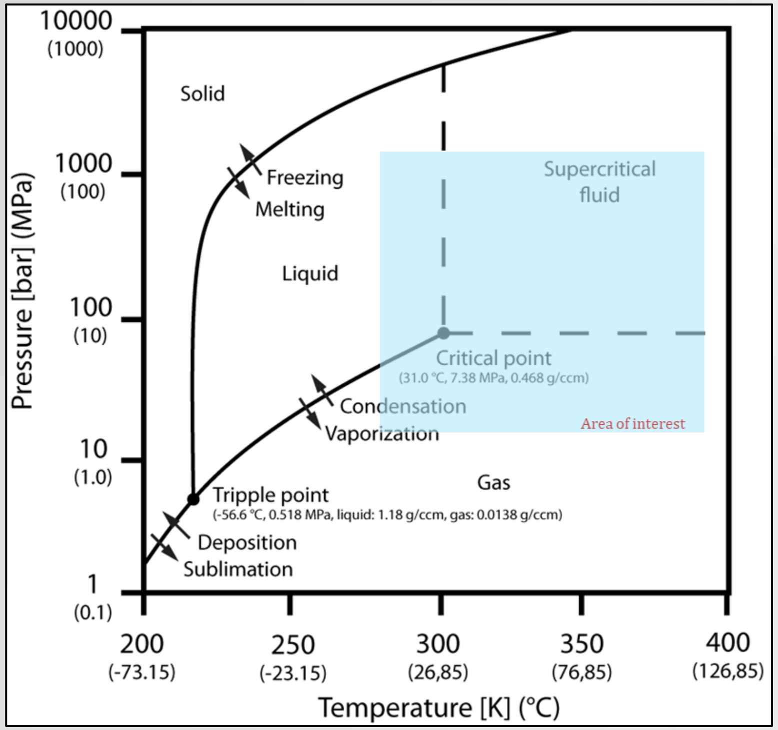
Ray tracing is an efficient and flexible approach for evaluating seismic surveys (fold, azimuth, amplitudes, offset-angle relationship, travel time, required migration aperture, ...), finding suitable shot and receiver grids, and for supporting interpretation and/or processing in different ways (e.g., by indicating the shot area that contributes to a given AOI).

Aquifer model setup



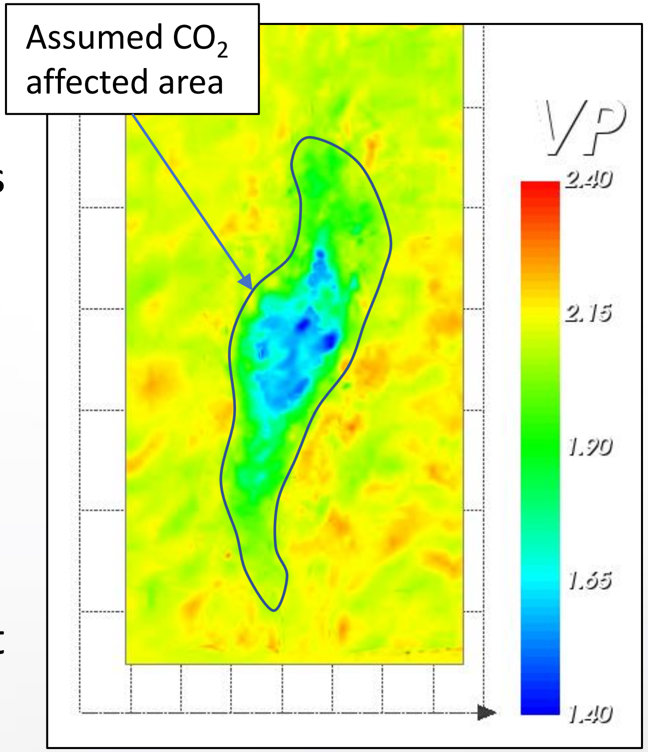
Property setup

Shale layers from sonic logs/literature: Vp=2270 m/s, Vs=850 m/s, Rho=2100 kg/m^3
Sand layers: Vp=2050 m/s (see below), Vp/Vs=2.7 (average value from literature), Rho=1700 kg/m^3
Overburden: partly from logs, partly from general North Sea trends
CO_2 filled sands in thin layers underneath intra-sand shales and in feeder channel: can it be modelled???



CO_2 phase diagram

- No well bore penetrates either the CO_2 plume or the exact stratigraphy that the plume now occupies. Quantitative analysis is thus challenging.
- CO_2 properties may change rapidly for small changes in pressure or temperature, especially close to the critical point.
- Velocity maps as of the 2010 seismic data give a guideline on the expected Vp drop due to CO_2 pore filling.
- Chadwick et al. (FB 34, 2016) mention that Gassmann fluid substitution suggests a Vp drop from 2050 m/s to 1430 m/s for full CO_2 saturation (this was used in the model).



Top Utsira Fm Vp (2010)

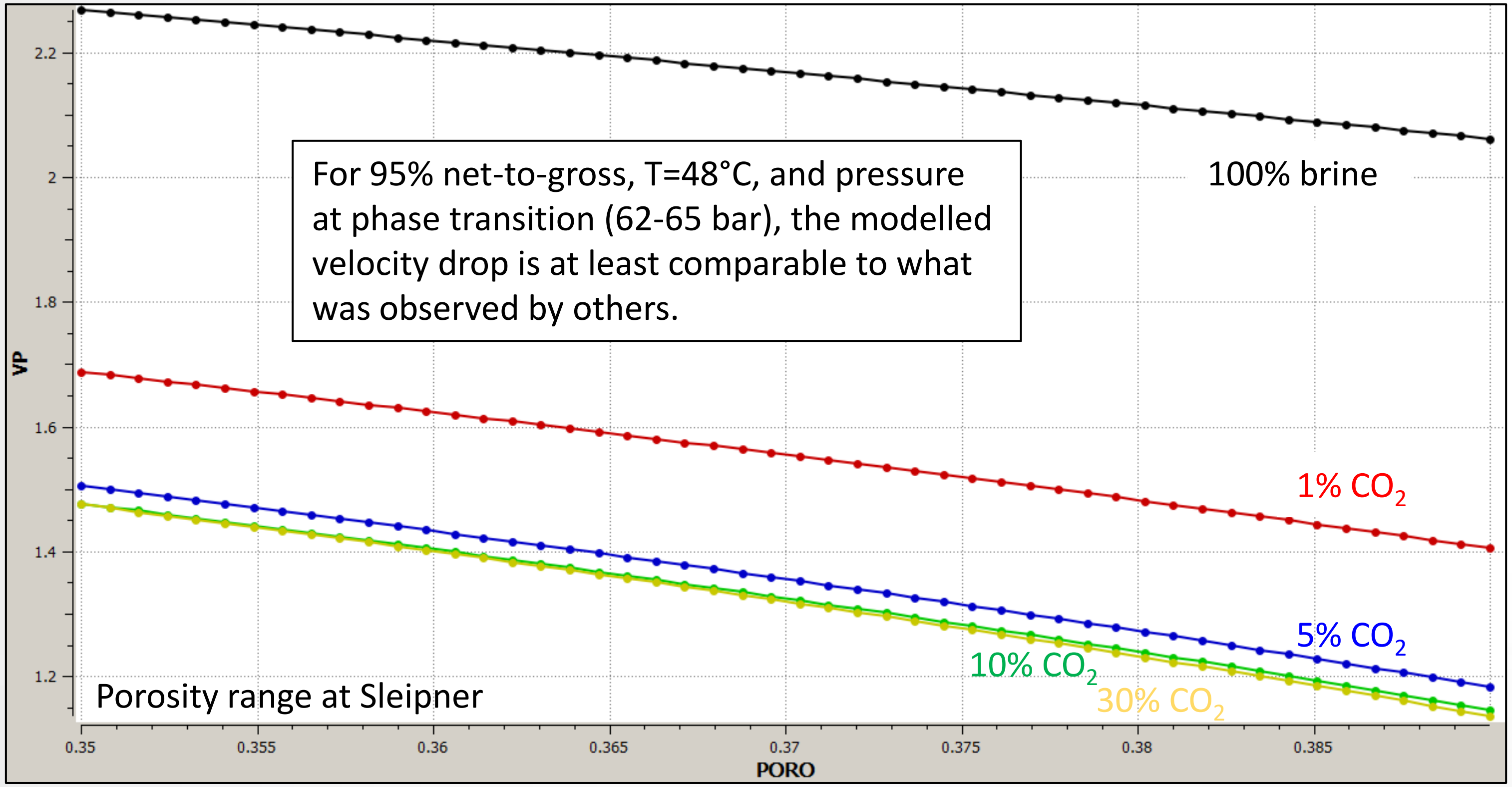
Modelling the effect of CO_2 saturation on Vp

Still, can the Vp drop be modelled?

Exactly? Probably not, at least not easily. To fit the purpose? Probably yes, if some (site specific) assumptions can be used:

- The focus is on Vp only. Vs and density will vary as well, but the first order effect is assumed to be the reduced Vp.
- Temperature changes are ignored (even though not true, as the CO_2 is cooling in the formation.)
- Dissolution into the brine, interaction with the rock frame, multi-phase flow, the effect of impurities etc. can be ignored for the first order effect.

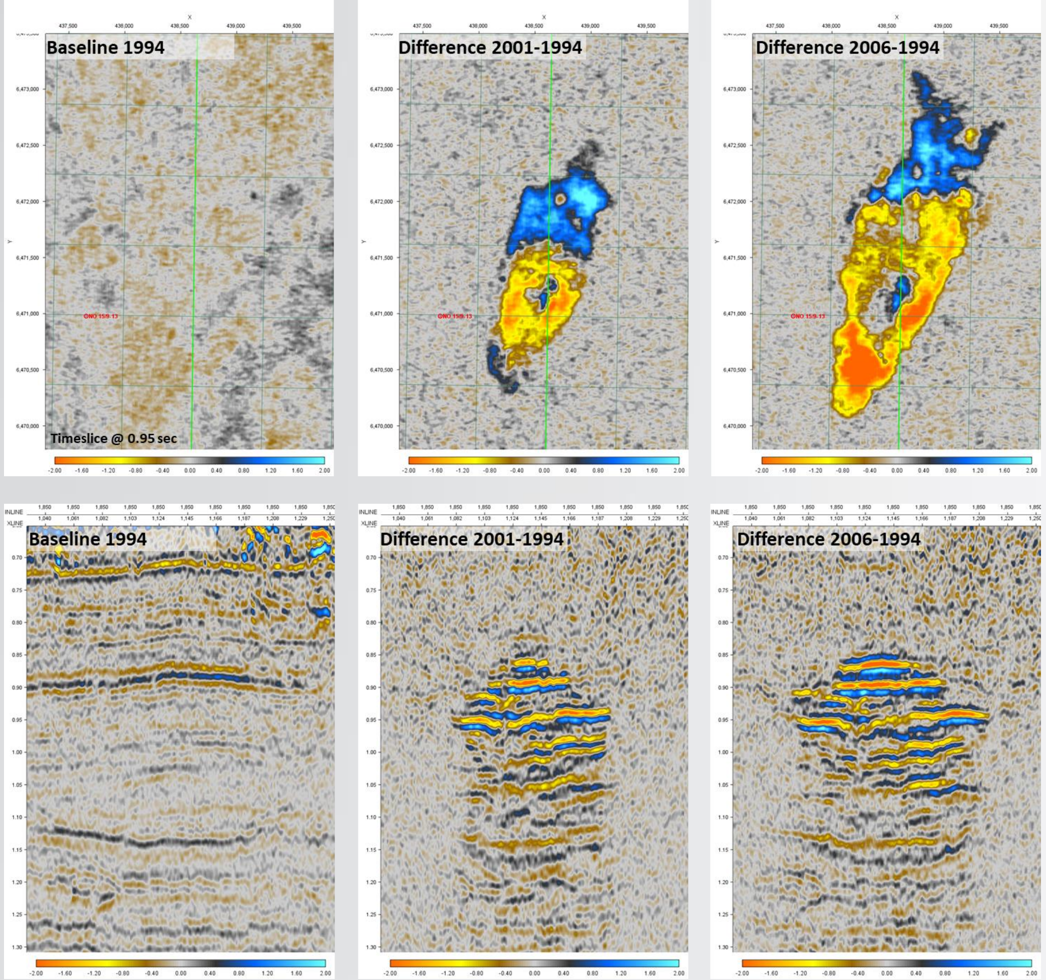
=> Gassmann fluid substitution using CO_2 properties as described by Span and Wagner*.



Why does it fit the purpose? Because the trend is very obvious: even a small amount of CO_2 affects velocity significantly, adding more CO2 has much less effect**. Absolute numbers vary strongly with input parameters and the decrease may be much slower than shown for this example, but representing CO_2 saturation in a "binary" way (fully saturated or nothing) by a velocity drop as observed in the field may be fully sufficient for a seismic feasibility study.

*Journal of Physical and Chemical reference data 25, 1996 **Lumley, ASEG Extended Abstracts, 2010; Lubrano-Lavadera at al., Energy Procedia 114, 2017

Seismic observations at the Sleipner aquifer



Data source: https://co2datashare.org/organization

- Injected CO_2 generates significant amplitude changes in seismic data
- The higher the compressibility of the reservoir (unconsolidated sand at Sleipner) and the larger the property difference between the fluids of interest (e.g., brine and CO_2), the larger is the expected 4D effect.

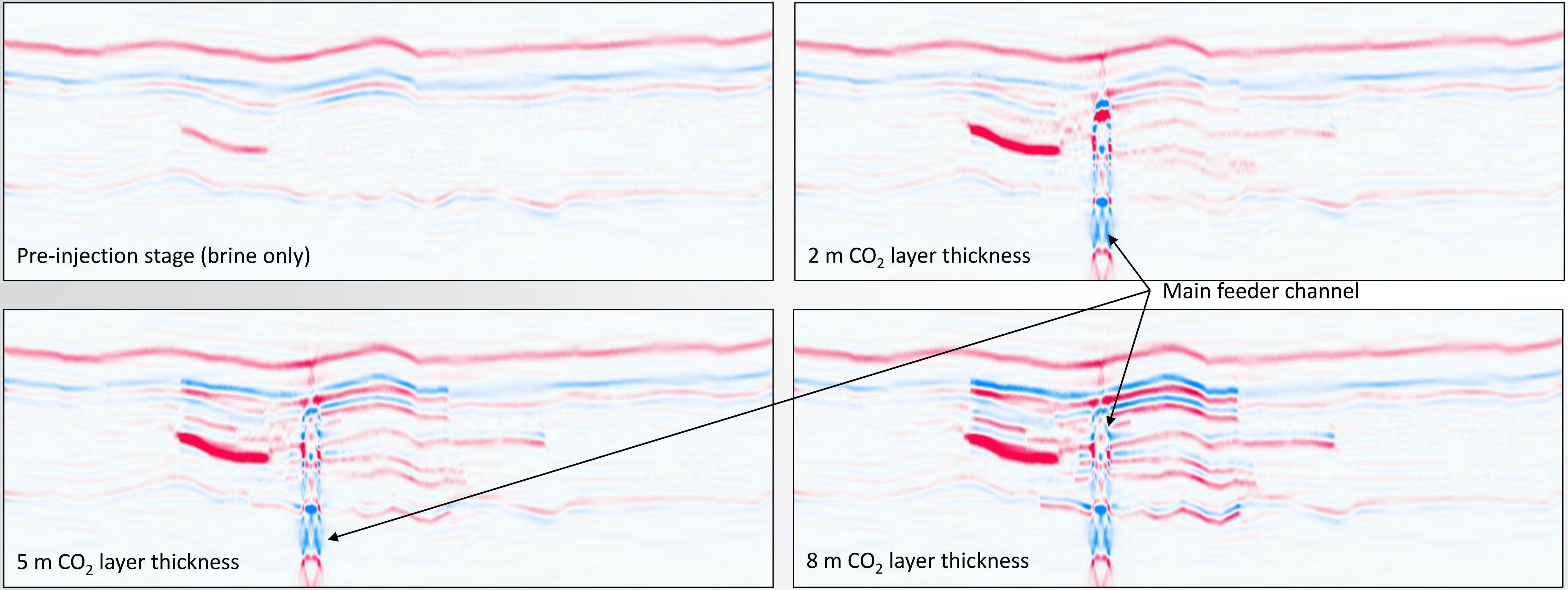
Challenges include:

- Difficult to estimate saturation from seismic data
- Difficult to discriminate between saturation and pressure effects from seismic data
- Repeated 3D surveys need to cover large areas but still provide sufficient resolution and sensitivity to changes, i.e., they are cost intense.

Seismic modelling can help optimizing surveys in a target oriented way.

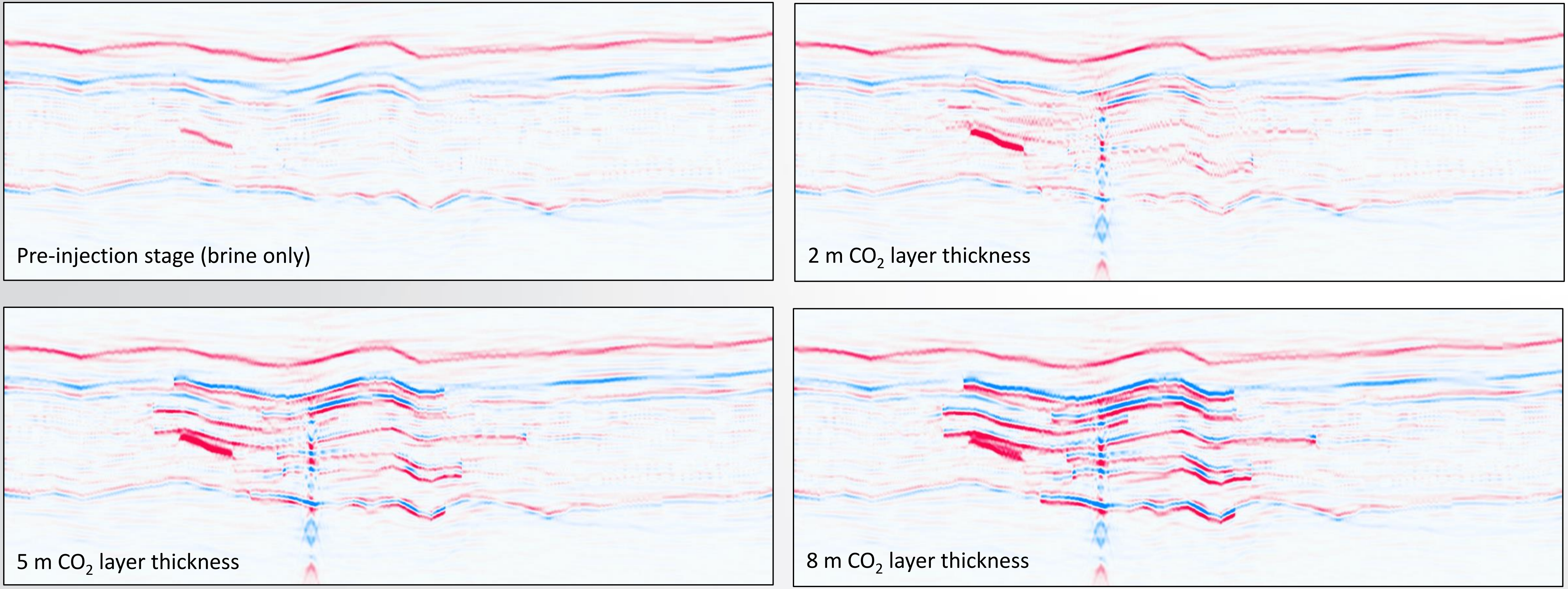
NORSAR fast-track PSDM simulation

Simulation for **30 Hz** wavelet (4D seismic interpretation). Target box width: 5 km. Target box height: 0.45 km.

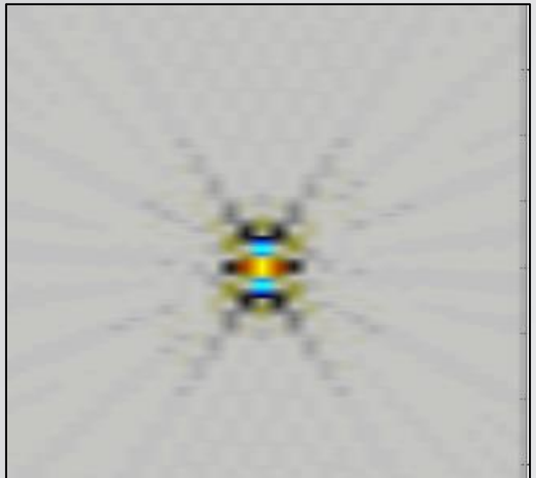


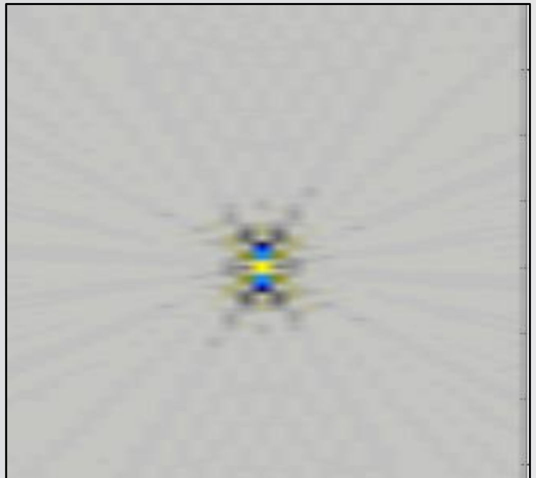
NORSAR fast-track PSDM simulation

Simulation for **60 Hz** wavelet (best imaging). Target box width: 5 km. Target box height: 0.45 km.



NORSAR fast-track PSDM simulation


Point-spread function 30 Hz


Point-spread function 60 Hz

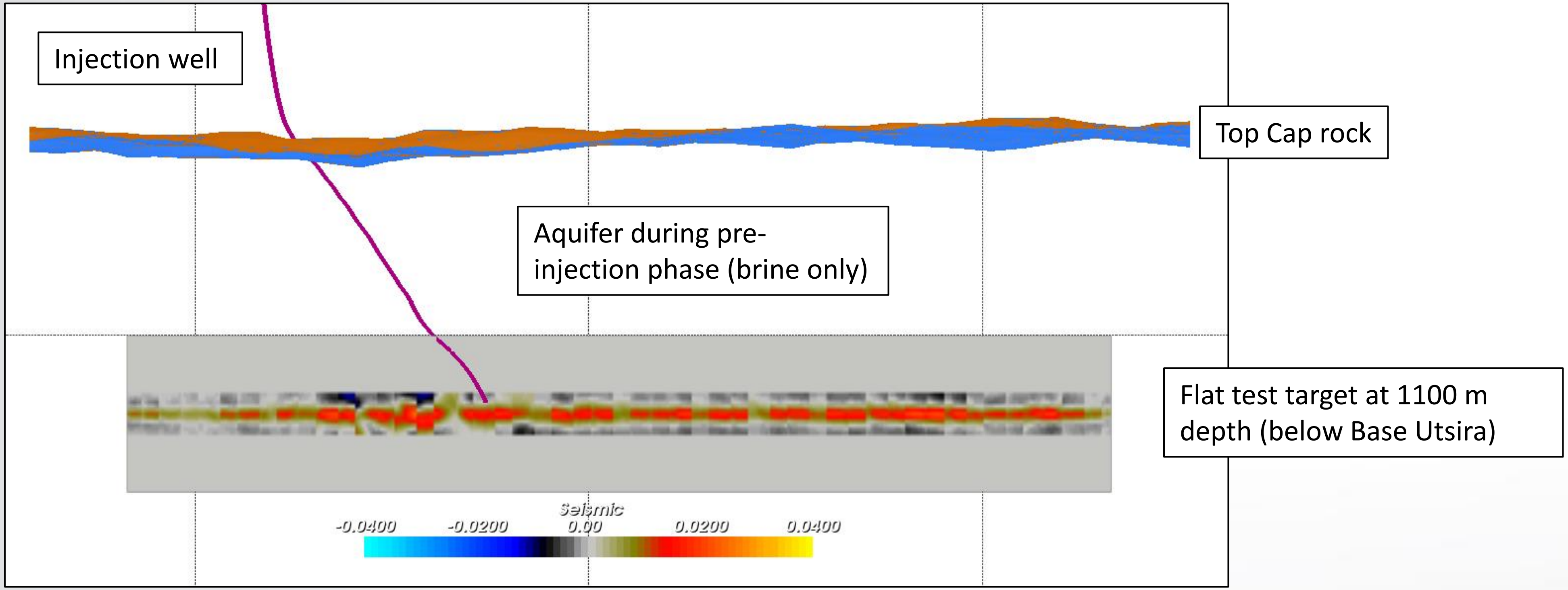
Fast-track PSDM simulation shows similar effects as observed in field data:

- During the pre-injection stage, inter-sand shales were detected but not sufficiently resolved to be continuously interpreted.
- Once CO_2 is accumulating underneath, intra-sand shales become visible, thereby indicating the extent of the CO_2 "plume".
- Amplitudes increase with the thickness of the CO_2 "layer". In the field, CO_2 layer thickness varies laterally according to the regional topography.
- The imaging effect is due to the increased reflectivity as caused by the velocity drop of CO_2 saturated sands, likely in combination with tuning effects.

As a side-effect of the fast-track PSDM simulation, point-spread functions are generated, depending on survey, overburden model, and wavelet frequency. Point-spread functions are in depth domain and thus provide a direct measure of both lateral and vertical resolution. They could be used to estimate the resolving power of seismic images at given target points, required for detecting faults and fractures that may develop into leakage zones.

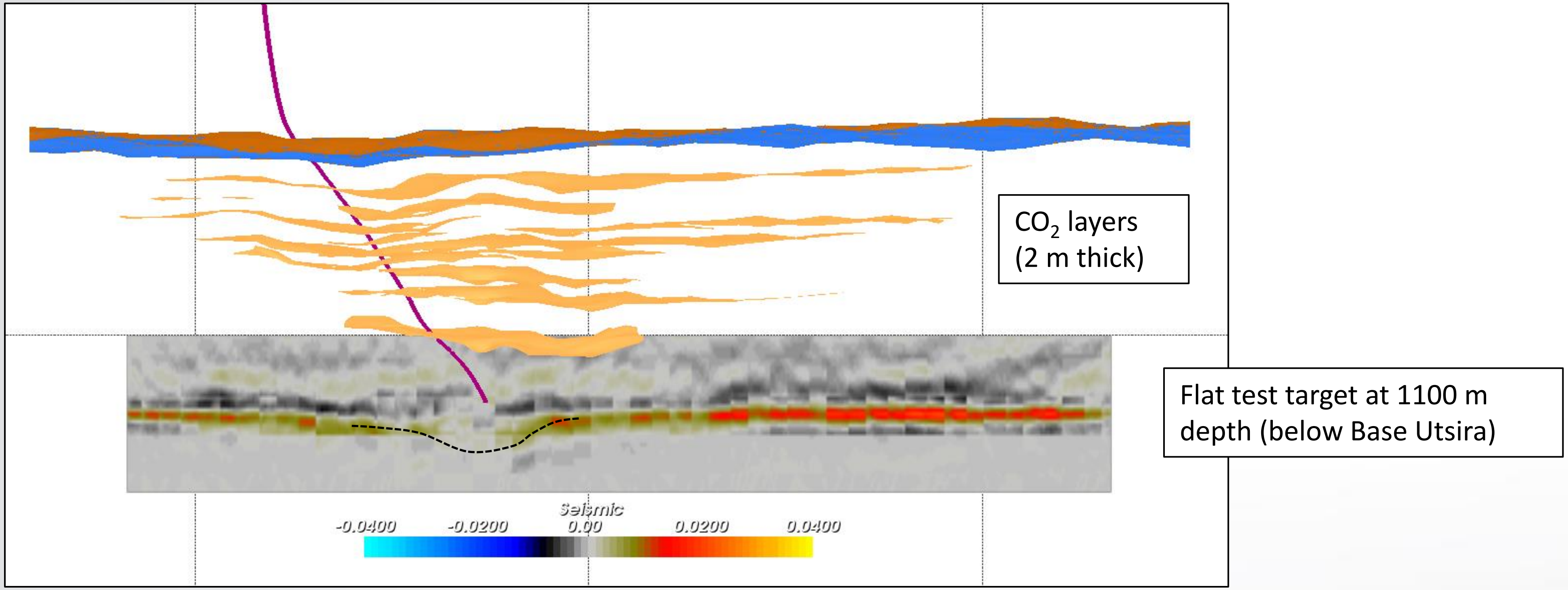
PSF display box size: 400 m x 400 m.

Kirchhoff modelling: pull-down effect underneath CO_2 layers



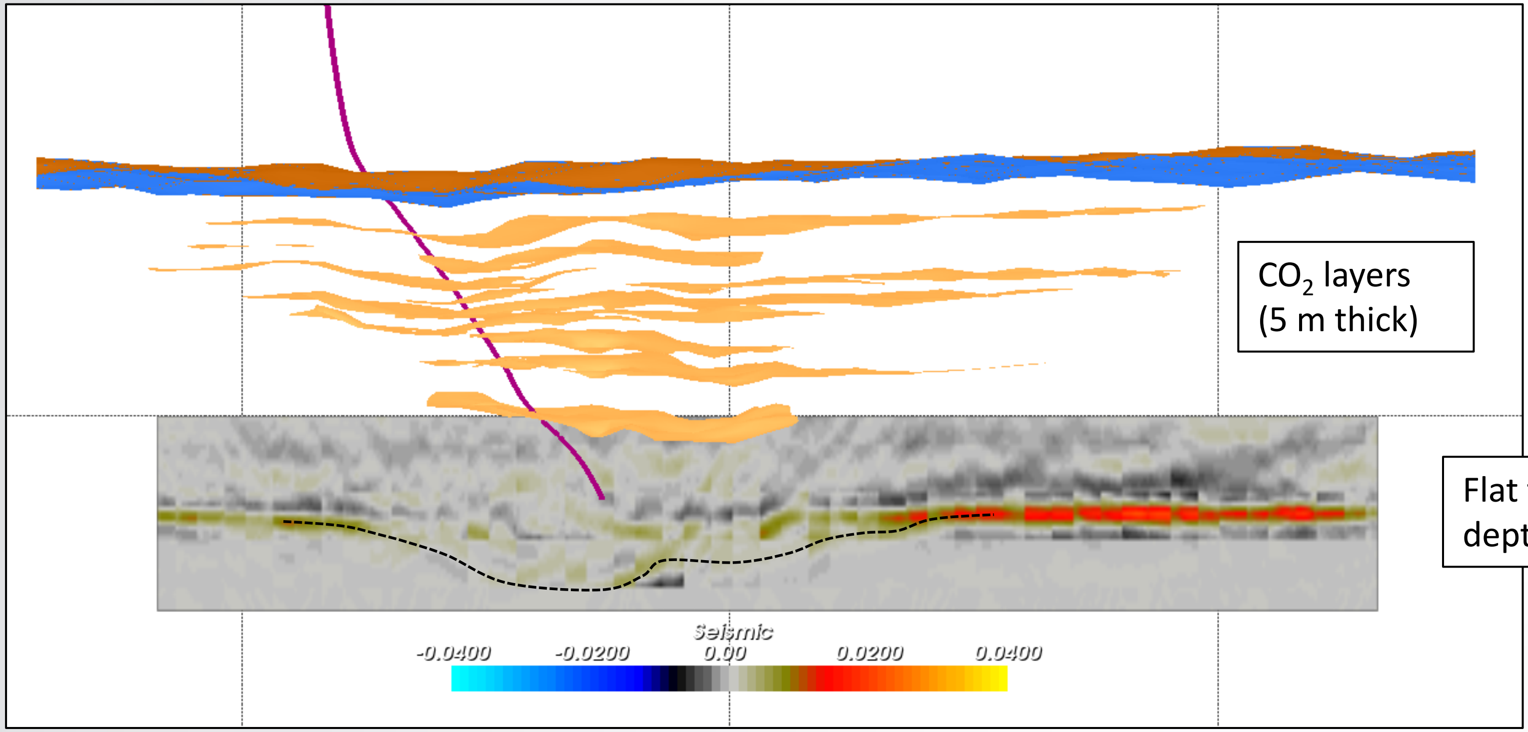
Kirchhoff modelling and target migration reproduce the flat reference layer if using the same velocity field for pre-stack data and migration. The velocity field as used for generating pre-stack data is considered as “correct” (simulating shot gathers as in the field).

Kirchhoff modelling: pull-down effect underneath CO_2 layers



Now Kirchhoff pre-stack data were generated for CO_2 layers of 2 m thickness. Migration was done for the pre-injection velocity field. As migration velocity is too large if CO2 is ignored, there is a slight pull-down effect underneath.

Kirchhoff modelling: pull-down effect underneath CO_2 layers



Flat test target at 1100 m depth (below Base Utsira)

The effect becomes more pronounced if CO_2 layers of 5 m thickness are assumed. Pull-down effects due to CO_2 saturation are also observed in field data. The target box is 5 km x 0.2 km large.

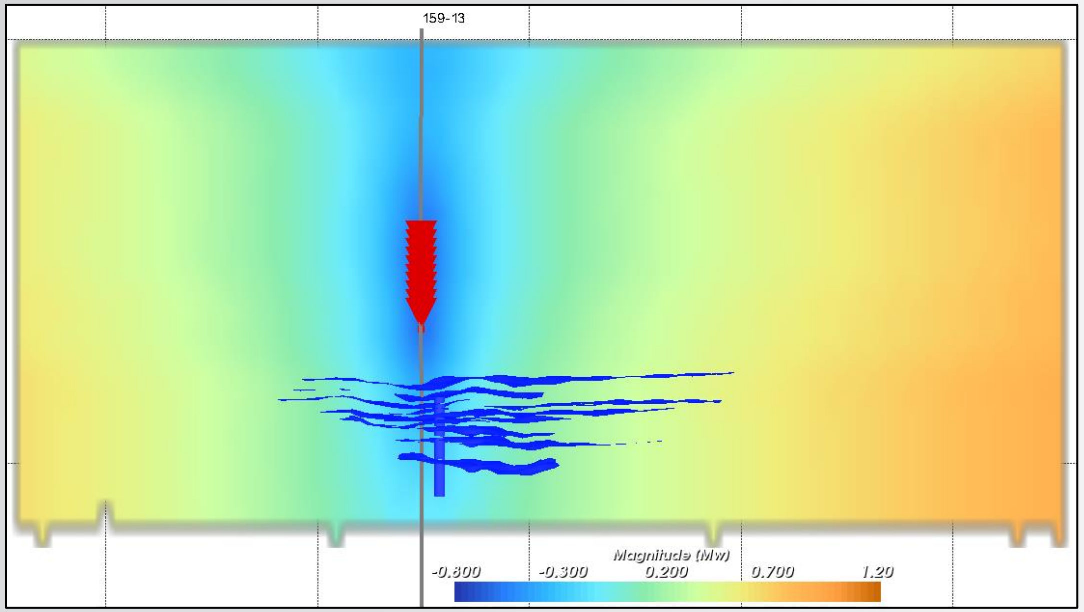
Microseismic monitoring:

Motivation:

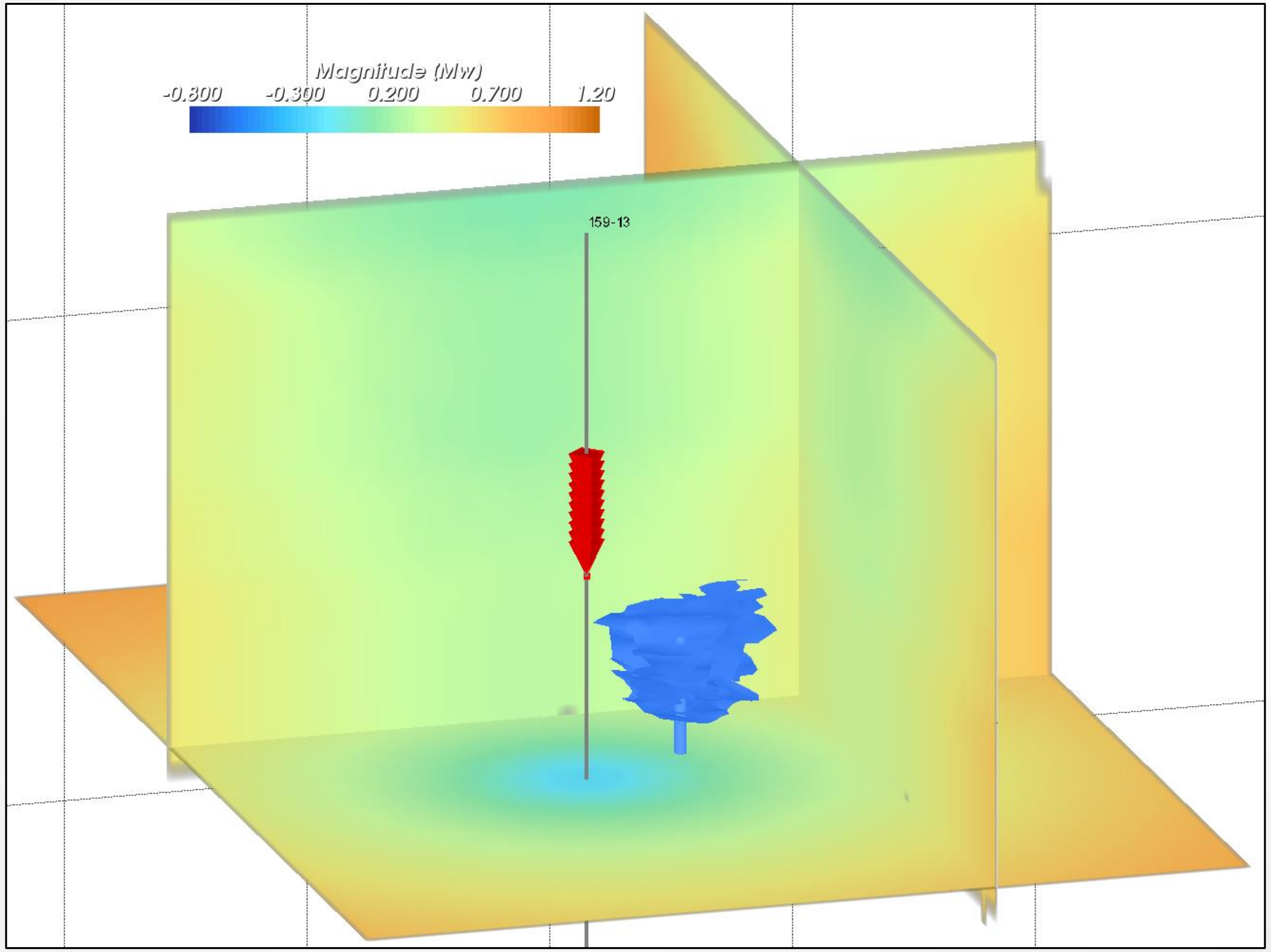
- The extent of the pressure perturbation (due to pushing away pore water) is much larger than the CO_2 plume extension. The pressure front can interact with far faults and areas of weakness, triggering microseismic events. Detecting the pressure front may provide an indication of how and where the injected CO_2 will migrate in the future. The change in pore pressure over time also leads to stress change in a larger area than the extent of the pressure perturbation*.
- There may be faults in the area that may be re-activated. One concern is potential leakage through the cap rock, but the key is that rupture along faults can create damage of the infrastructure. As such, microseismic monitoring needs to be part of the local and regional risk assessment**.

* Braim et al., First Break 41, 2023; Rutqvist, Geotech Geol Eng 30, 2012. ** Goertz-Allmann et al., Geophys. J. Int, 2014; Bussat et al, First Break 34, 2016

Microseismic monitoring: Expected detectability



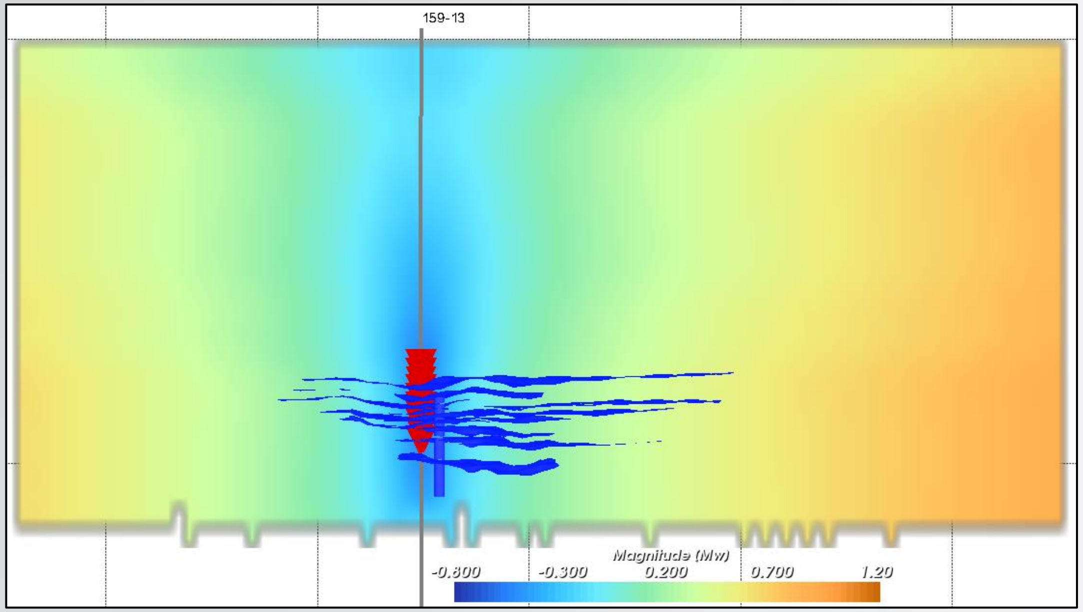
Detectability as 2D slice through well location



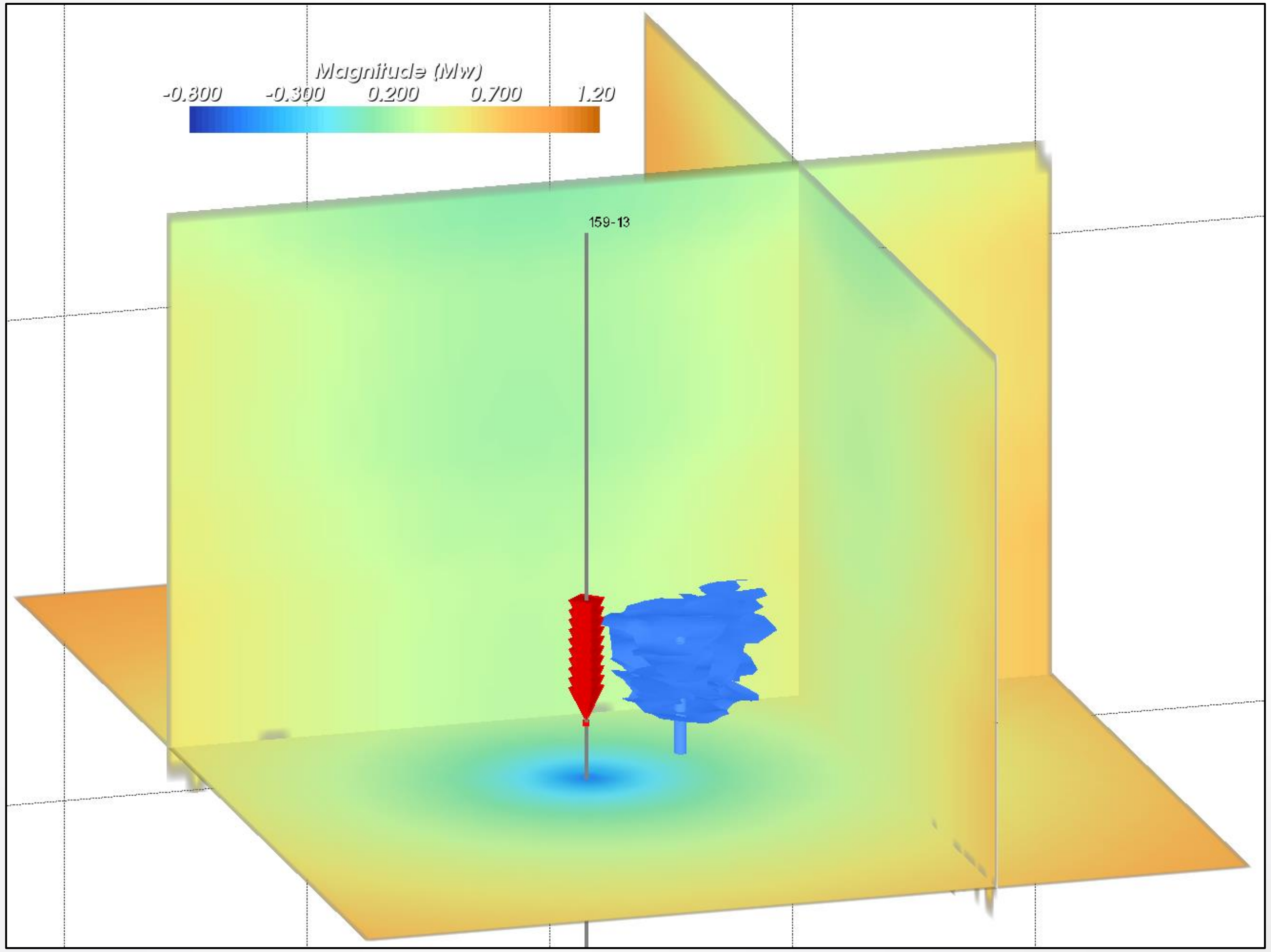
Detectability as 3D cube

Event detection for a sensor string in the well obviously works best in close vicinity to the well. If using classic sensors rather than a DAS cable, it also depends on the depth range of the sensors (next slide).

Microseismic monitoring: Expected detectability



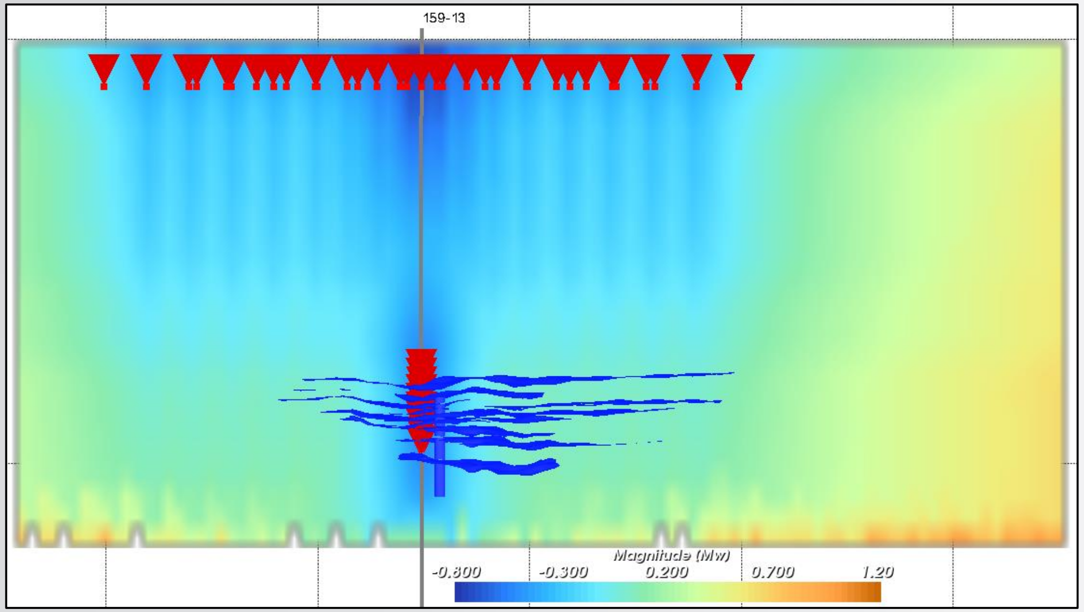
Detectability as 2D slice through well location



Detectability as 3D cube

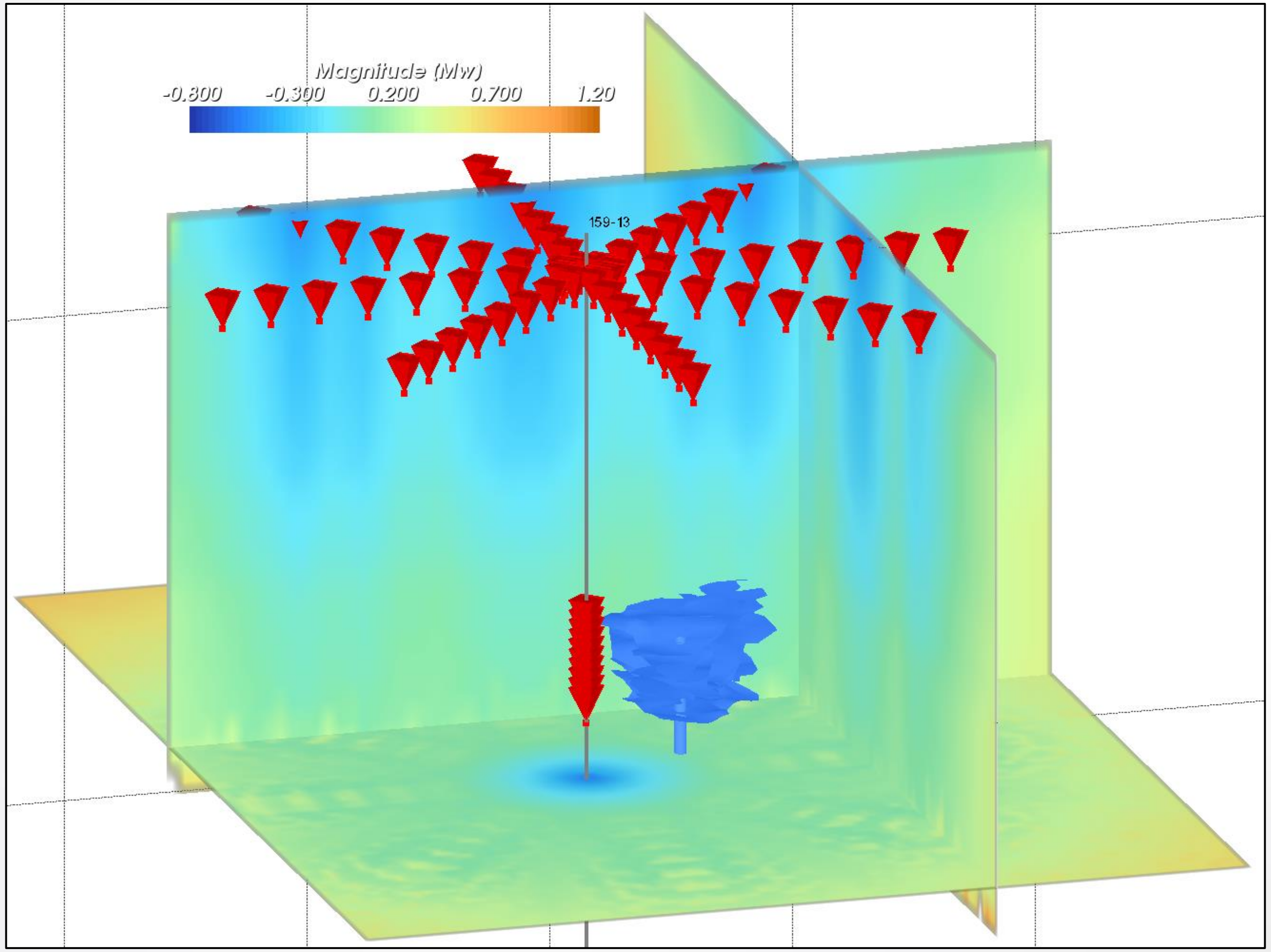
Event detection for a sensor string at the depth level of the storage volume and the feeder channel. Detection can be improved if the sensors in the well are supplemented by a surface grid (next slide).

Microseismic monitoring: Expected detectability



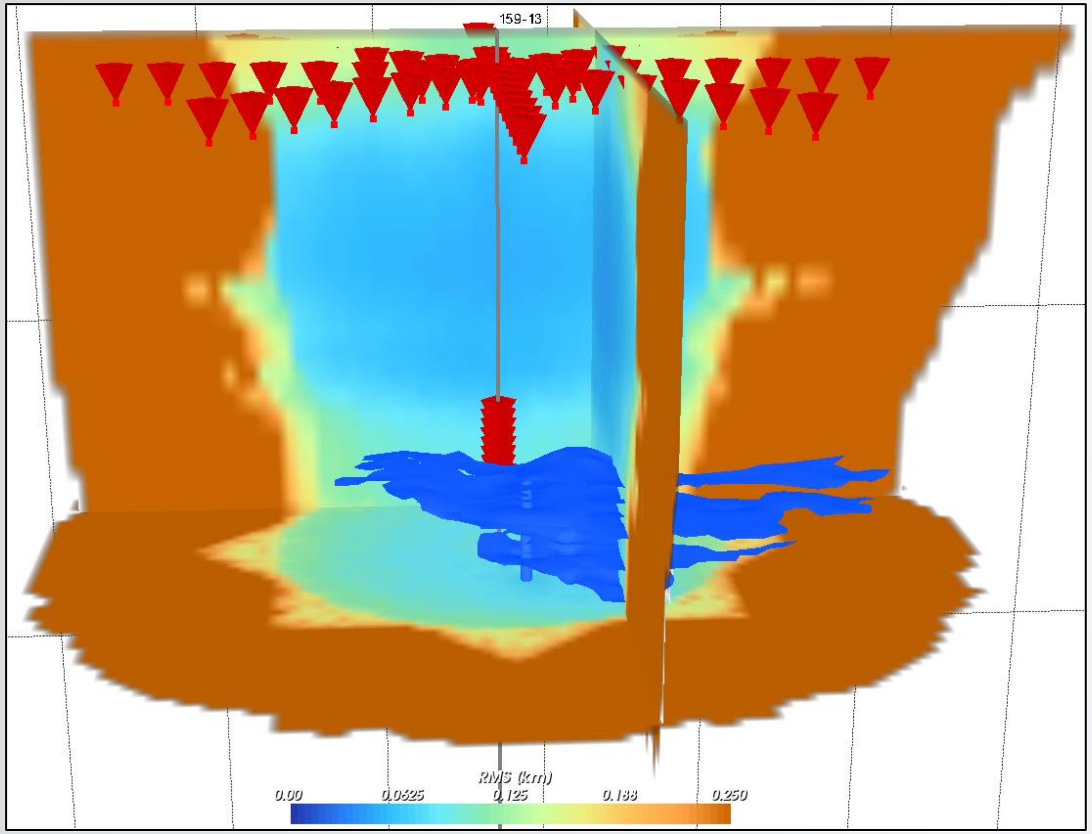
Detectability as 2D slice through well location

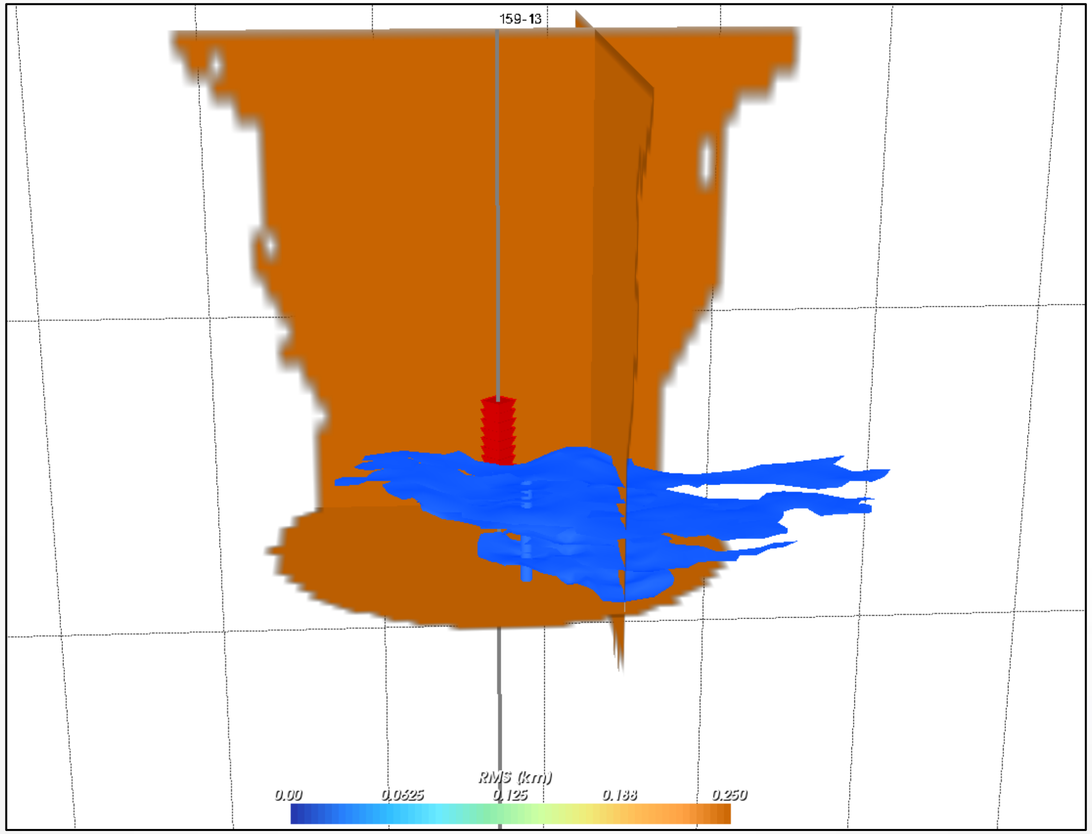
Detectability for combined surface and well sensors, providing improved detectability inside the aquifer and above.



Detectability as 3D cube

Microseismic monitoring: Expected location uncertainty





However, the key advantage of adding surface sensors is much decreased location error, as the sensor string in the well suffers from azimuth errors and the limited survey aperture. Note that even the combined sensor network as used in this example would not be sufficiently large to cover the full expected pressure front...

Conclusion

Carbon Capture and Storage requires monitoring for making sure that CO_2 remains safely contained in the aquifer. One key method is repeated seismic imaging for detecting time-lapse changes within the storage volume or above. Seismic modelling can help to plan and evaluate the respective surveys and may provide support for both seismic processing and interpretation.

Once CO_2 is involved, seismic modelling may need to account for a wide range of different processes that may or may not affect elastic properties. Modelling these in detail may be possible but requires substantial effort and sufficient subsurface information. However, depending on the modelling task at hand, site-specific considerations may allow for simplifications that make seismic feasibility studies highly beneficial.

Recommendations:

$\Rightarrow$ Define appropriate assumptions (simplify while keeping the appropriate focus)

$\Rightarrow$ Use site-specific information for tailoring the approach

$\Rightarrow$ Separate between seismic modelling from geo-mechanical, geo-chemical, and flow model related aspects by, e.g., concentrating on observed elastic property changes

$\Rightarrow$ Exploit the benefits of seismic modelling while keeping the (site-specific) limitations in mind