

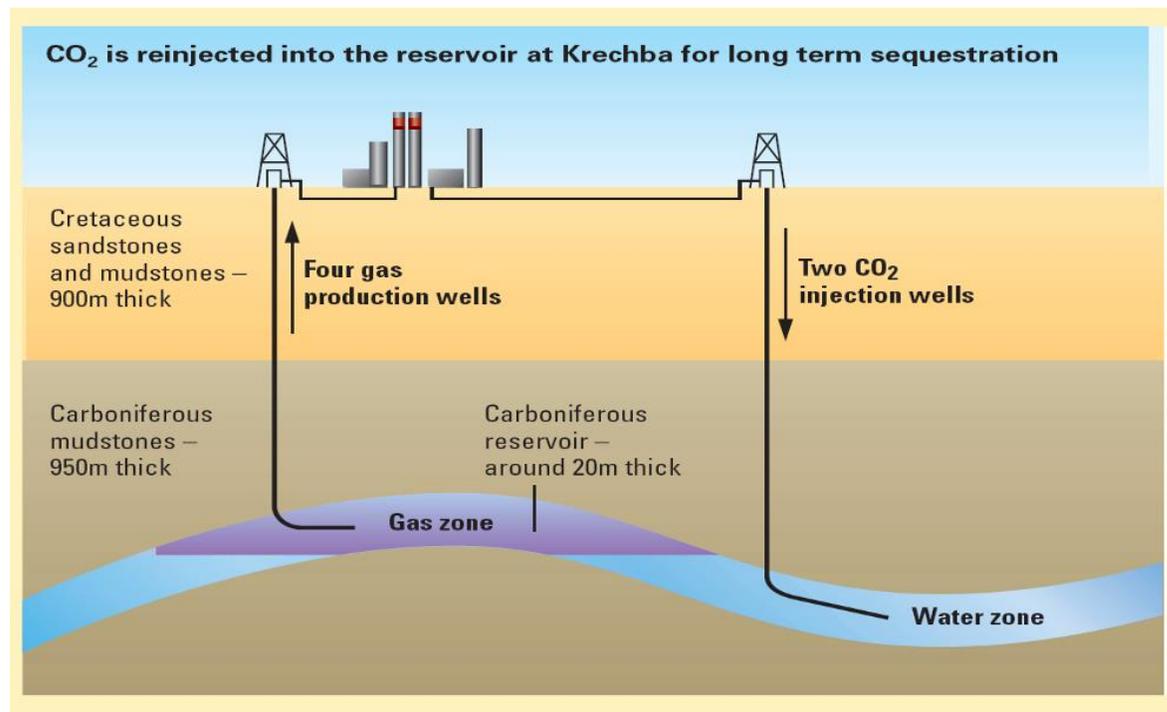


***CO₂ STORAGE MONITORING:
UPFRONT DOCUMENTATION OR REMEDIATION***

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CCUS STUDENT WEEK 2018, Oct. 2018, Golden CO

In Salah gas field, Algeria

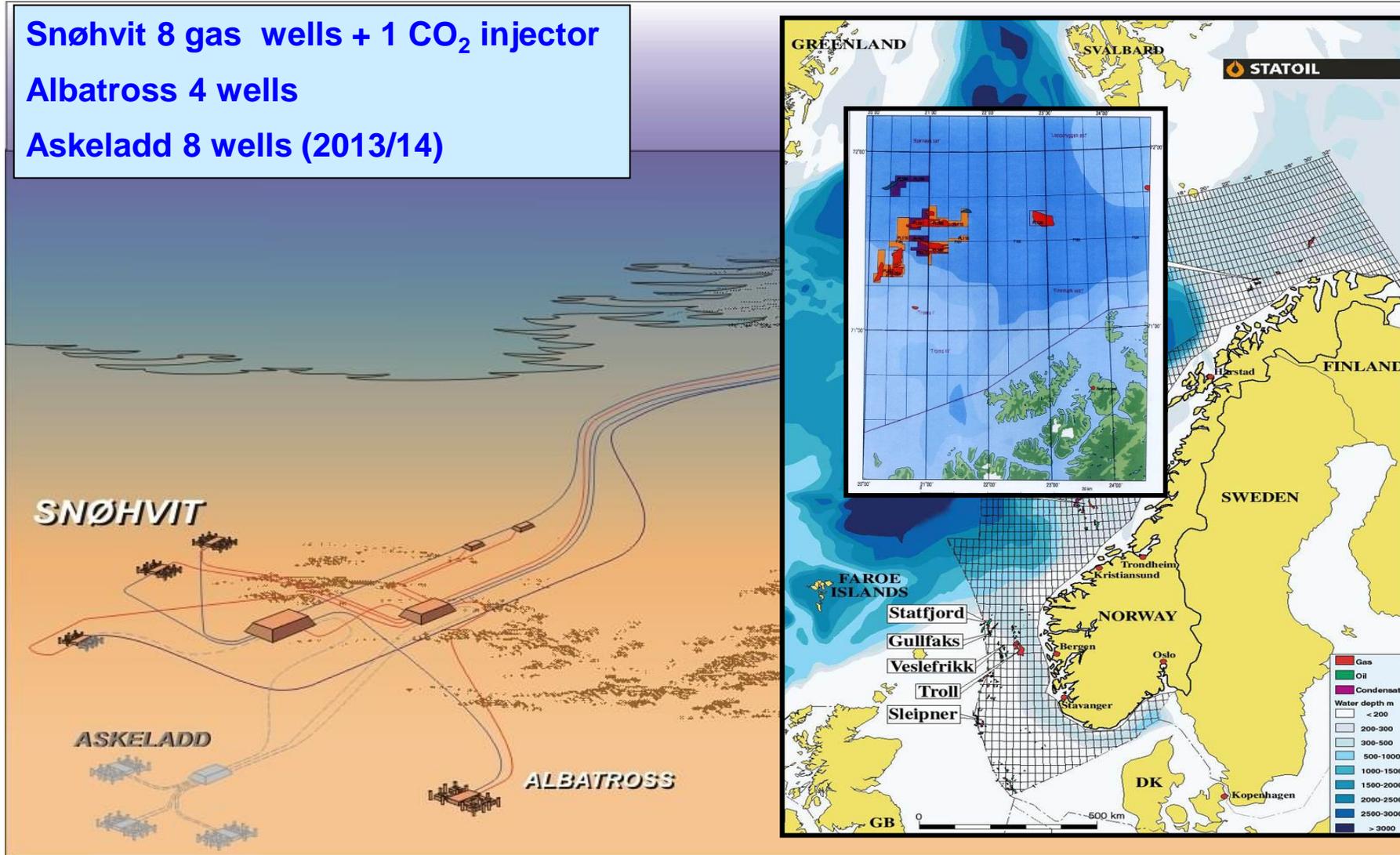


Snøhvit – a subsea development

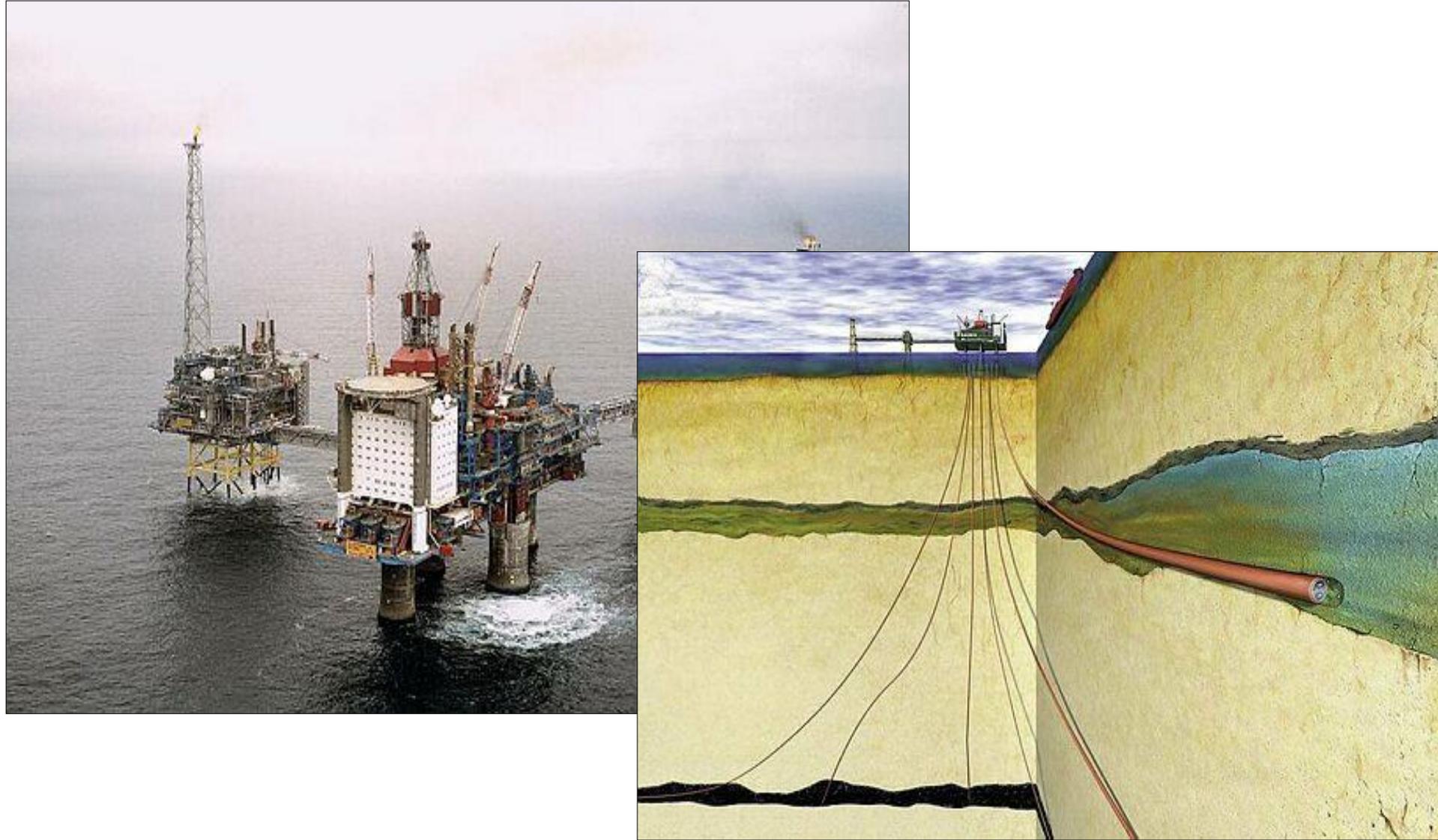
Snøhvit 8 gas wells + 1 CO₂ injector

Albatross 4 wells

Askeladd 8 wells (2013/14)



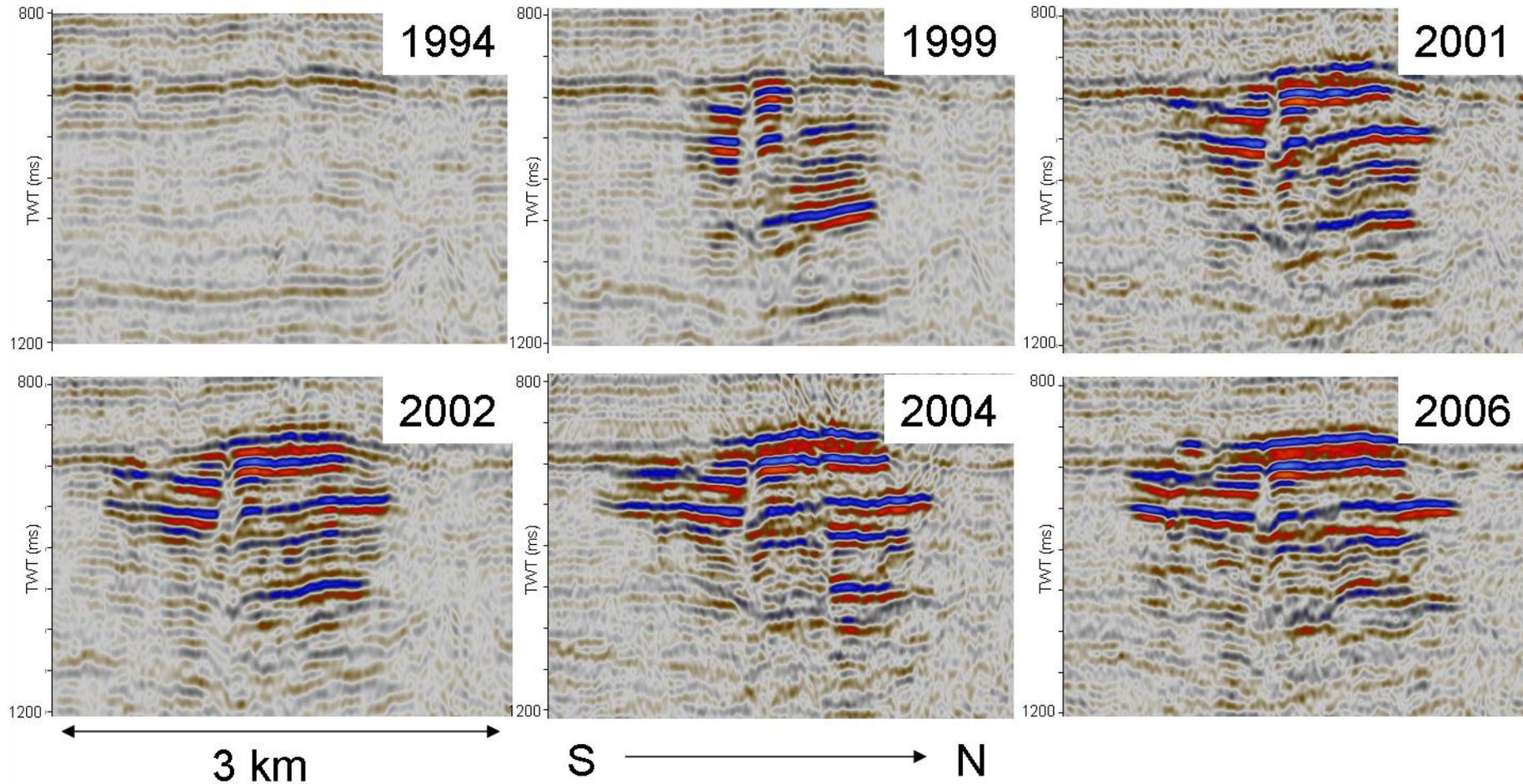
Sleipner, started in 1996, 22 million tonne CO₂ injected



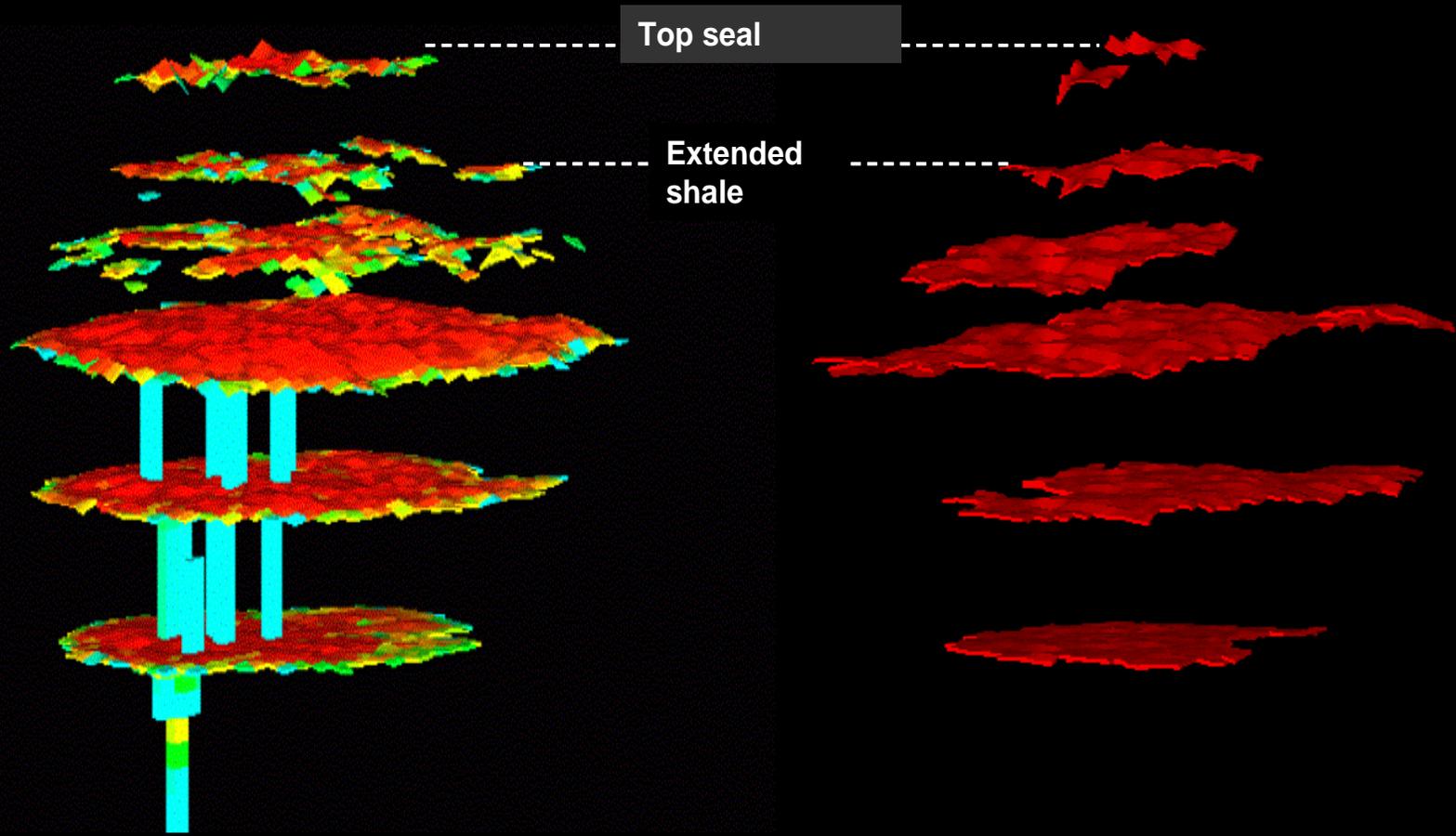
Separating and injecting 1 mill. tonne CO₂ annually
Storing in saline aquifer at 800 -1000 m depth

Sleipner CO₂ injection is carefully monitored by geophysical methods

here: seismic profiles of the CO₂ plume



September 1999, 3 years of injection



Simulated CO₂ saturation

Seismic images

- Can the Risks of CO₂ Escape from Geological Storage Aquifer be predicted before injection?

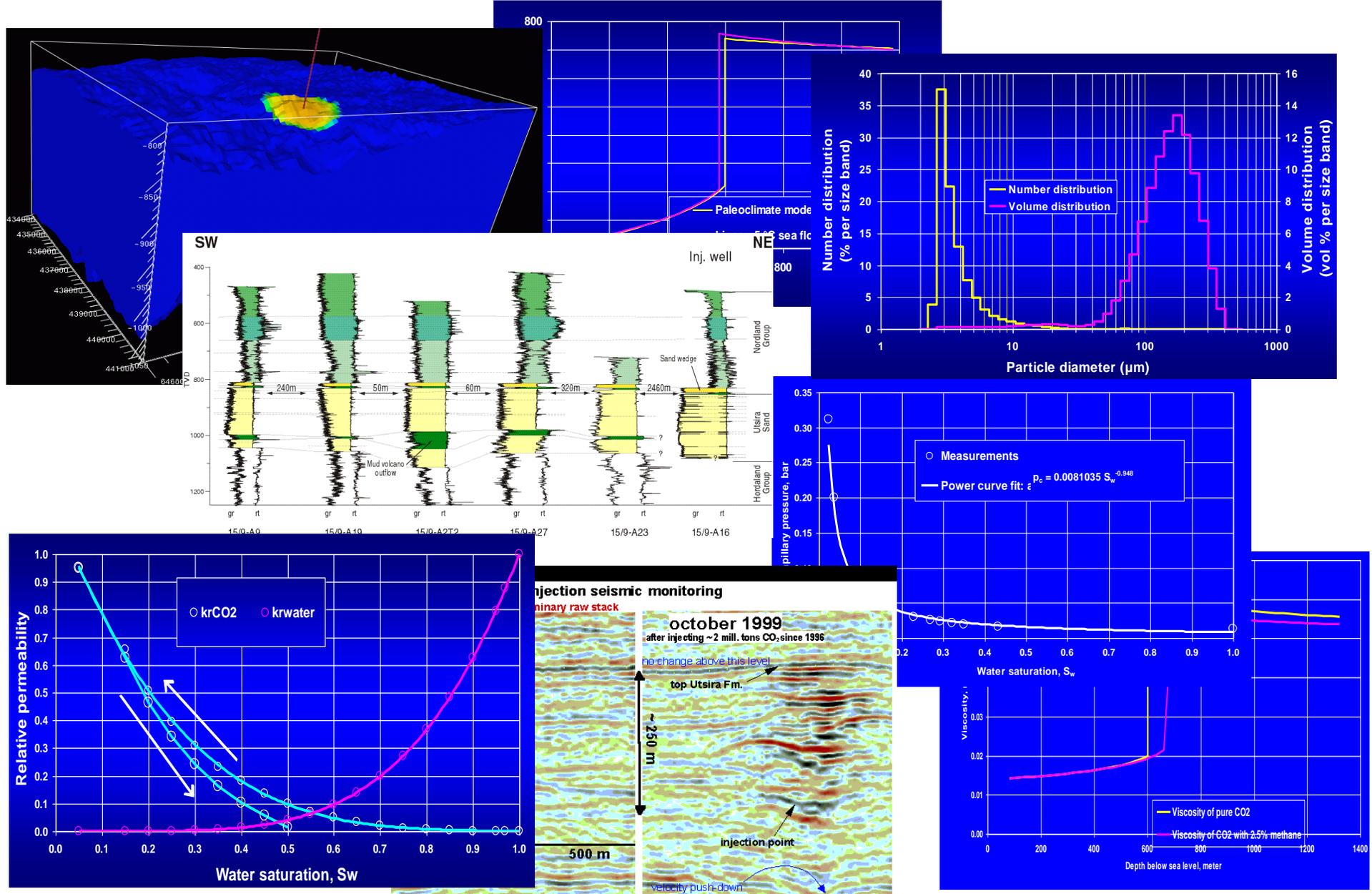
No, it is not possible to predict the risk of escape from aquifers by quantifying the probability of leakage through the capillary seal

GHTH-8, Trondheim, June 21. 2006

Documentation strategy for CO₂ storage

- Qualification of a storage site for CO₂ must be based on a comprehensive documentation of the geology that may retain CO₂ for at least 5 000 to 10 000 years
- This documentation must not only justify that the capillary seal itself is tight, but that there are no conducting faults or spill points that can be reached and that any CO₂ exposed well will be sufficiently tight. Also thorough documentation of the overburden will be needed
- Based on all geological data the probability for leakage must be estimated
- Consensus on this estimate must be communicated and agreed upon with the regulating authorities
- **Even the most comprehensive studies of the overlaying geology will not provide a reliable estimate of the probability of leakage over a certain period of time**

Reservoir behaviour can be predicted with simulation tools based on reservoir information from different sources, this is however not sufficient to predict the retention of CO₂



Remediation strategy for CO₂ storage: The Concept

- The storage performance has to be determined by carefully monitoring the performance of the storage (nothing new)
- There must exist a remediation plan for each project that has to be actuated if the performance deviates from the design criteria, *i.e.* if the updated model indicates excessive leakage
- The measures in such a plan will depend on the seriousness of the observed deviation and when the deviation is detected and can vary from:
 - simply stop the injection and continue the injection somewhere else to
 - the ultimate corrective measure: produce the injected CO₂ from the storage site and inject it into an alternative site. The cost of this operation will typically be small compared to the penalty due to CO₂ tax or quota prices

Remediation strategy for CO₂ storage: Monitoring

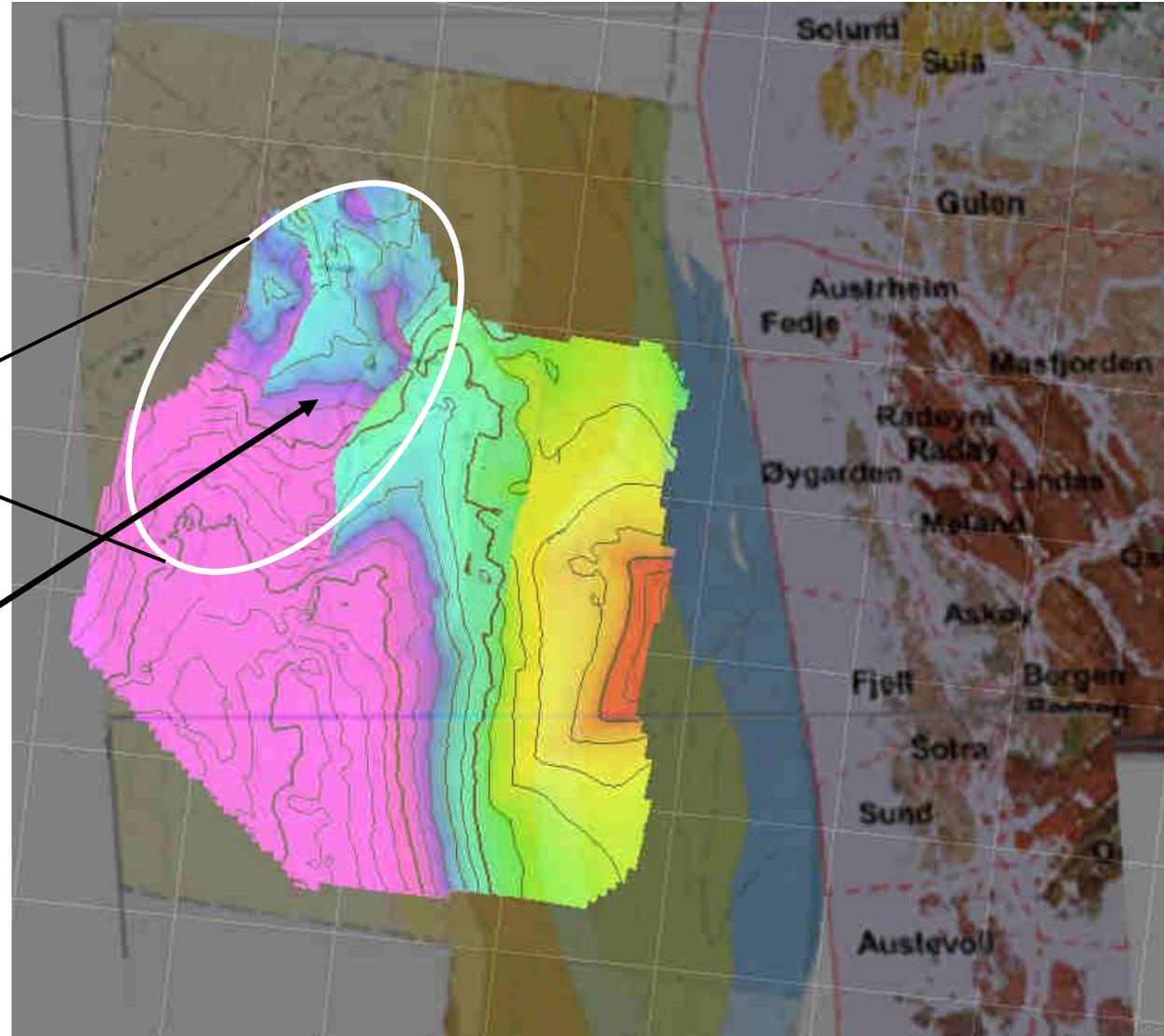
- Monitoring of injected CO₂ with emphasis on penetration through the capillary seal
- The monitoring techniques must be sufficiently sensitive so the appropriate corrective action can be launched sufficiently early to avoid escape. This represents a challenge on how early deviations can be detected by various techniques period of time
- The monitoring should be continued for a sufficiently long
 - In the long run some cheaper methods may be sufficient *e.g.* gravimetry which is relay sensitive to detect small changes the distribution of a buoyant fluid as demonstrated by Scott, Eiken and Thibeau

Remediation strategy: Consequences for site selection

- More aquifer sites may be considered as candidates for storage and less documentation on the capillary seal may be needed
- Site must be selected so that the ultimate remediation measure is present (re-production and re-injection in an alternative site)

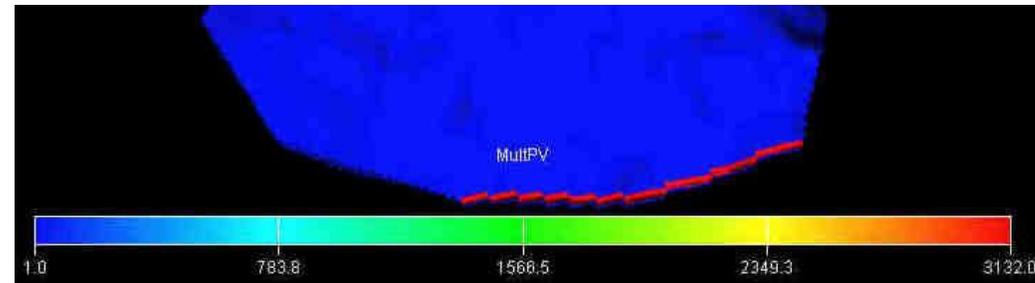
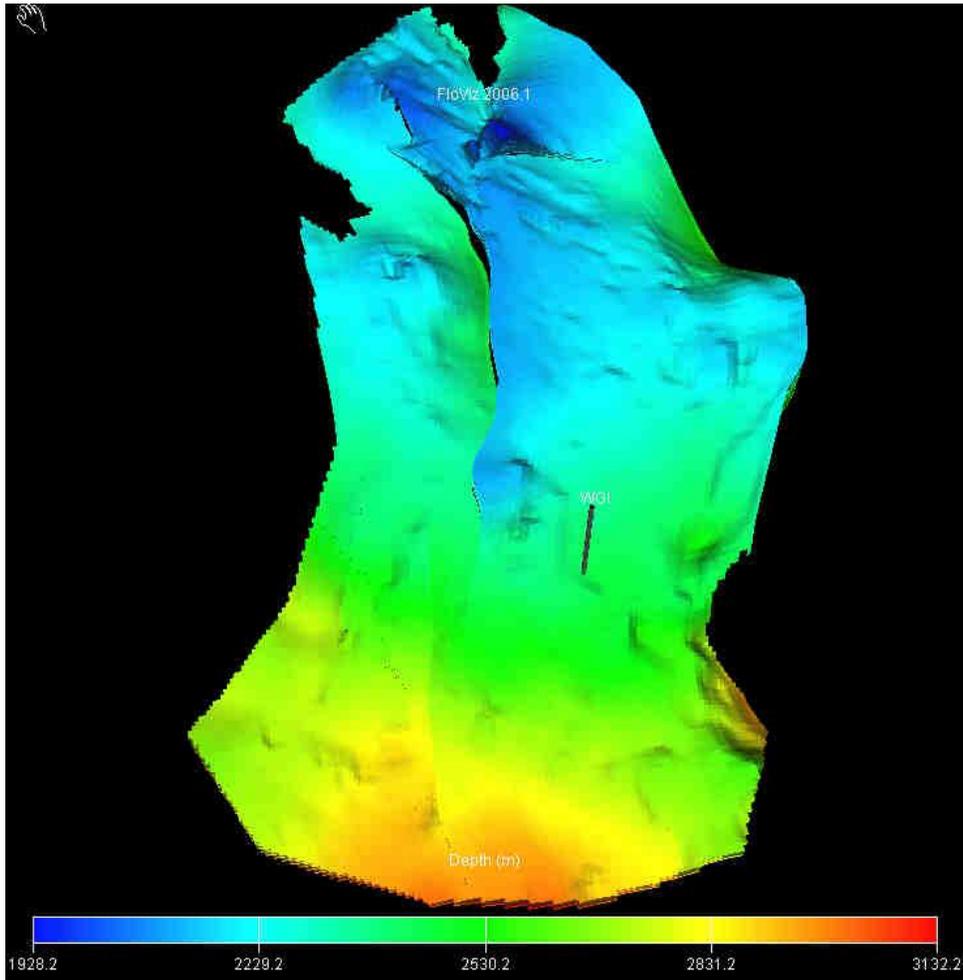
Example on flexible storage strategy: Johansen formation for Mognstad CO₂

- Depth:
~1500-2500 m
- Simulation model
- Injection point



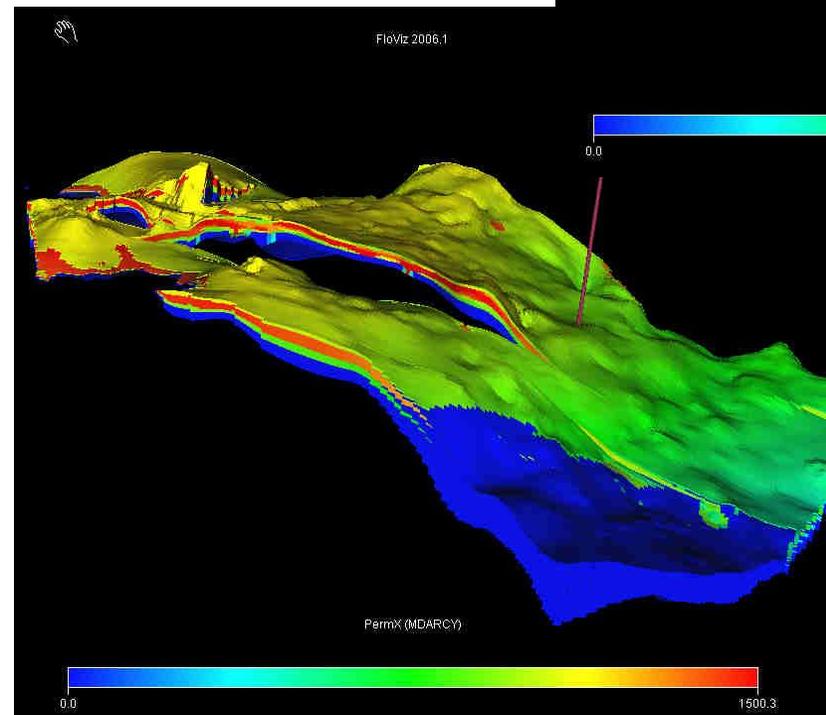
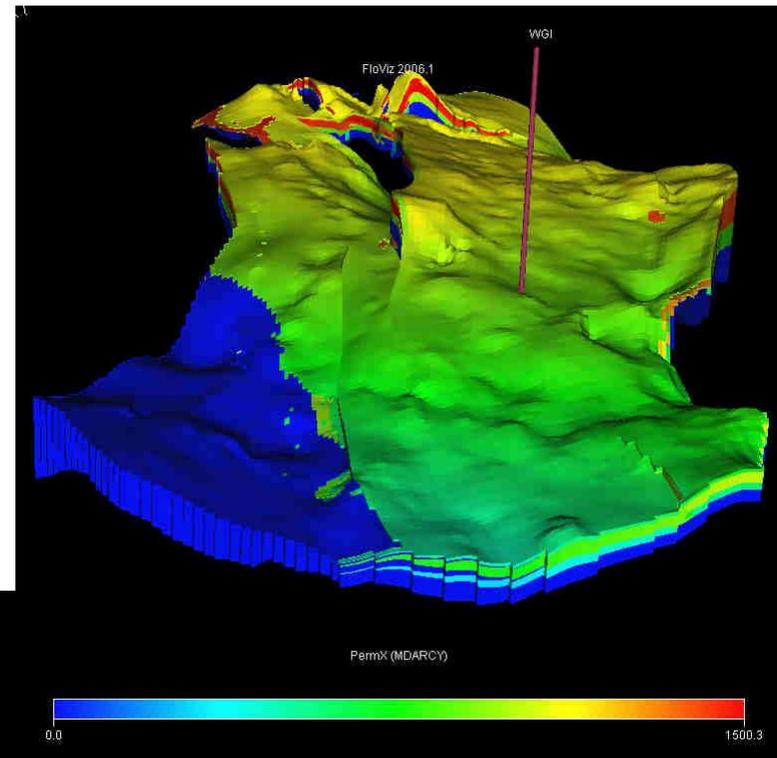
Simulation model

- ~250000 grid blocks (200x200 m)
- Figure showing depth
- No flow boundaries
- Increase size of model (aquifer) by increasing pore volume in boundary grid blocks to the south



Layering

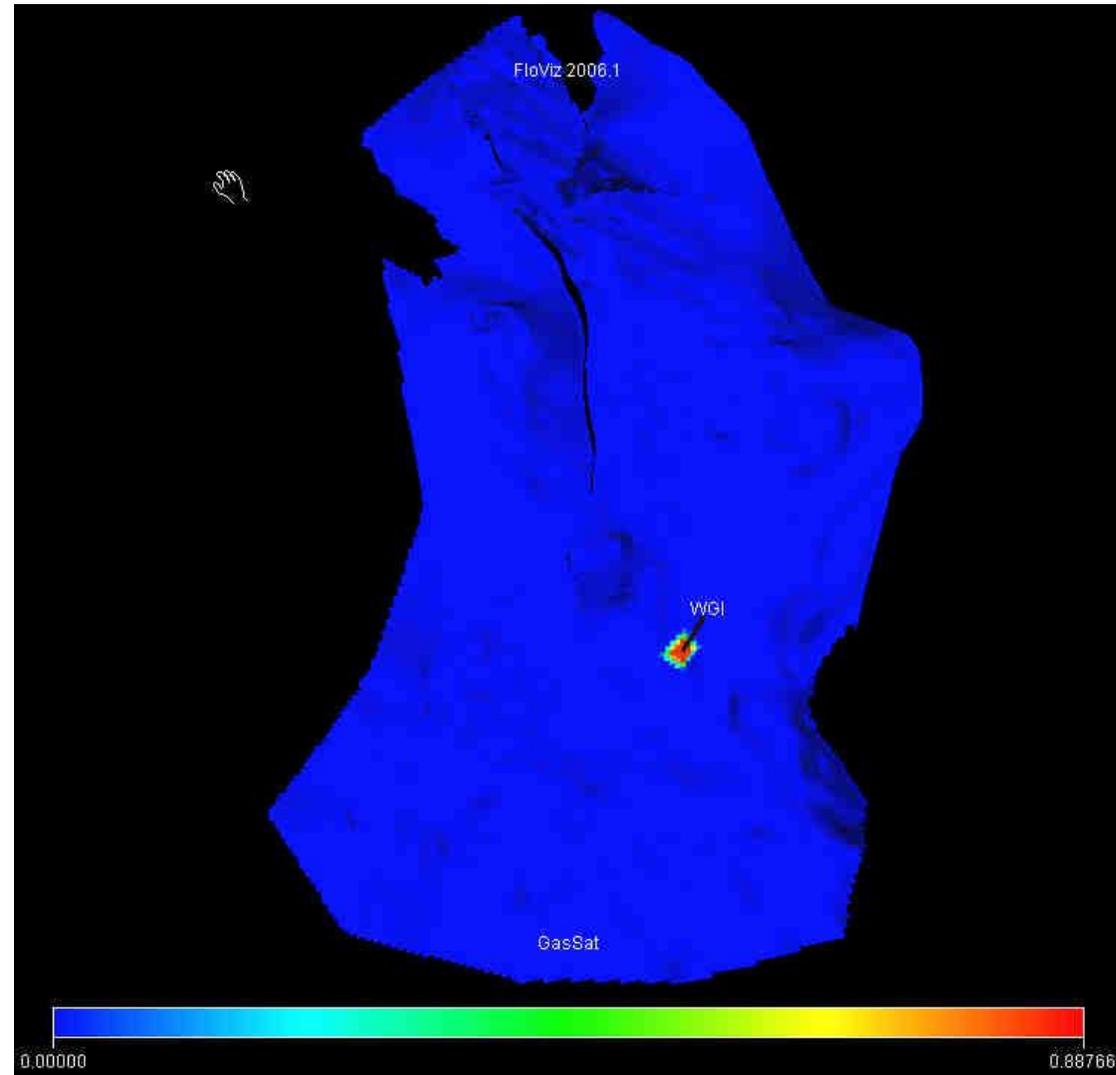
- Sand and shale layers



Permeability

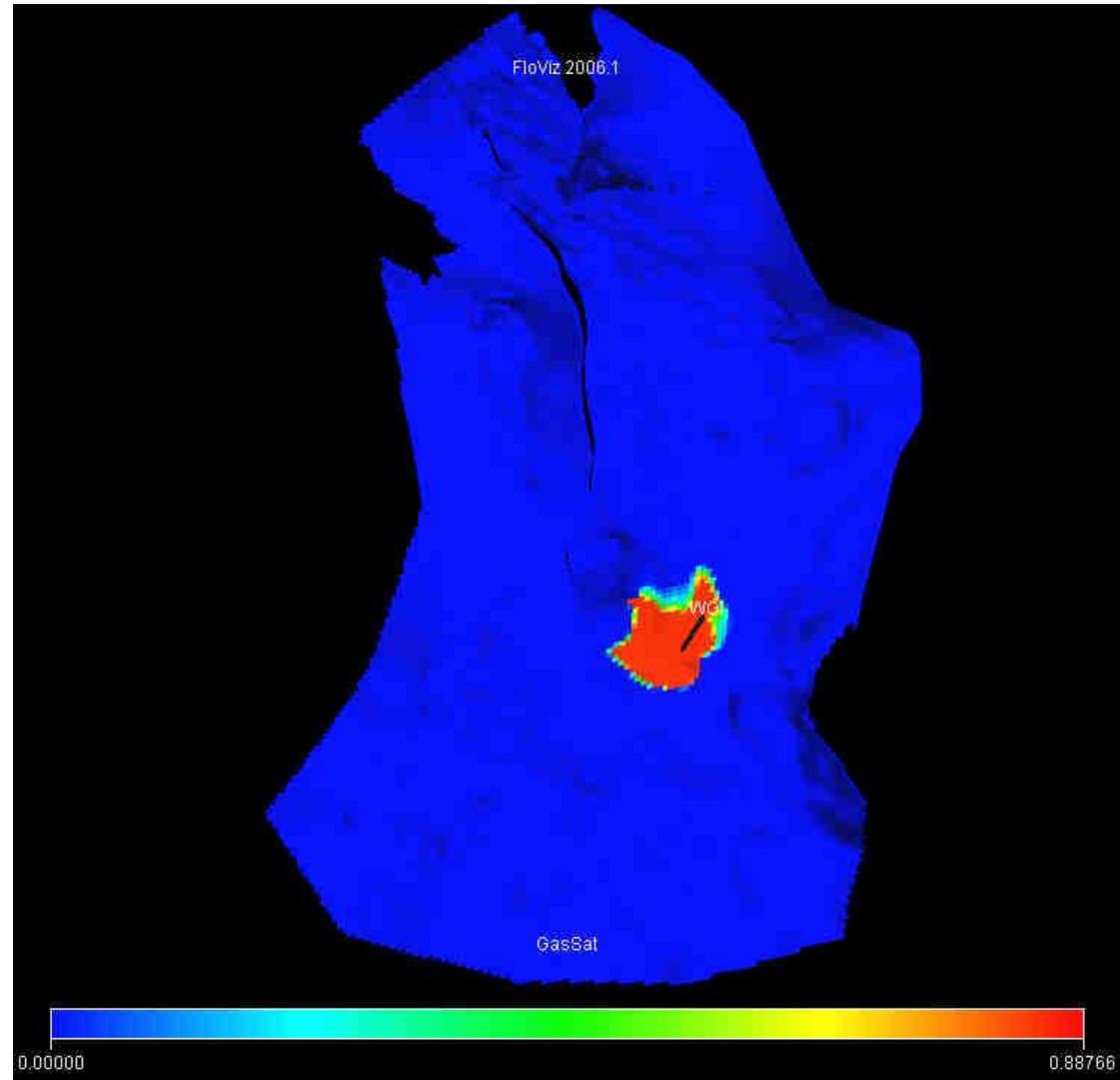
Simulation results

- Distribution of CO₂
- Year: 2020
(6 months after start of injection)



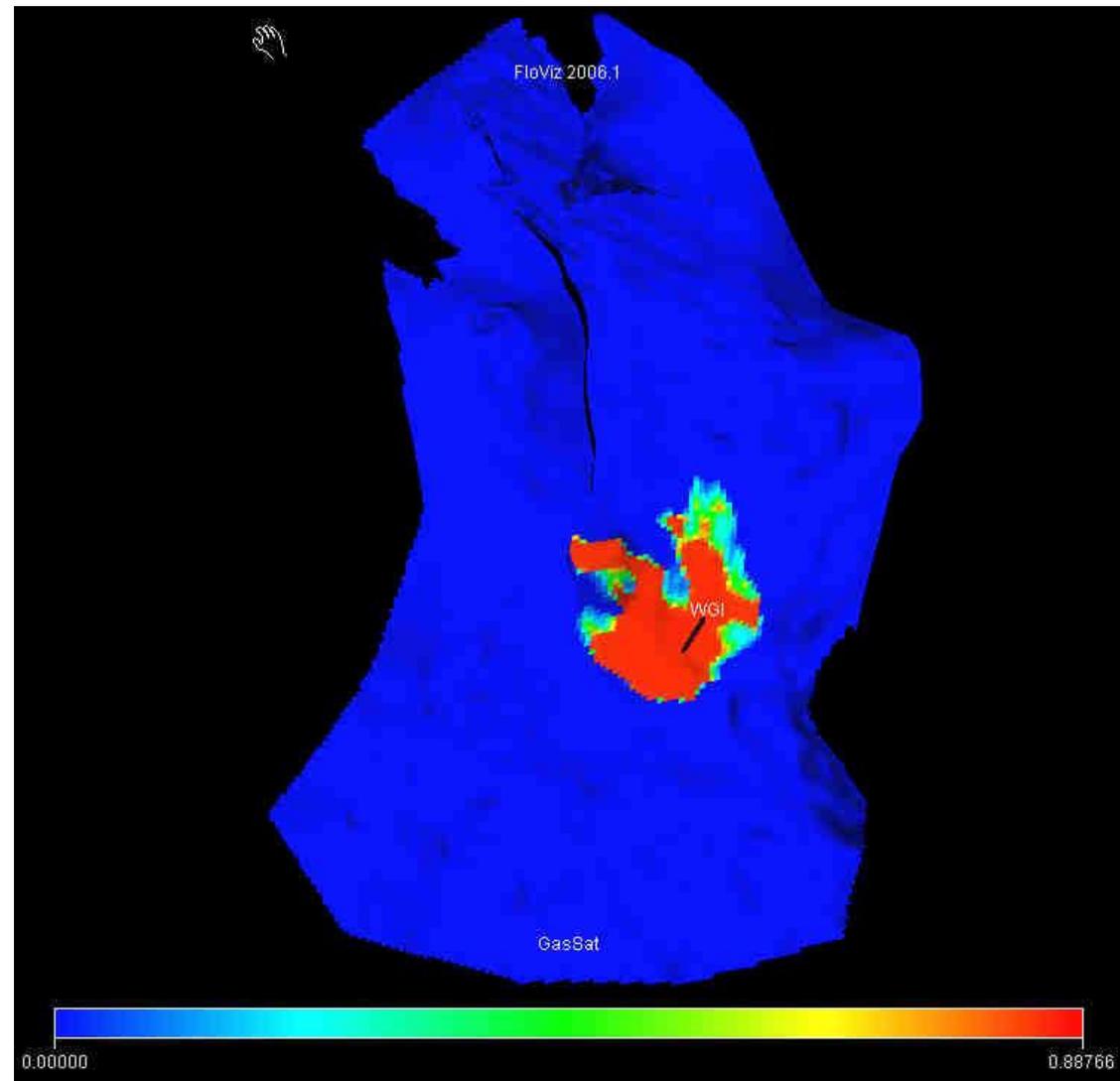
Simulation results

- Distribution of CO₂
- Year: 2025



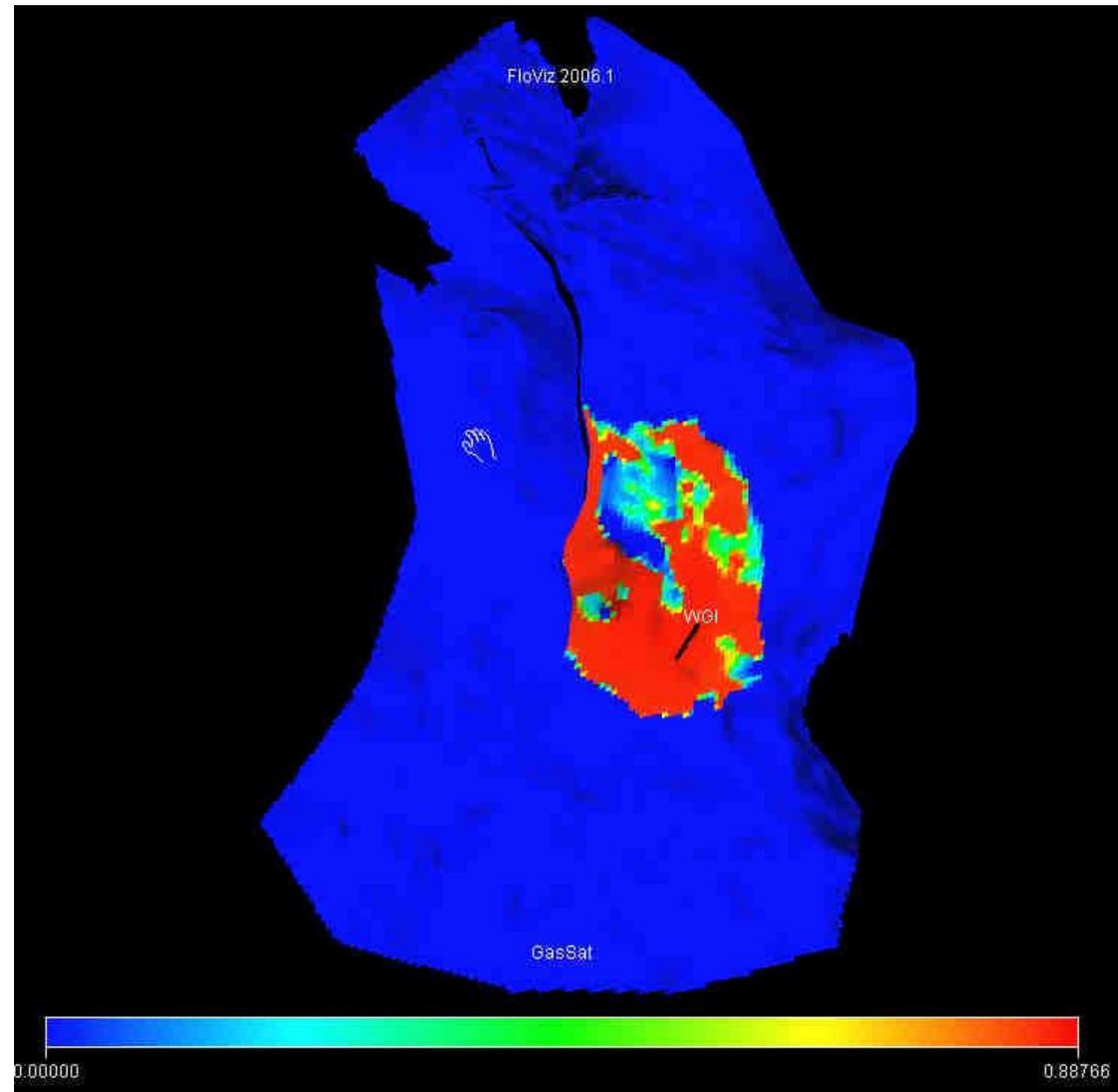
Simulation results

- Distribution of CO₂
- Year: 2039



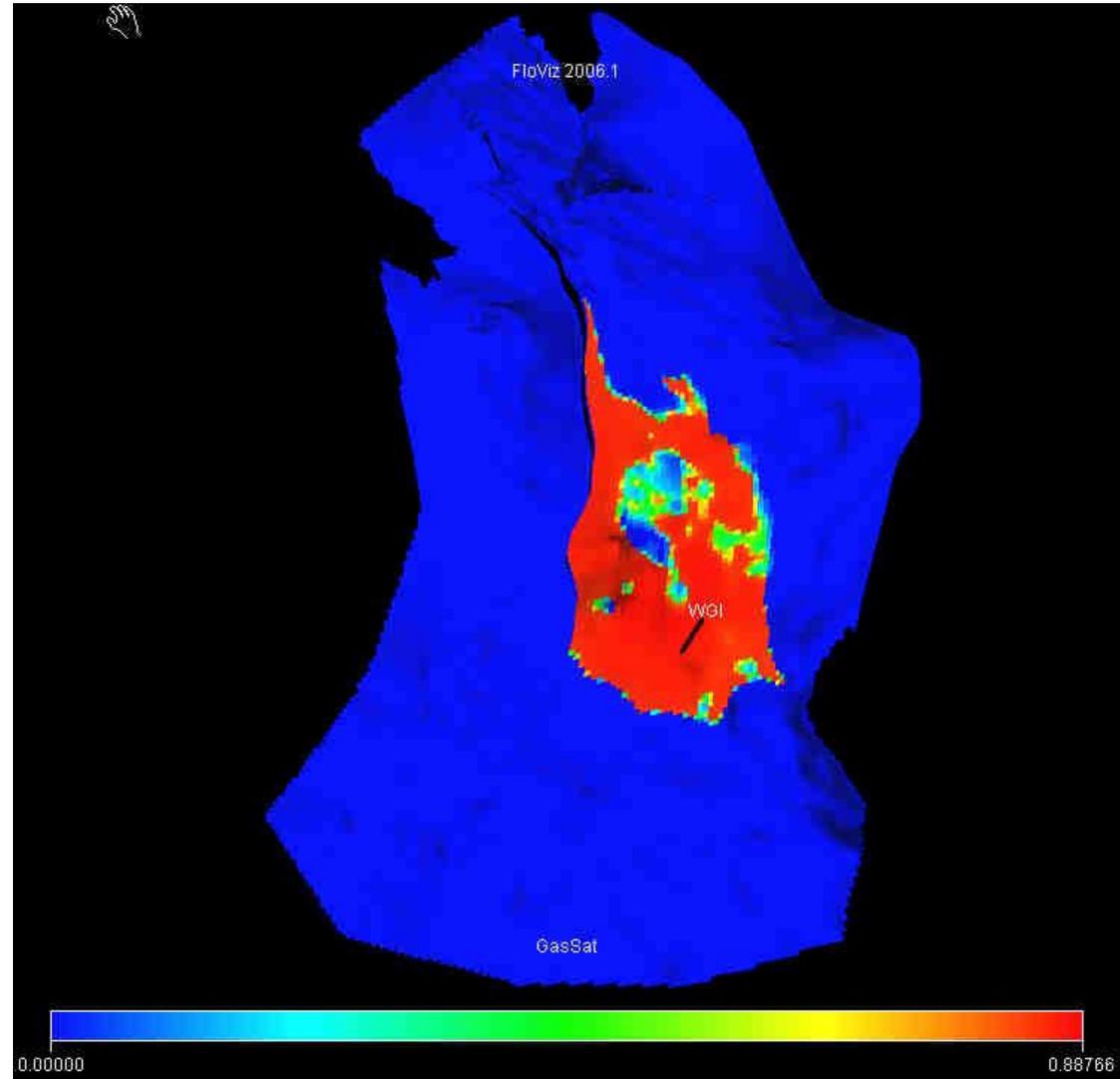
Simulation results

- • Distribution of CO₂
- Year: 2069



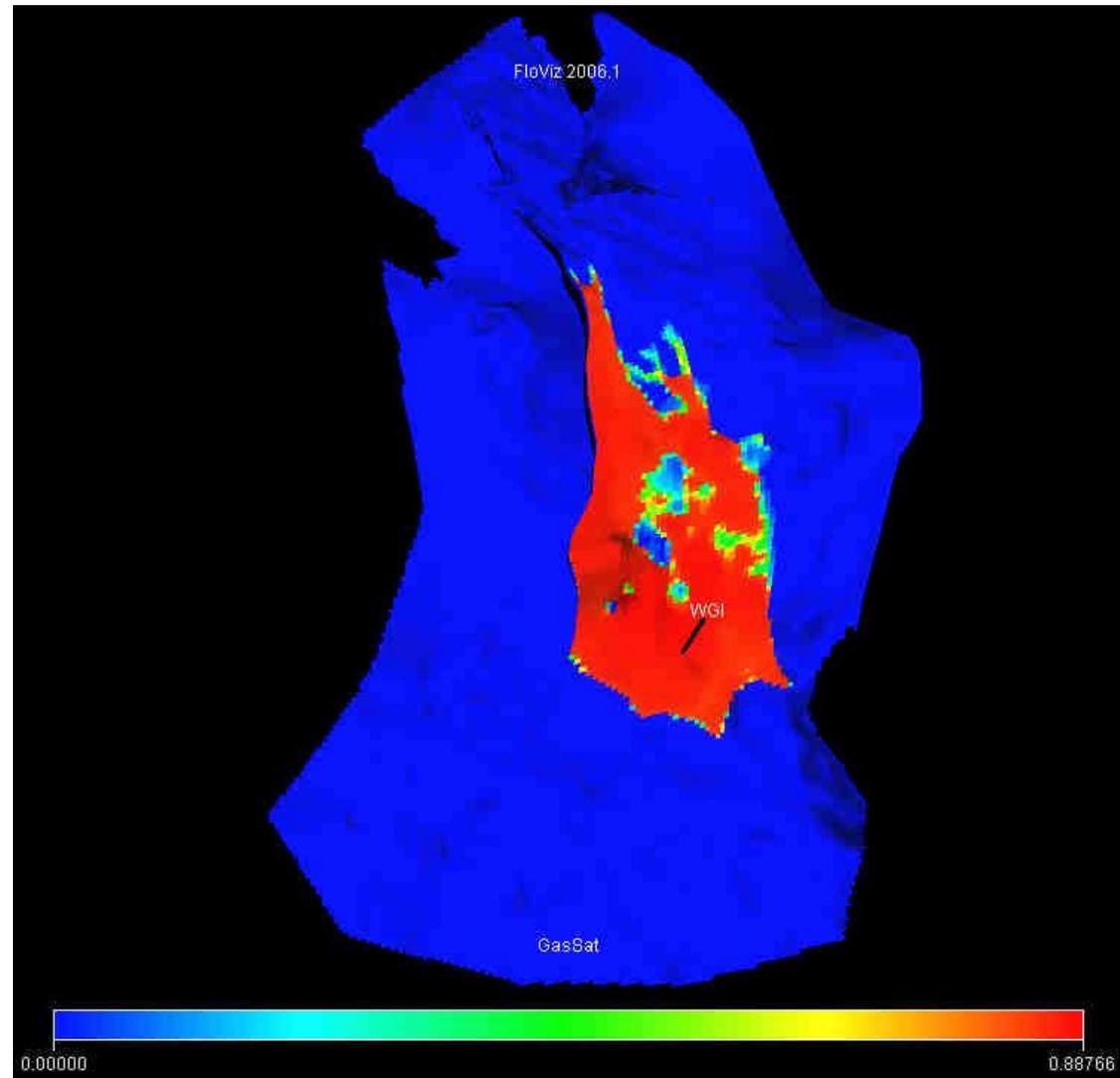
Simulation results

- • Distribution of CO₂
- Year: 2099



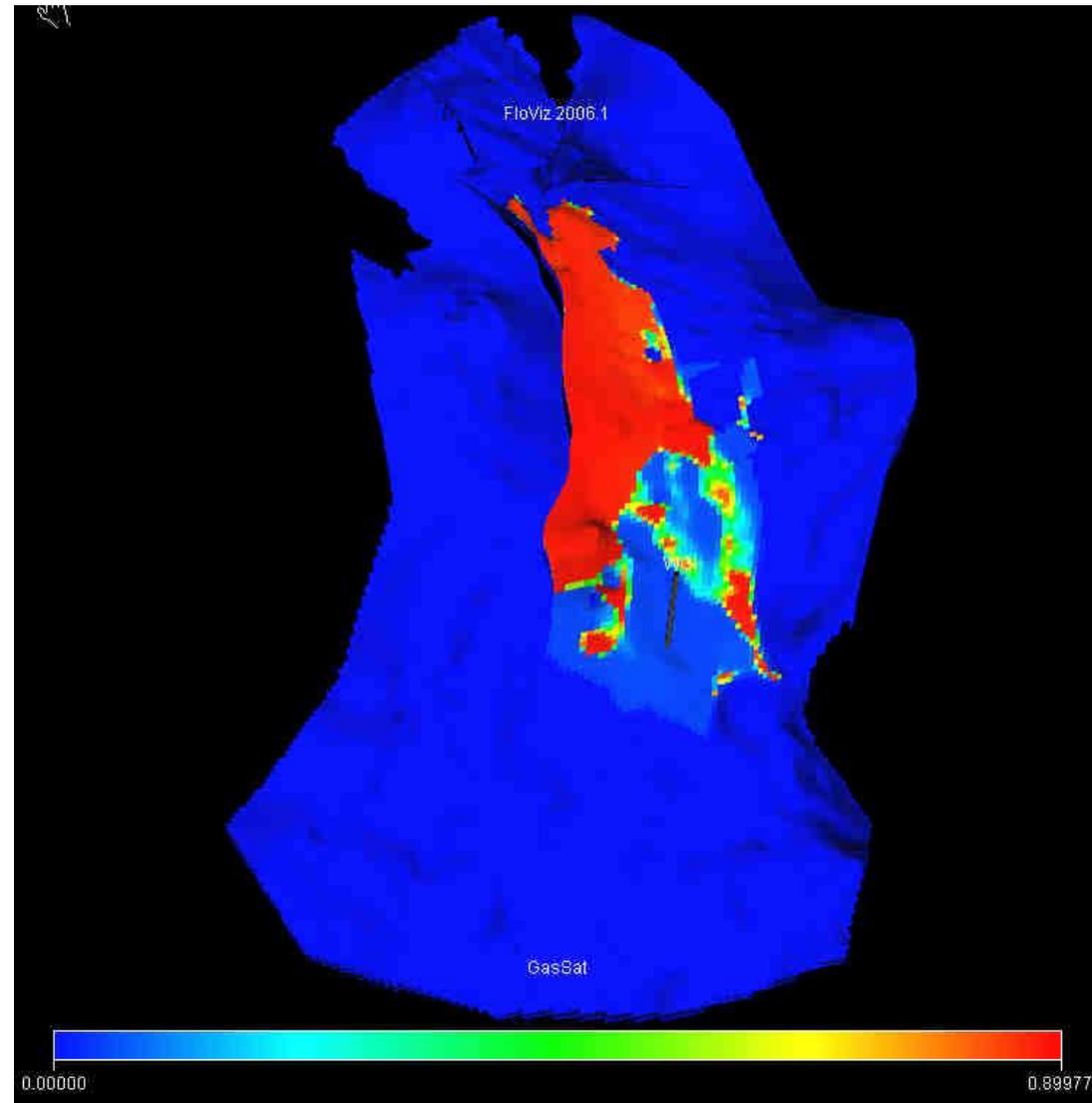
Simulation results

- Distribution of CO₂
- Year: 2129
- End of injection period



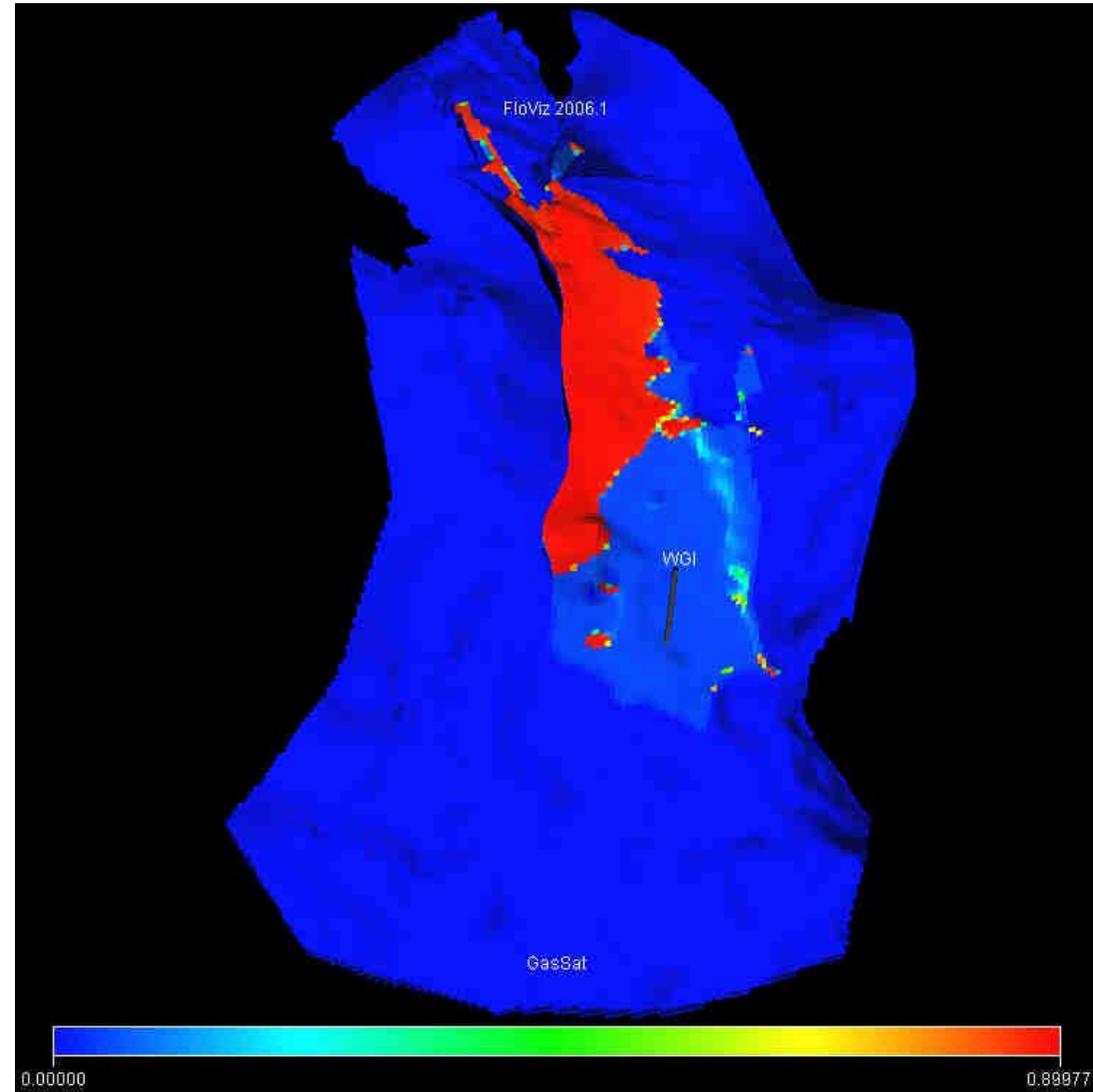
Simulation results

- Distribution of CO₂
- Year: 2229
- 100 years after end of injection



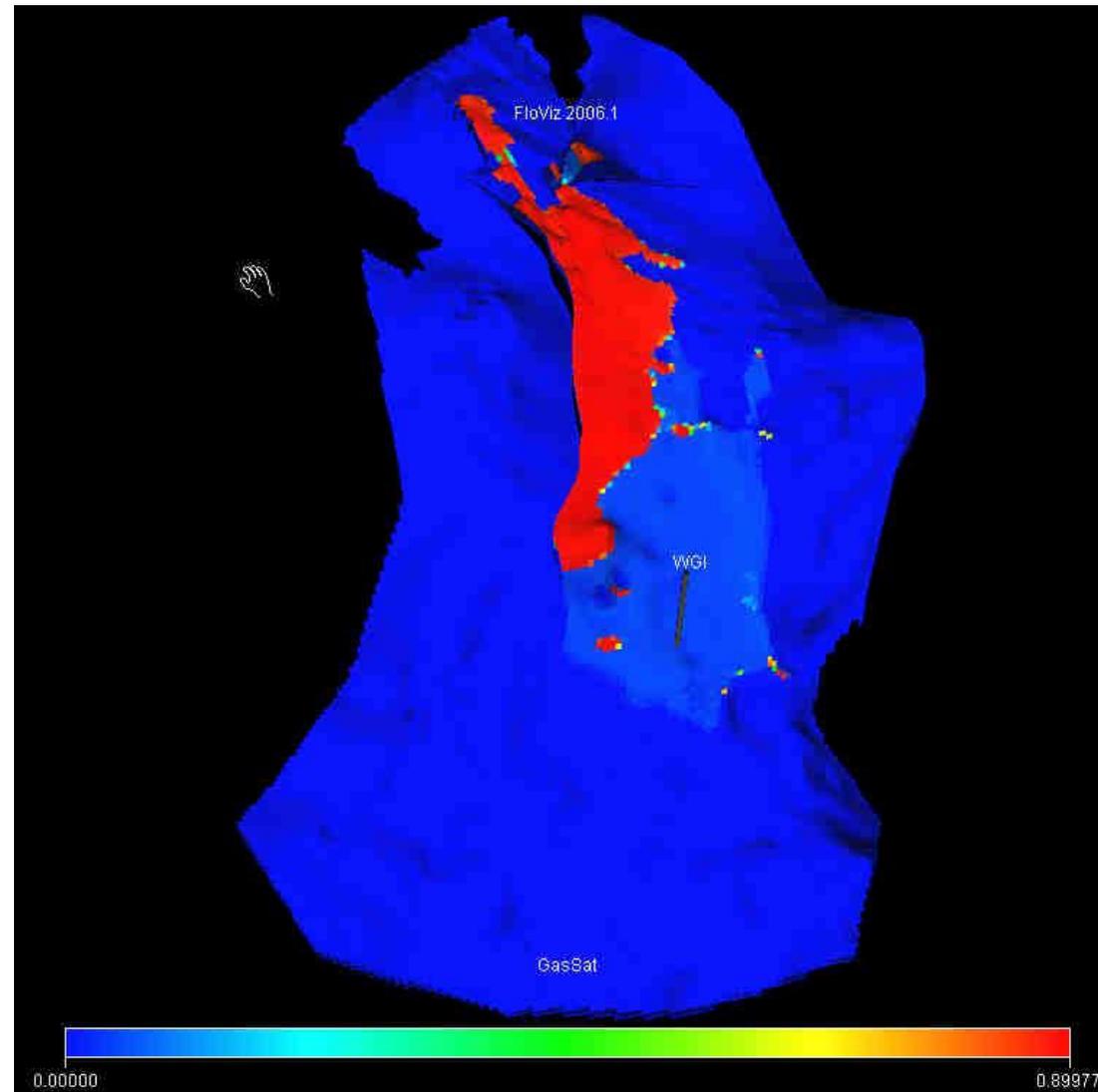
Simulation results

- • Distribution of CO₂
- Year: 2329



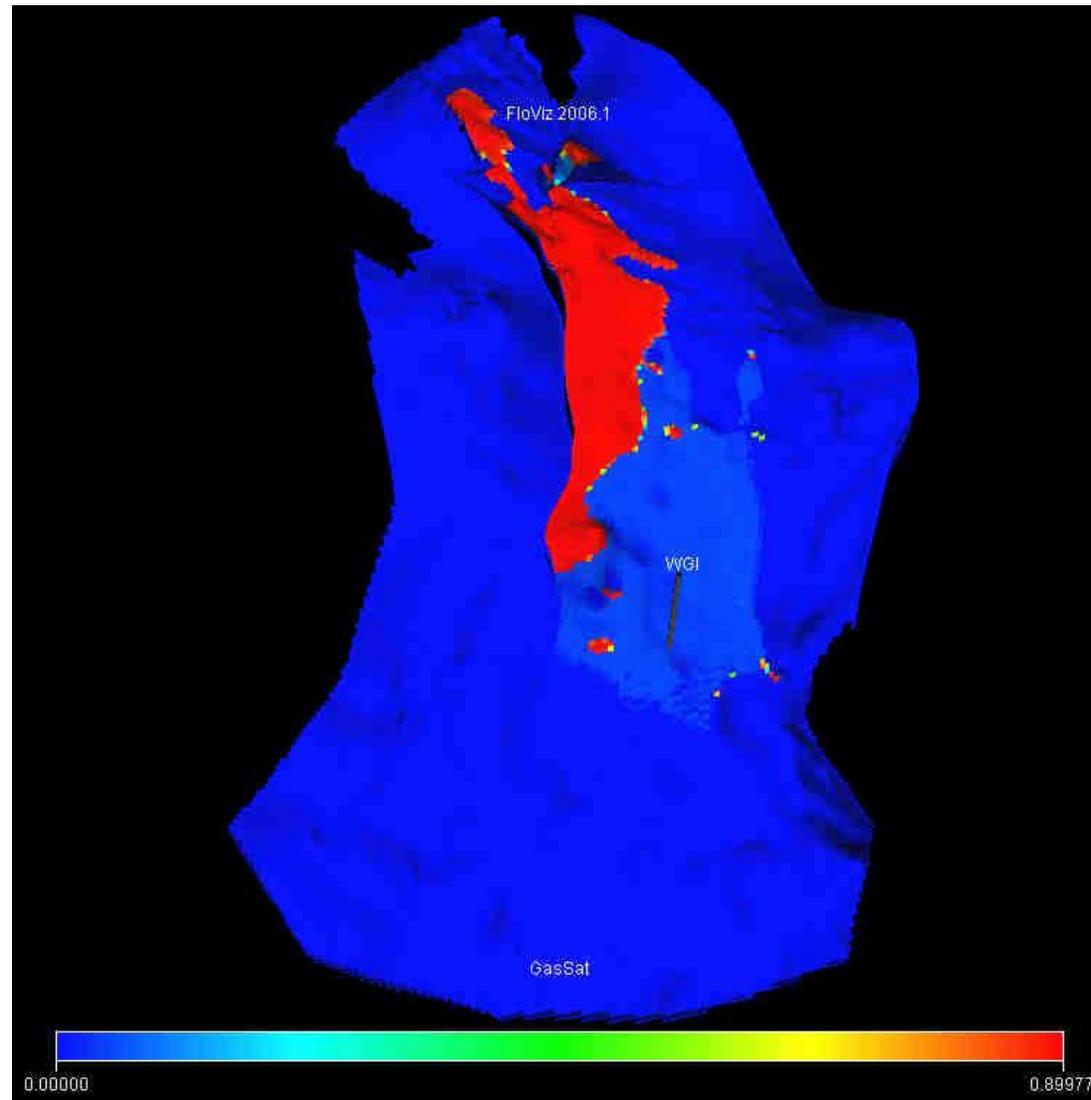
Simulation results

- • Distribution of CO₂
- Year: 2429



Simulation results

- Distribution of CO₂
- Year: 2529
- End of simulation



Remediation strategy: Consequences for future research on CO₂ storage

- The focus should shift towards
 - Monitoring with special emphasis on detection of early deviations from predicted behaviour
 - Remediation measures for a given events
- Less attention could be paid to
 - Long-term fate of CO₂ underground
 - Diffusion induced convection
 - Geochemical modelling of trapping CO₂
 - Comprehensive risk assessments that depend on probability functions of geological input and rather emphasise “what if..” studies

Monitoring of the Sleipner CO₂ injection project, summary

- The 3D seismic has been a great success and has received a lot of national and international attention. The seismic data have been distributed to a number of institutions and have been thoroughly analysed
- The project has been a unique demonstration and laboratory for permanent CO₂ storage
- The attention around the project is decreasing and other large scale projects are gaining interest from the scientific and engineering community
- However, the special quality and size of this project qualifies it for further investigation

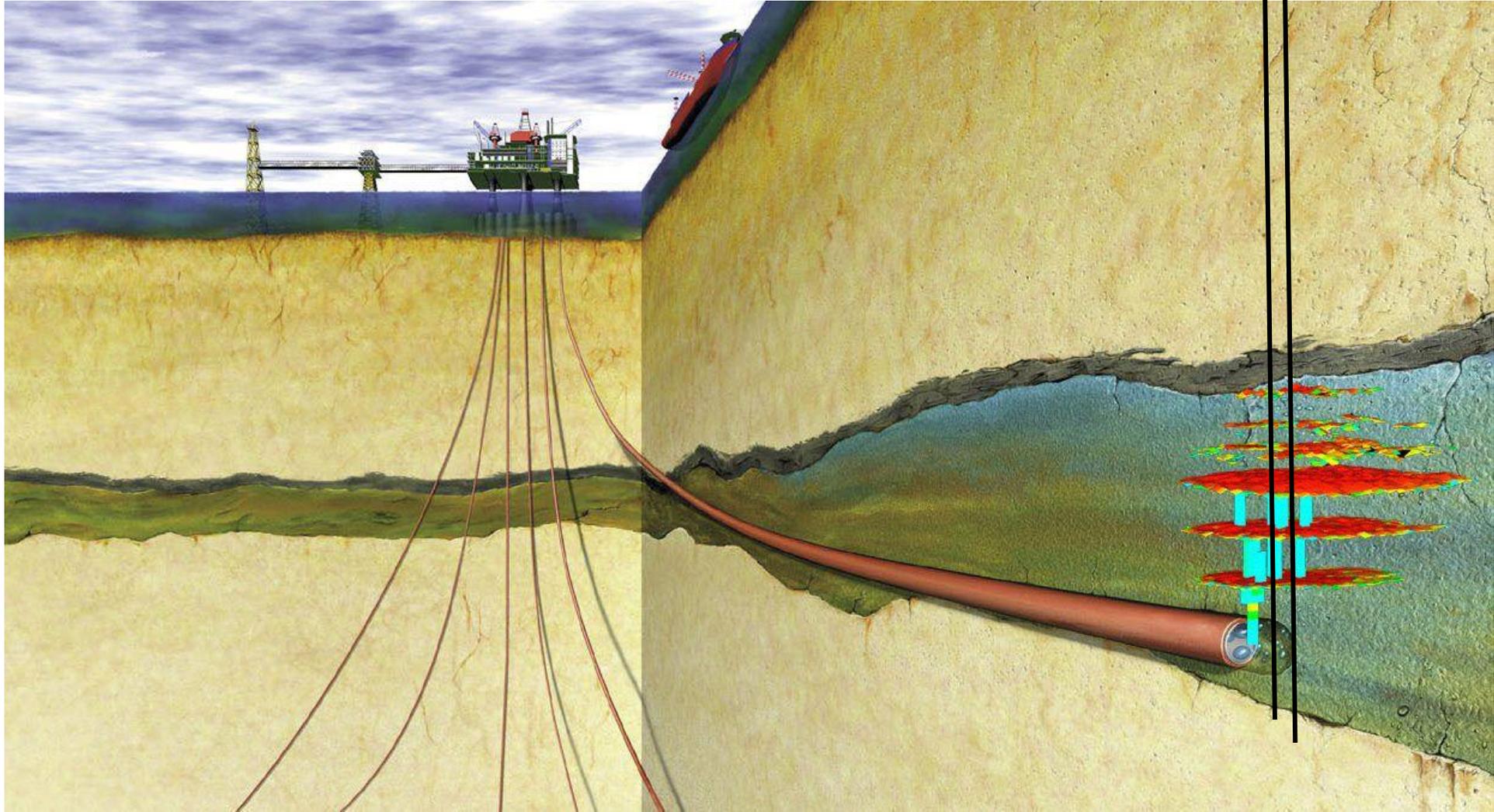
Monitoring of the Sleipner CO₂ has raised new questions

- The result of the studies has raised a number of questions that is not easy to answer without other observation methods.
 - Volume balance of injected CO₂
 - The “chimney”
 - How is CO₂ transported through the 6 m shale layer near the top (it has the same signature on the well logs as the Nordland shale)
 - The long northward extension of the top plume is difficult to explain from the topography of the sealing shale
 - How much CO₂ has actually been dissolved?
 - Has any CO₂ migrated into the Nordland shale?
 - What is the reservoir pressure and temperature?
 - How dispersed is the CO₂ between the plumes?
 - What is the residual water saturation in the plumes (sic)?
 - What is the chemical composition of the formation water after 14 years of CO₂ exposure
 - Is there any hydrodynamic activity in the formation (aquifer wind)?
 - The lower CO₂ plumes are apparently being depleted according to the two last seismics, is this real (maybe the sealing capacity of the layers has decreased) or is it an artefact due to attenuation of the massive plumes above?
 - The vertical velocity (seismic calibration)

Feasibility of monitoring wells Sleipner

- Most of the problems raised above will be illuminated by the installation of two observation wells located in the central part of the injection area and not separated too much
- Feasibility study of the technical aspects was performed in the SACS II project ten years ago, many aspects of this study are still valid

Sleipner CO₂ observation wells



Project ideas to be scrutinized in a feasibility study

- Vertical wells can not be drilled from the platform
 - Minimum interference with the Sleipner operation is desired
 - Wells are therefore drilled from a separate drilling vessel.
 - Even if these shallow wells can be drilled with lighter equipment than ordinary exploration drilling, the mobilisation cost is significant, it will therefore be optimal and cost effective to drill **two** wells, especially from the scientific aspects
 - Will it be necessary to drill with full mud pressure control? (The site is extremely well surveyed, *e.g.* location of shallow gas – not present above plumes)
 - Can a light or heavy intervention ship be used to drill the soft unconsolidated sediments?
 - Could Bucentaur be used ?
 - Maximum drill string 1050 metres API steel pipe
 - Approximately 950 m depth will be needed to drill well below the deepest plume
 - Excellent suited for full length coring

Geotechnical Drilling Vessel, MV Bucentaur



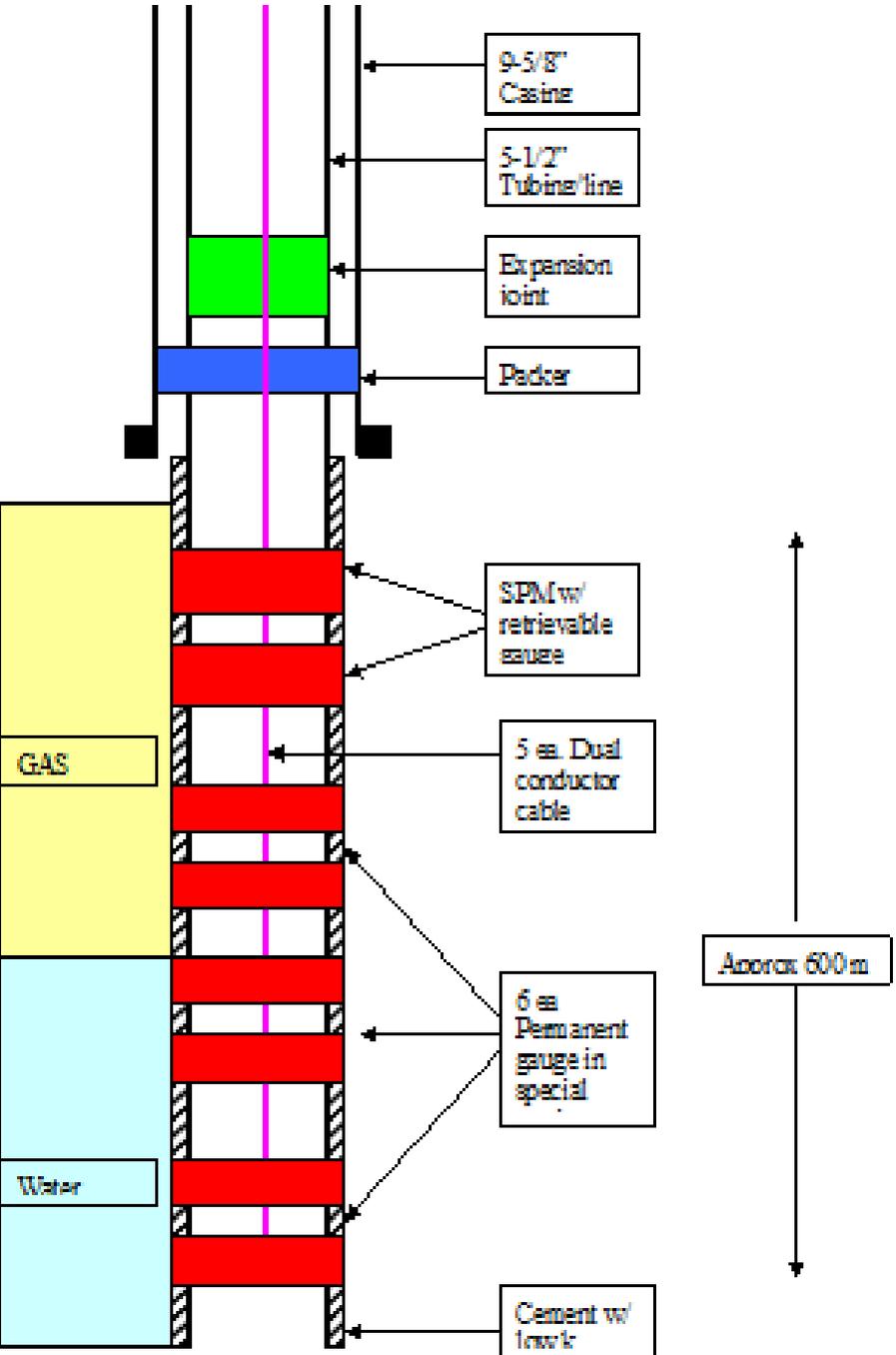
1. Intensive campaign phase (vessel available)

- Measurement and logging while drilling
- Full length coring (at least the Nordland shale and Utsira formation)
- Logging (wire line)
 - Calliper, gamma, resistivity (laterolog), neutron, density, sonic, formation imager (FMI), VSP
- Water sampling (production test?)
- Etc.

2. Passive observation phase (no vessel)

- Signals from well
 - Either transferred to Sleipner A on cables and transmitted by satellite to laboratories or
 - Transferred to buoy and transmitted
- Instrumentation:
 - Pressure
 - Temperature
 - Well-to-well resistivity
 - Seismic (VSP)
 - Well-to-well seismic
 - Sonic (along well)
 - Etc.

Well outline (example proposed by Roxar)



Other well prospective

How to safely drill and complete a well directly in a CO₂ plume – a significant demonstration aspect

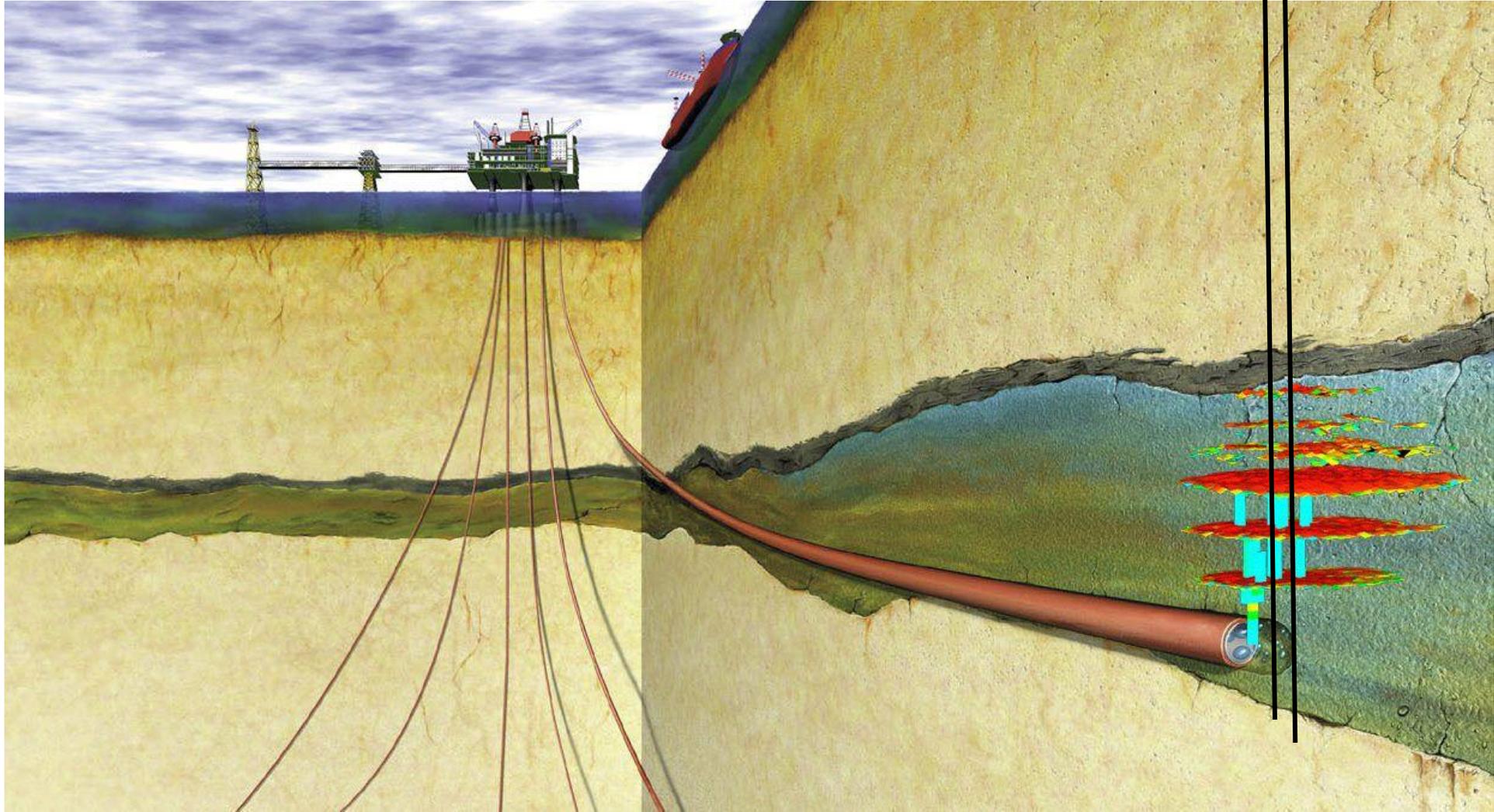
How can inexpensive wells be planned in the future?

Are our methods to monitor the CO₂ underground sufficiently sensitive?

Project outline

- 100 to 150 million NOK project
- International consortium, EU, industry, SACS and CO2Store partners plus new non-EU affiliated partners
- Time is right for this kind of projects, both from a scientific perspective and seen in the light of the EU efforts on CO₂ storage demonstration

Sleipner CO₂ observation wells



Svelvik Field Laboratory





Injection control manifold Svelvik Field Lab





Technology for a better society