

Fourteen years' experience of monitoring CO₂ injection in the Utsira Sand at Sleipner, offshore Norway

Kyoto, 9 december 2010

TNO | Knowledge for business

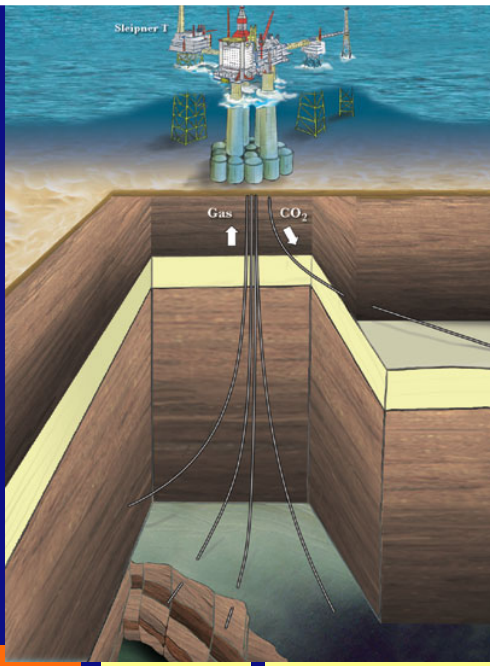
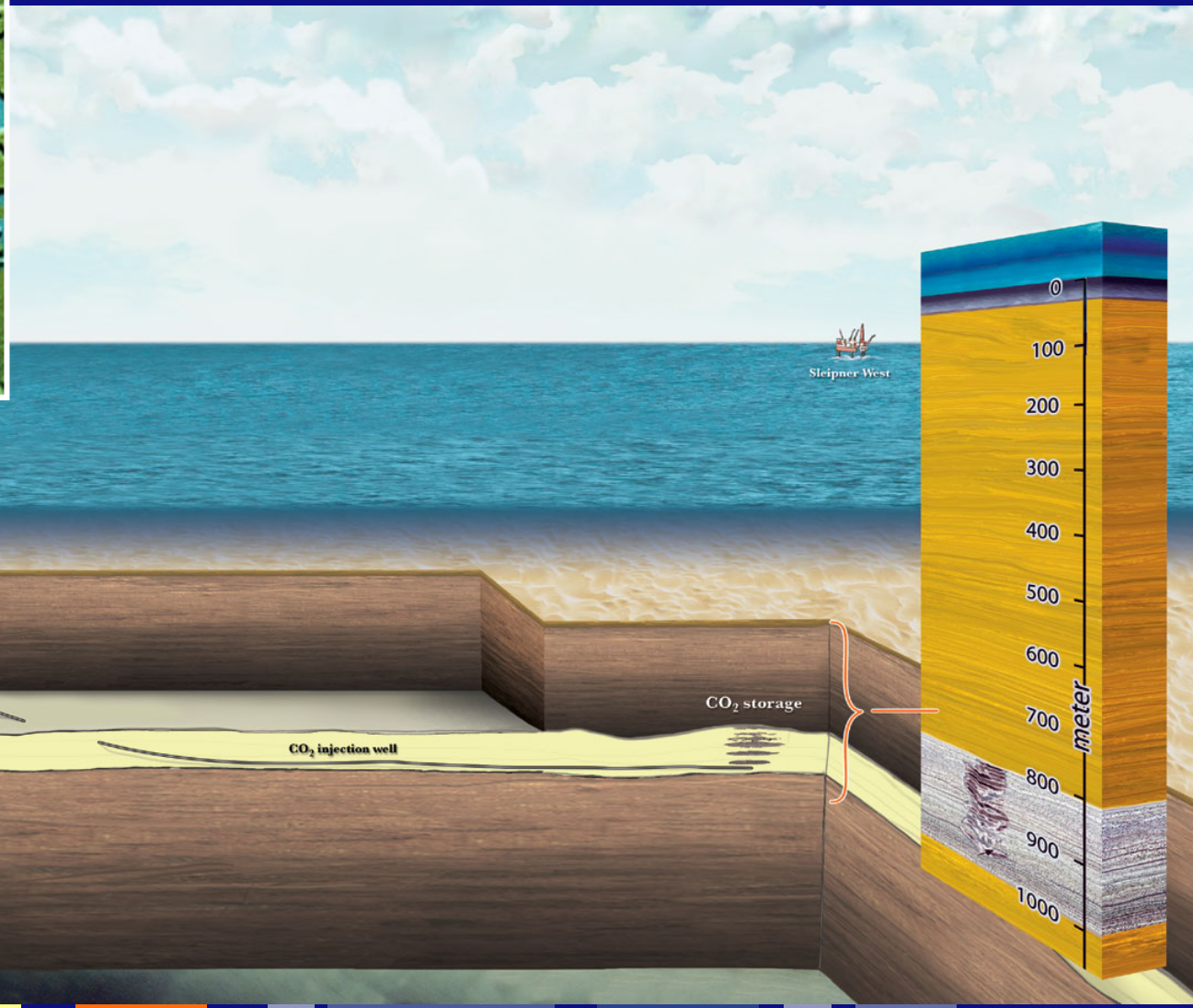


Rob Arts, Andy Chadwick & Ola Eiken

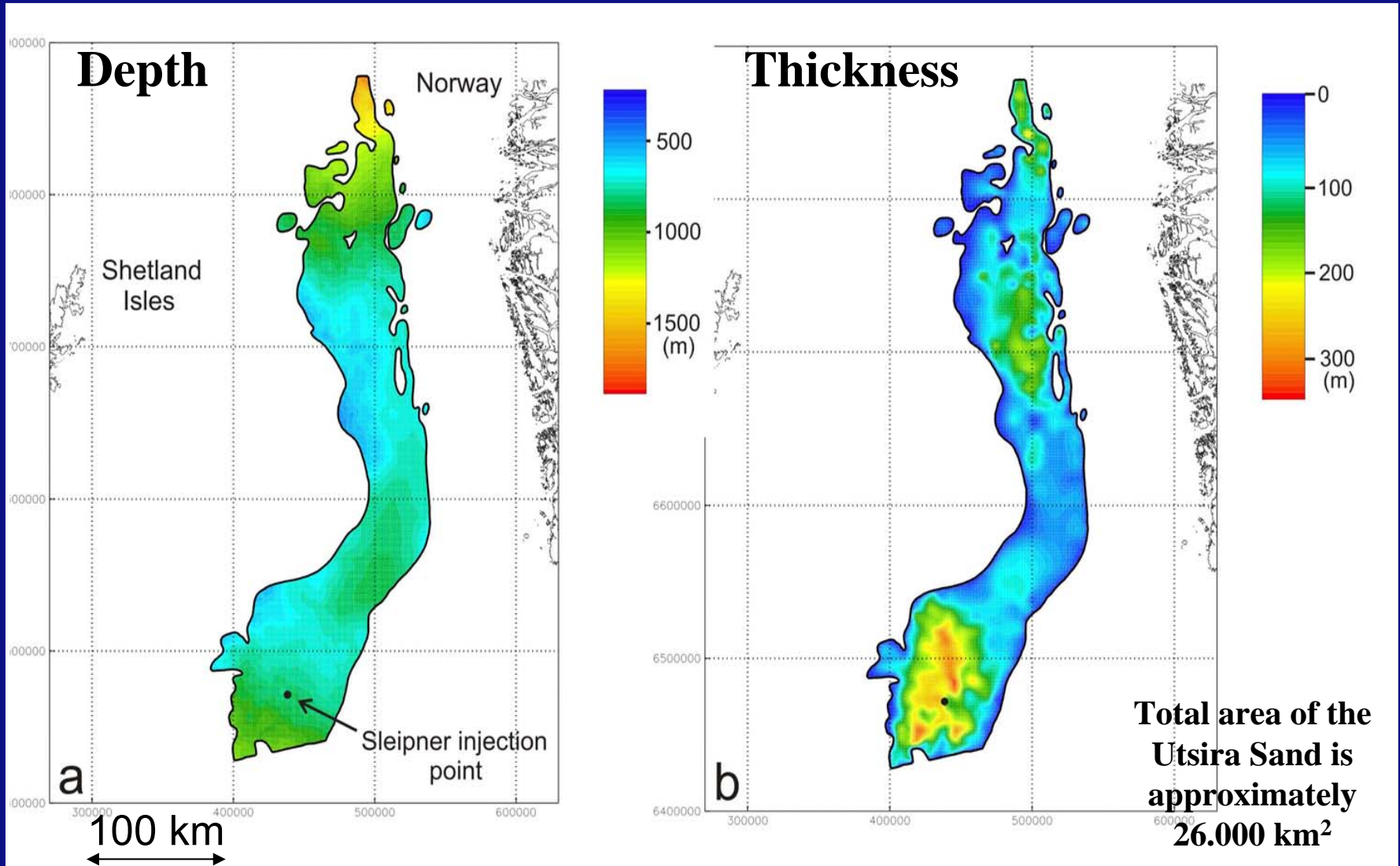
Overview

- Introduction to the Sleipner CO₂ injection site
- Analysis of the seismic monitoring data
 - Quantitative interpretation of the data
 - Match to the reservoir simulation
 - Synthetic seismic modeling
 - AVP (Amplitude vs. ray parameter) analysis
- Gravity monitoring results
- Seafloor imaging
- Concluding remarks

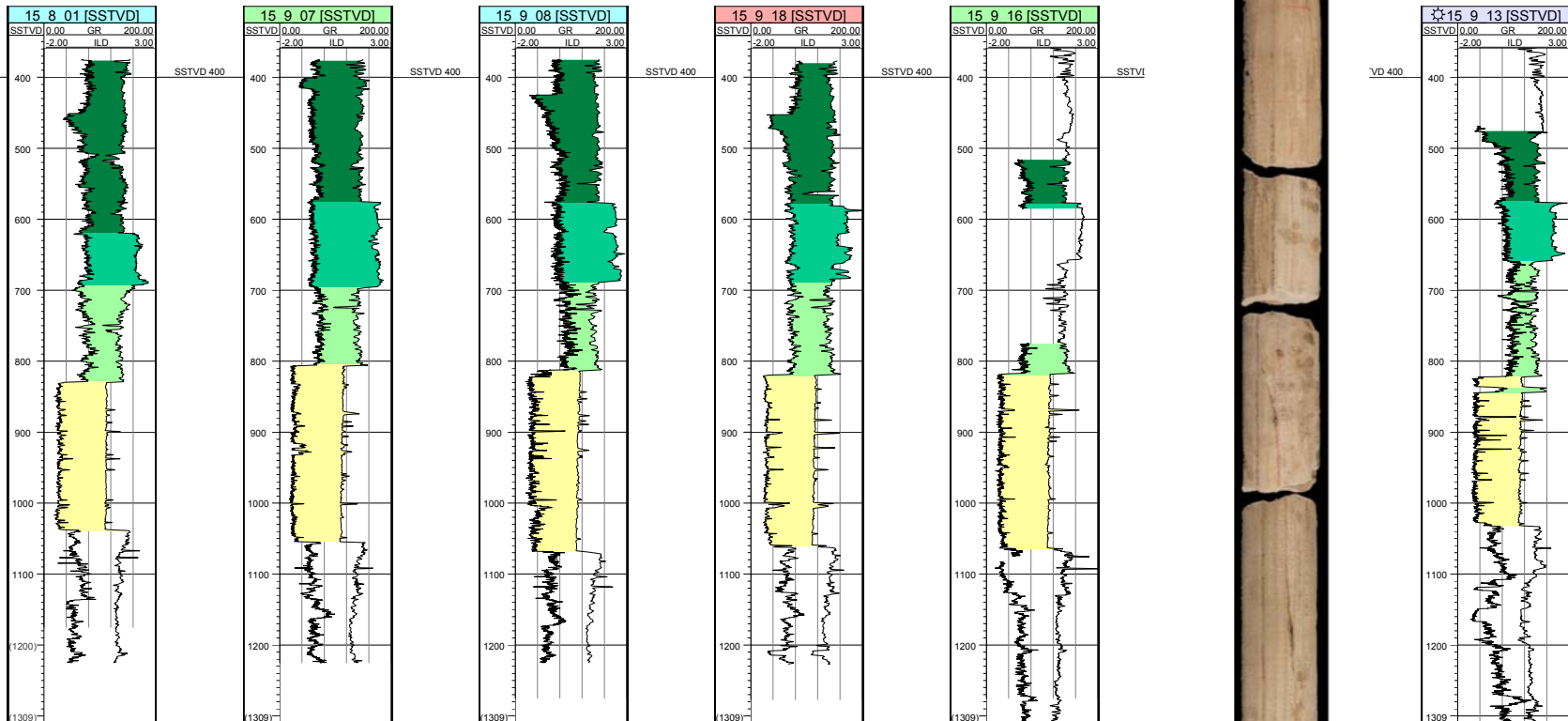
Injection scheme at Sleipner



Extension of the Utsira Sand



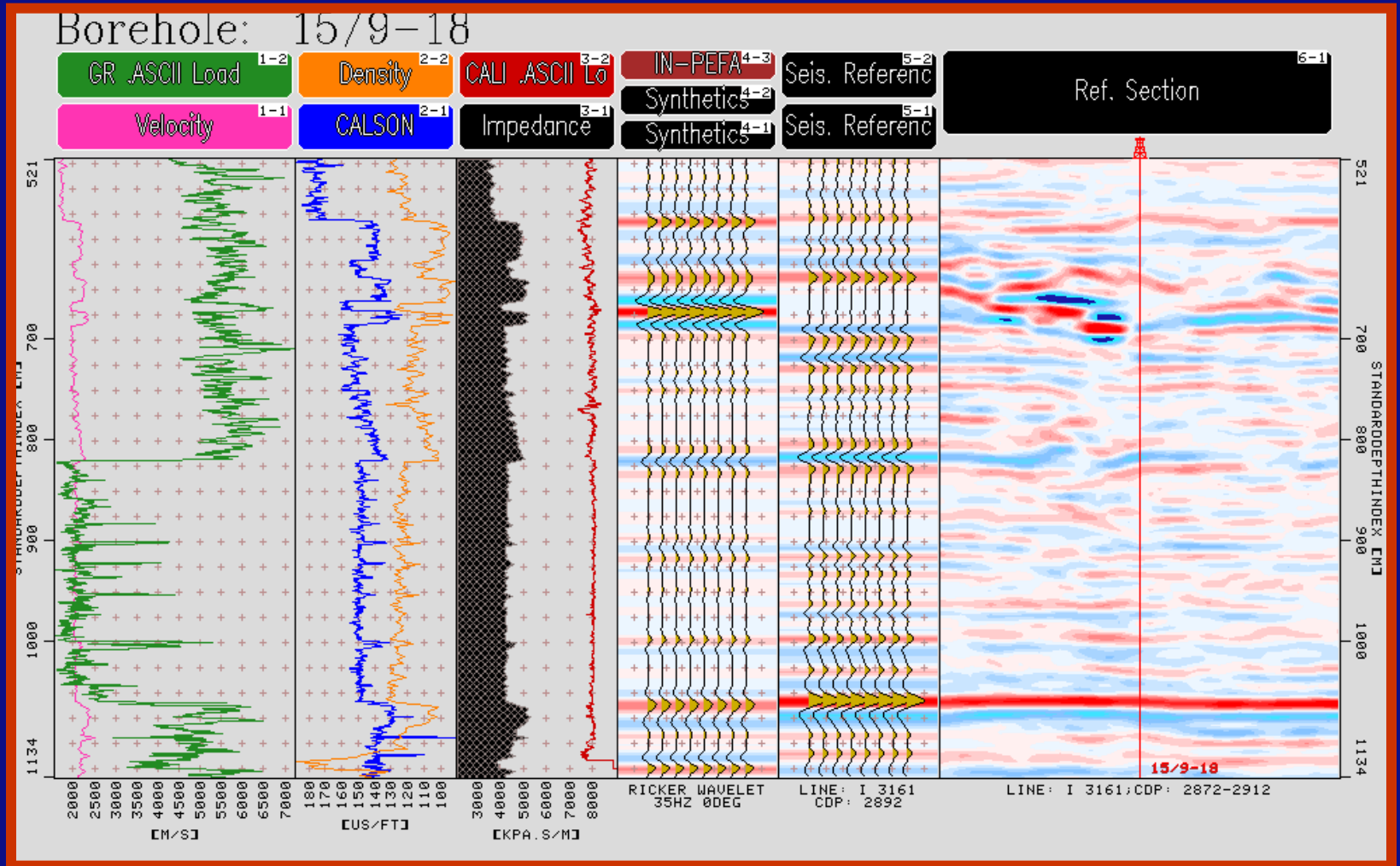
Reservoir characteristics: Log panel (W-E, 20 km)



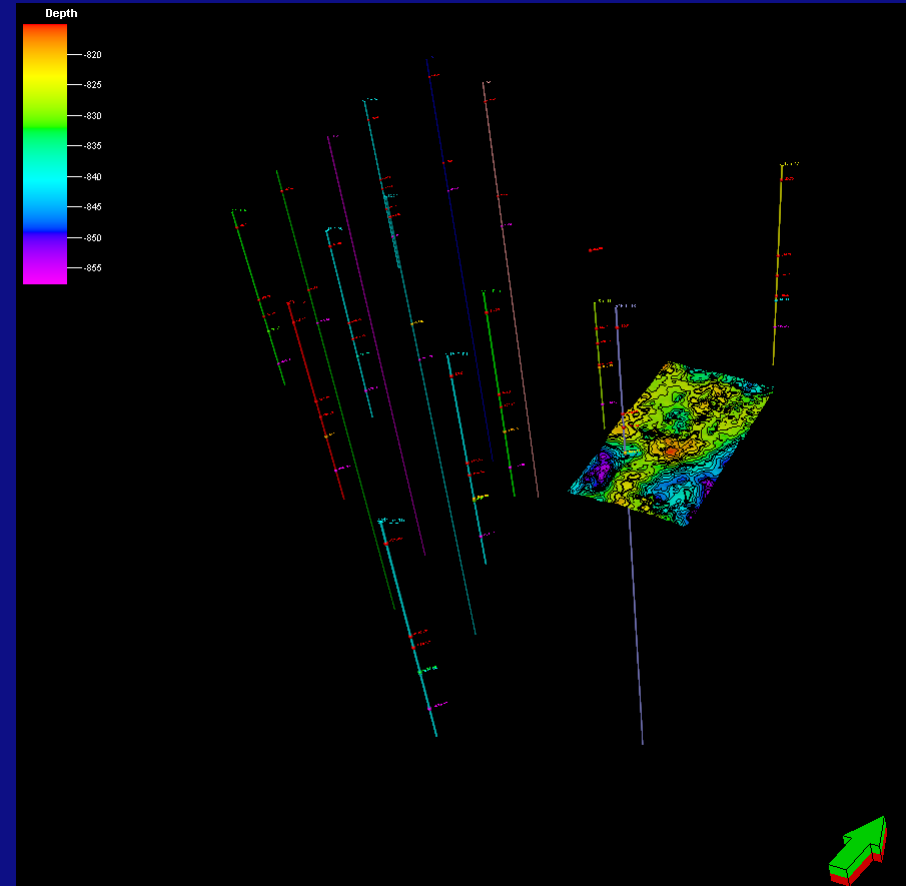
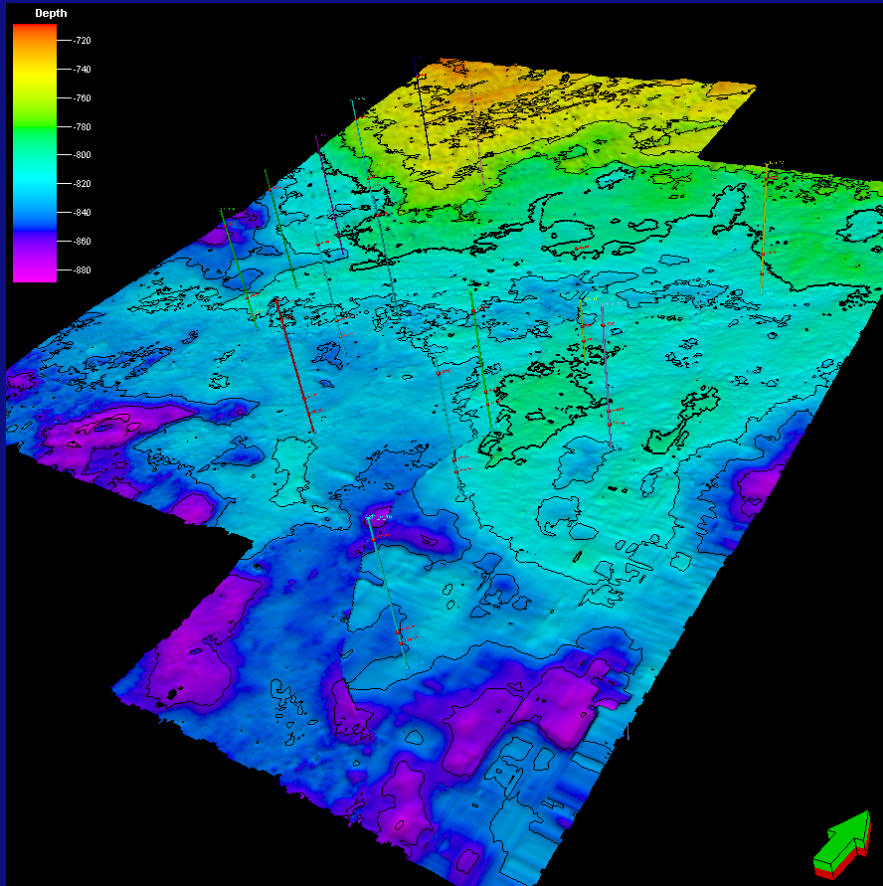
Reservoir analogue



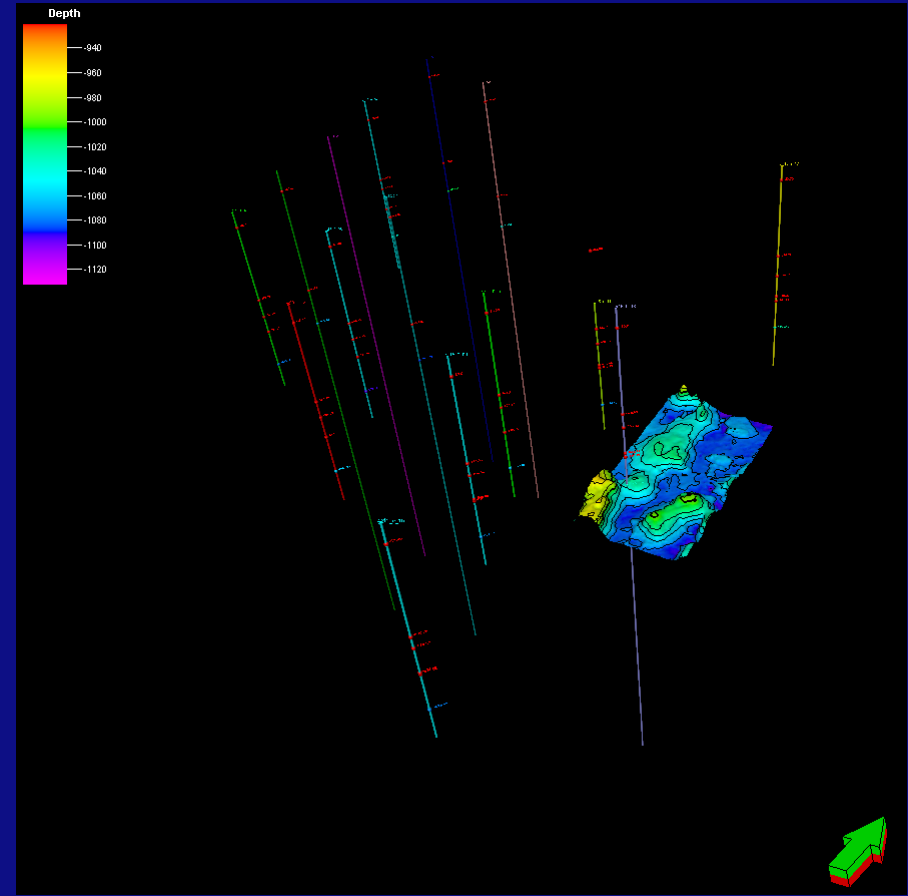
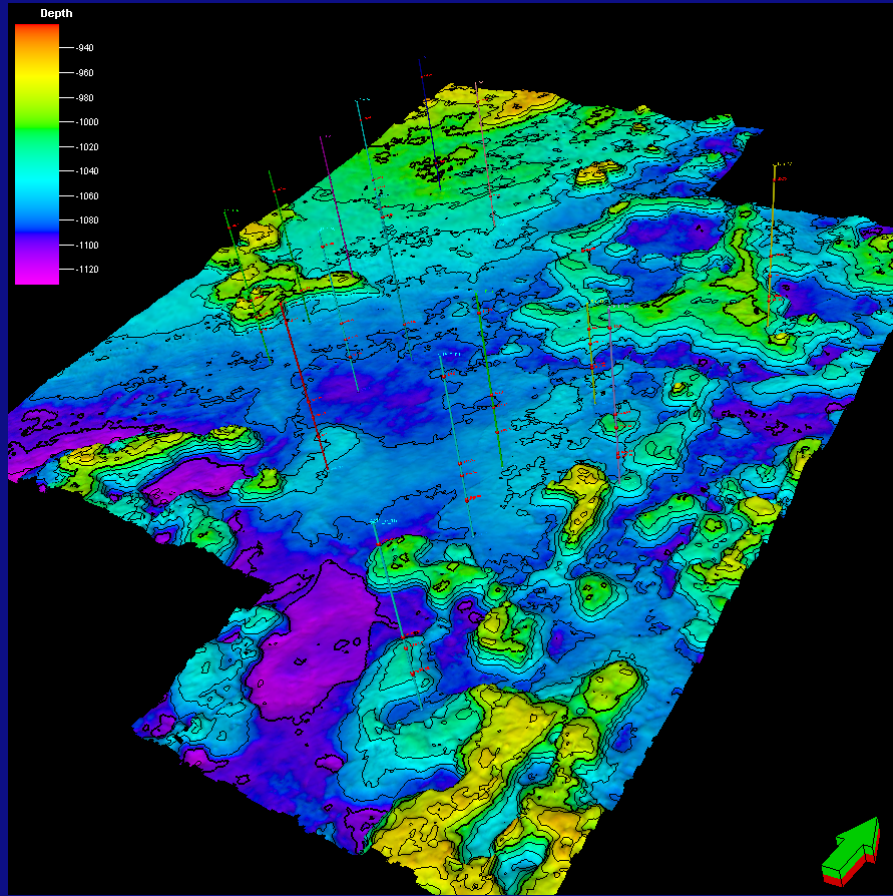
Synthetics of well 15/9-18



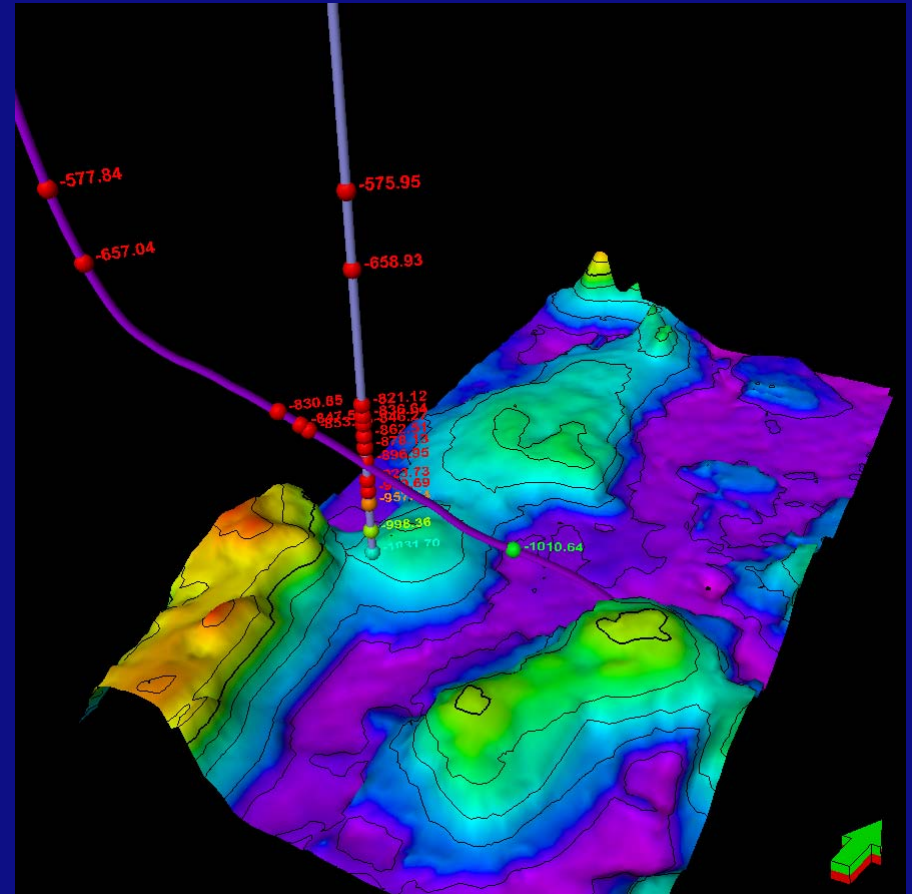
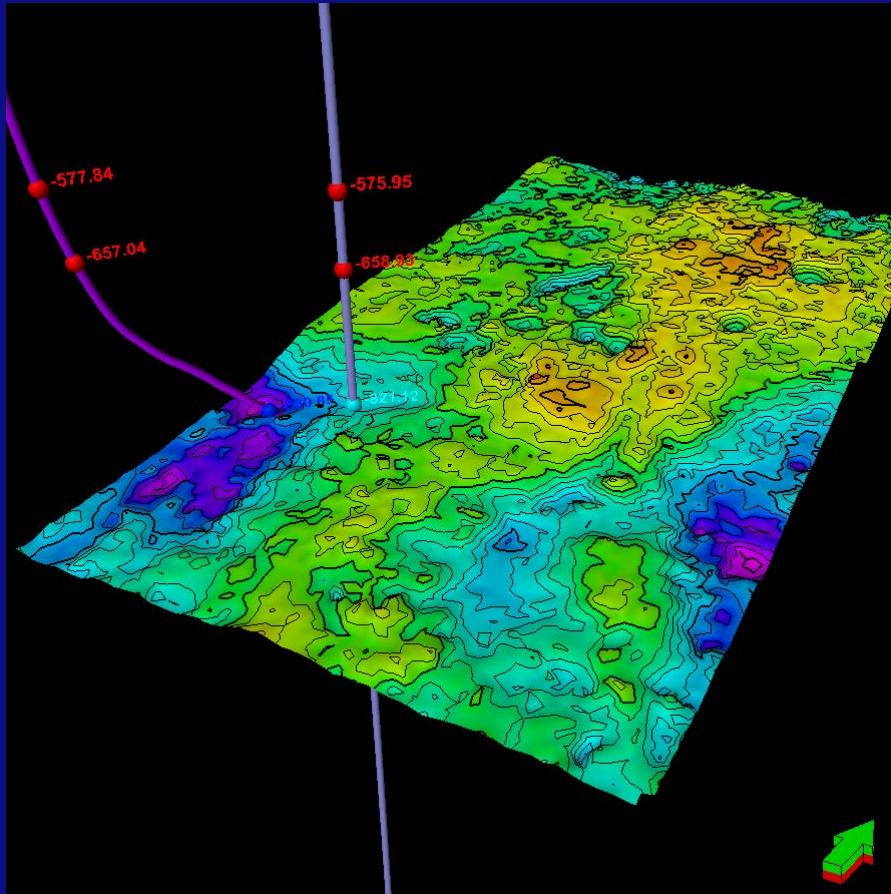
Top Utsira



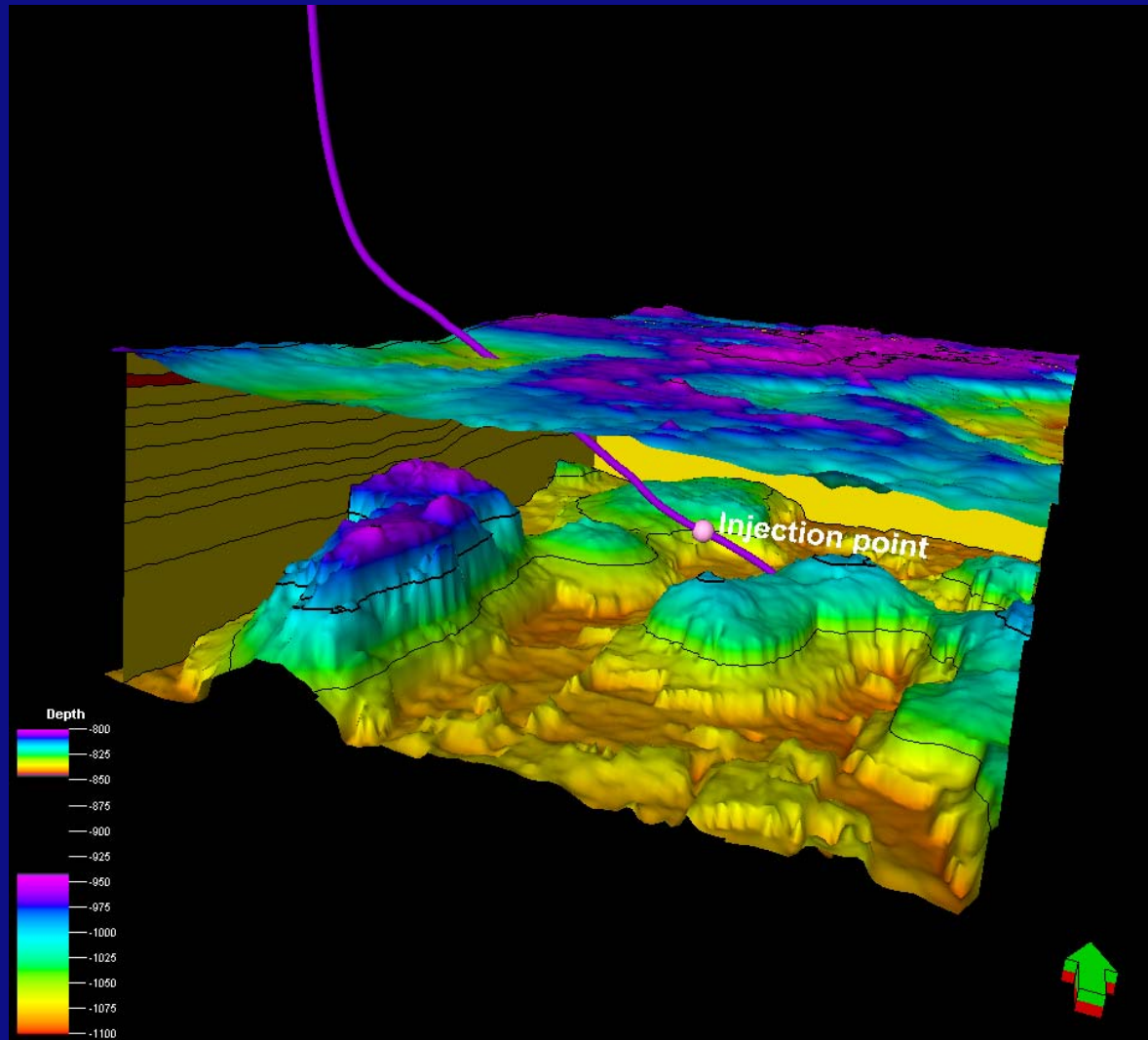
Base Utsira



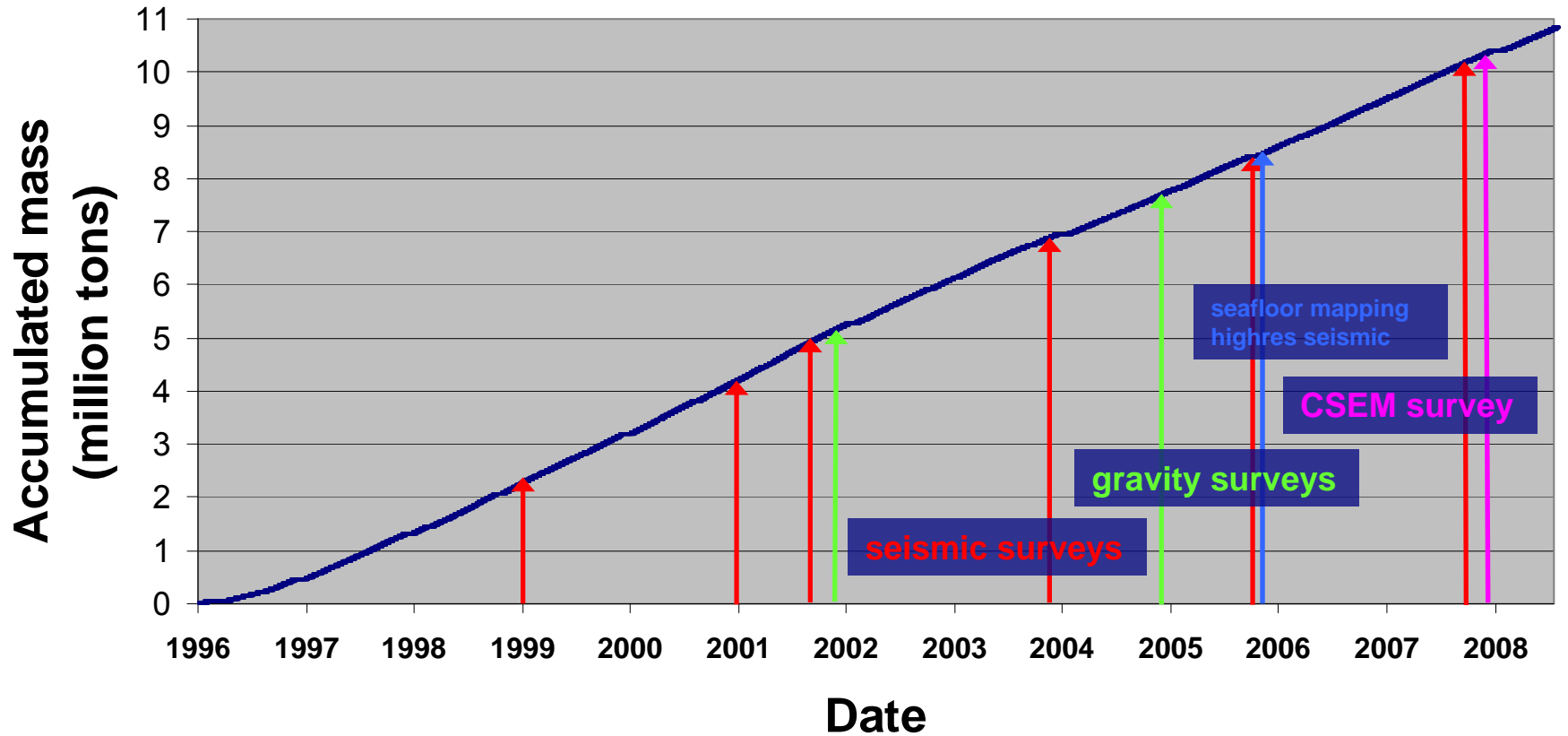
Top Utsira around the injection point



The Utsira reservoir



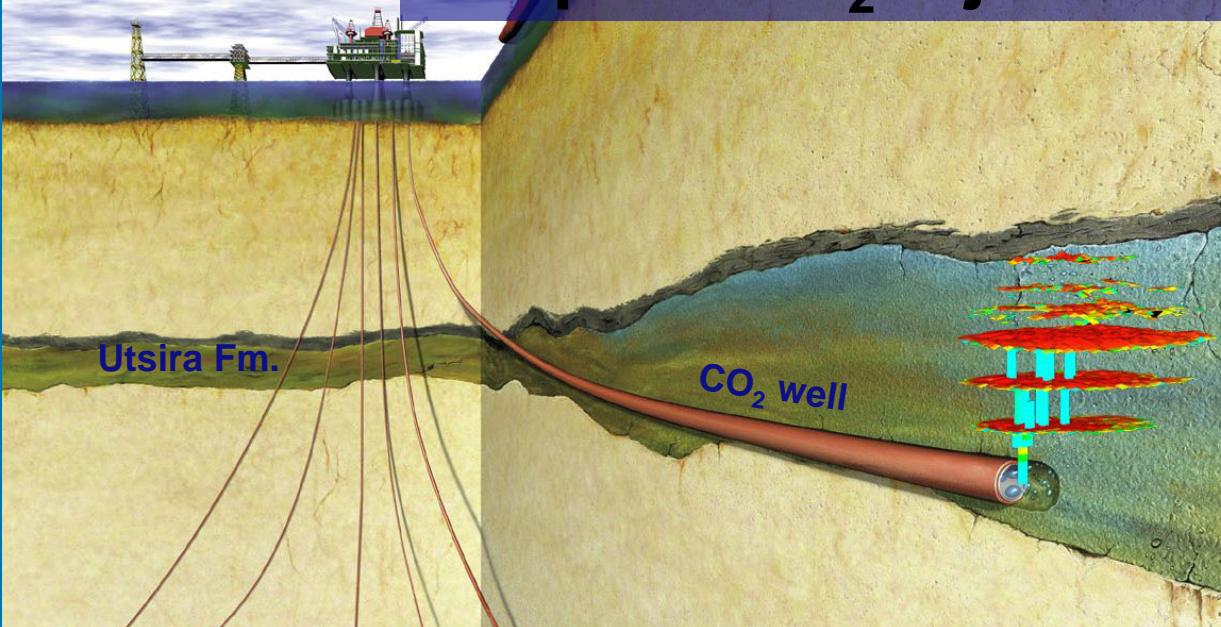
Injected CO2



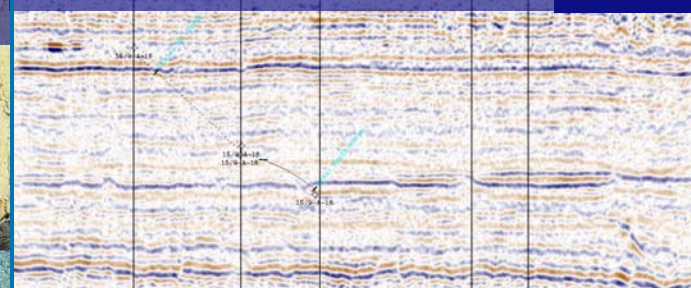
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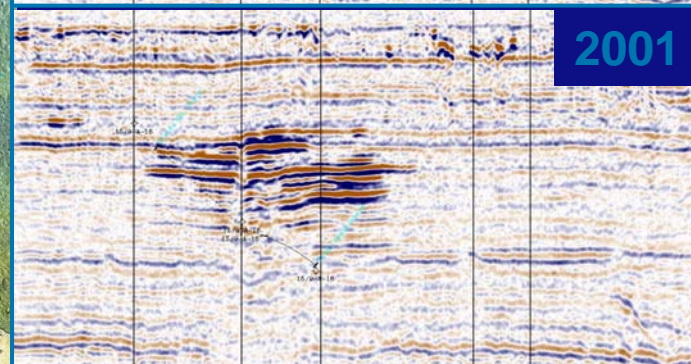
Sleipner CO₂ injection



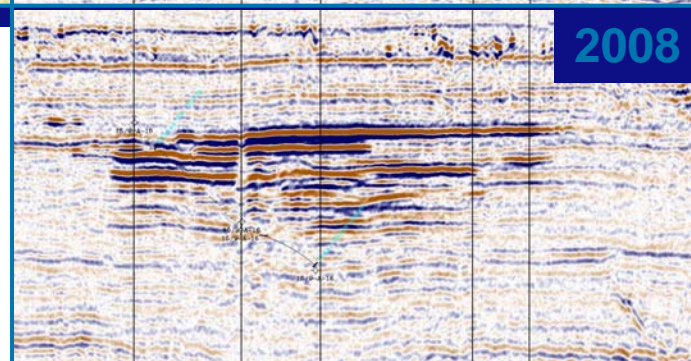
Time-lapse seismic data 1994



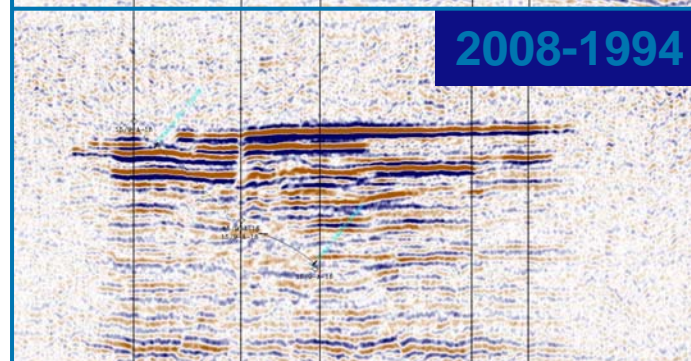
2001



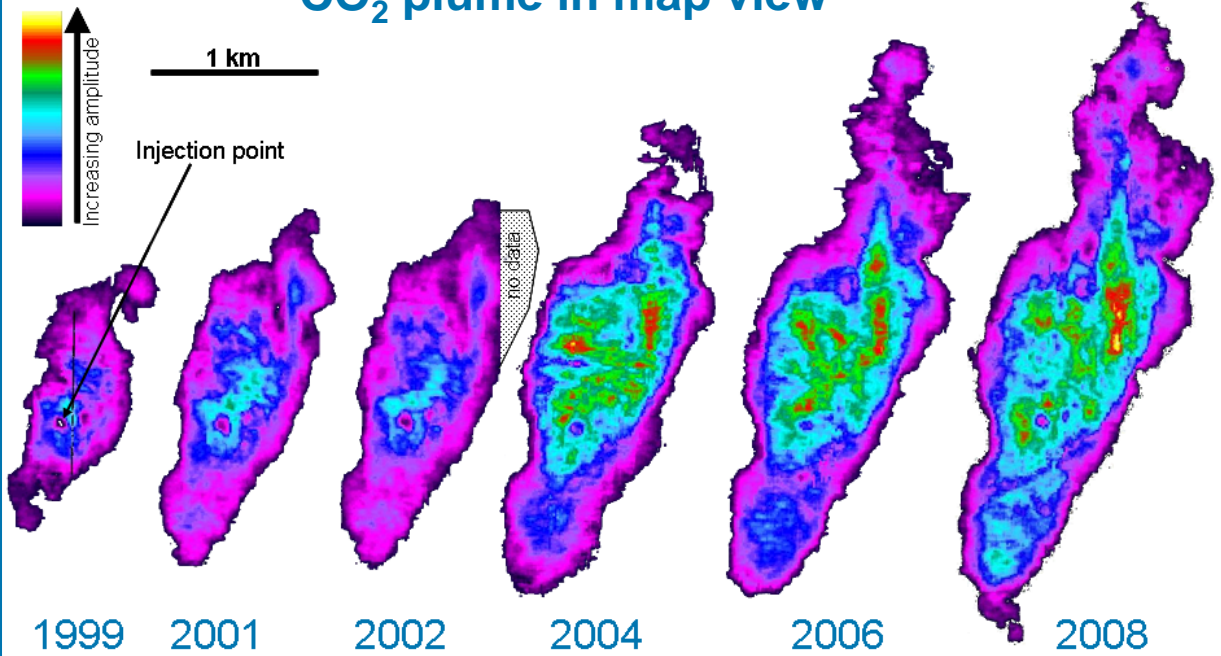
2008



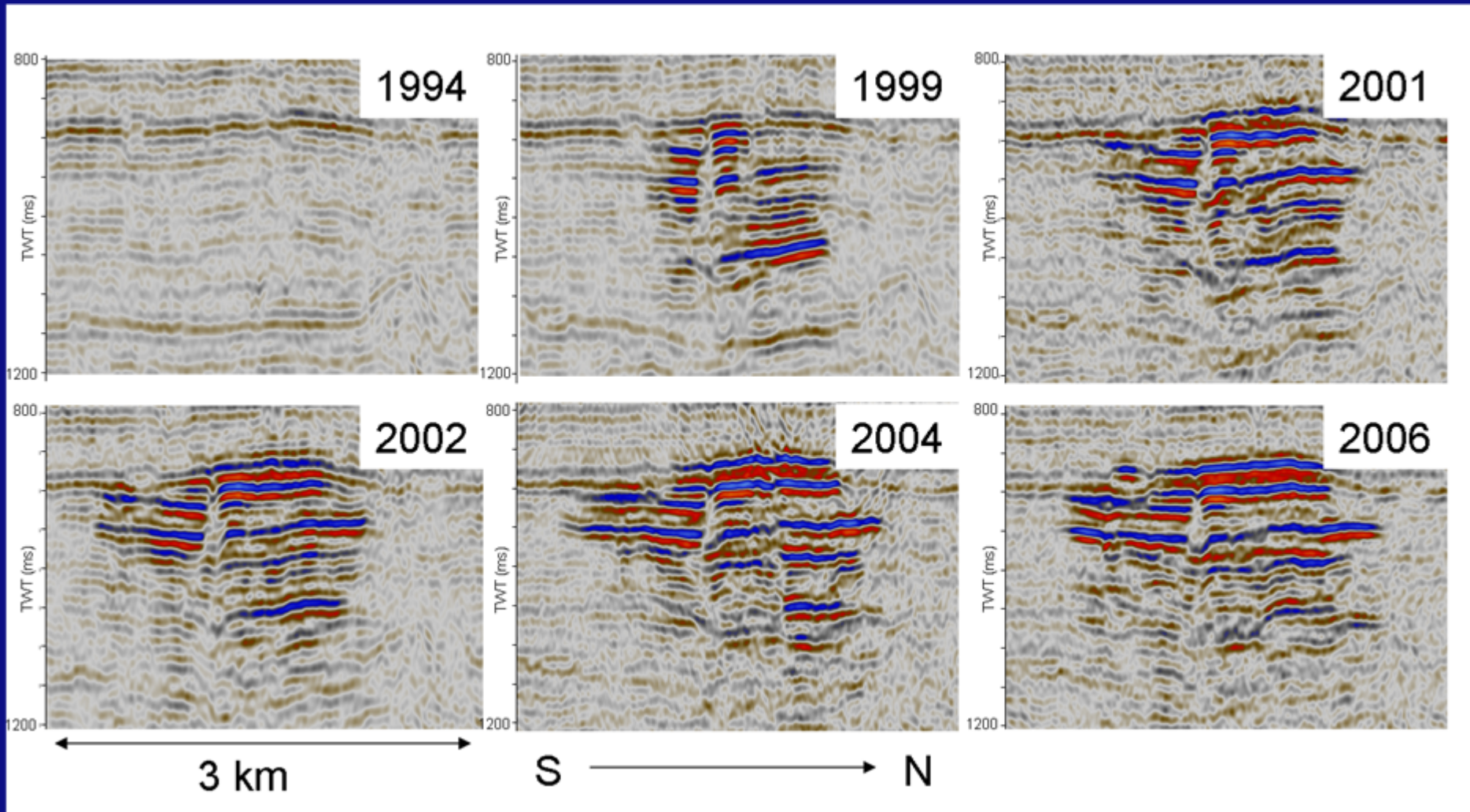
2008-1994



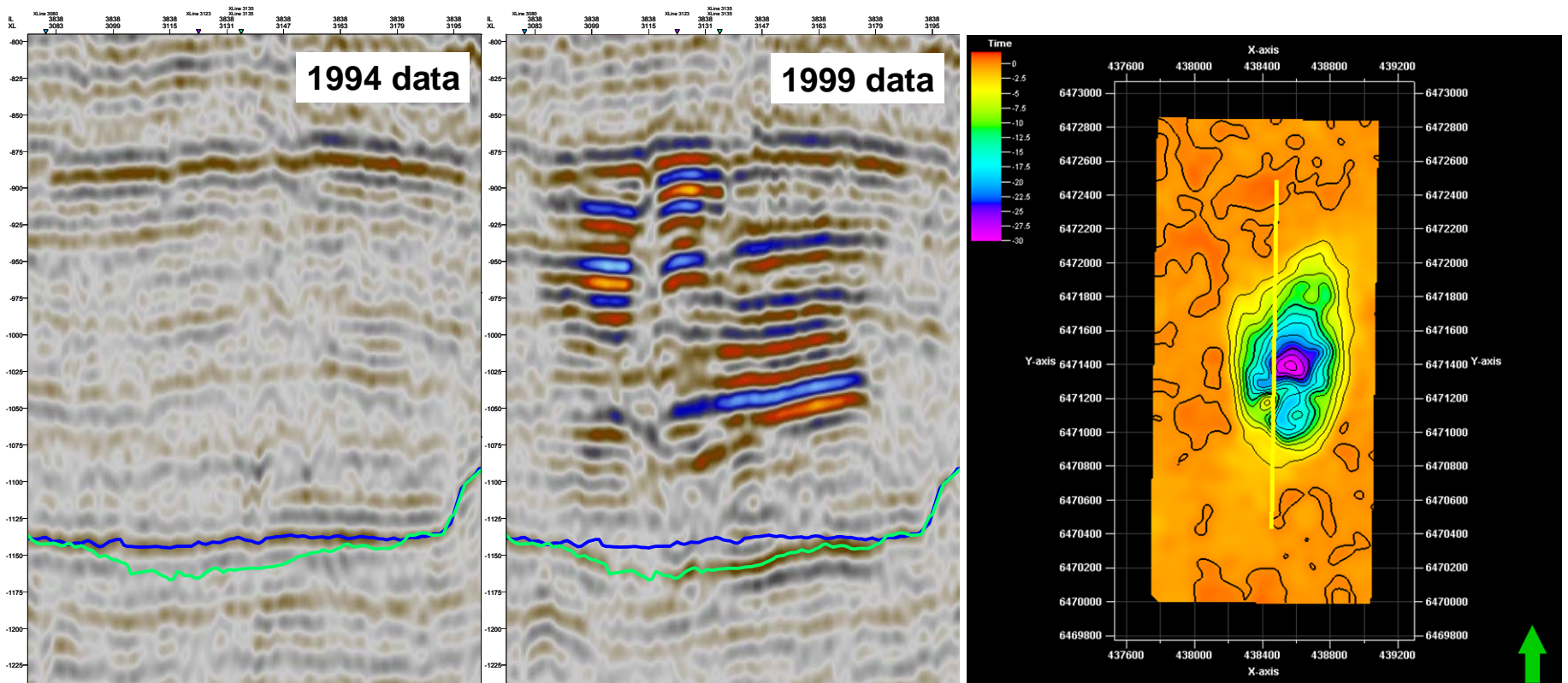
CO₂ plume in map view



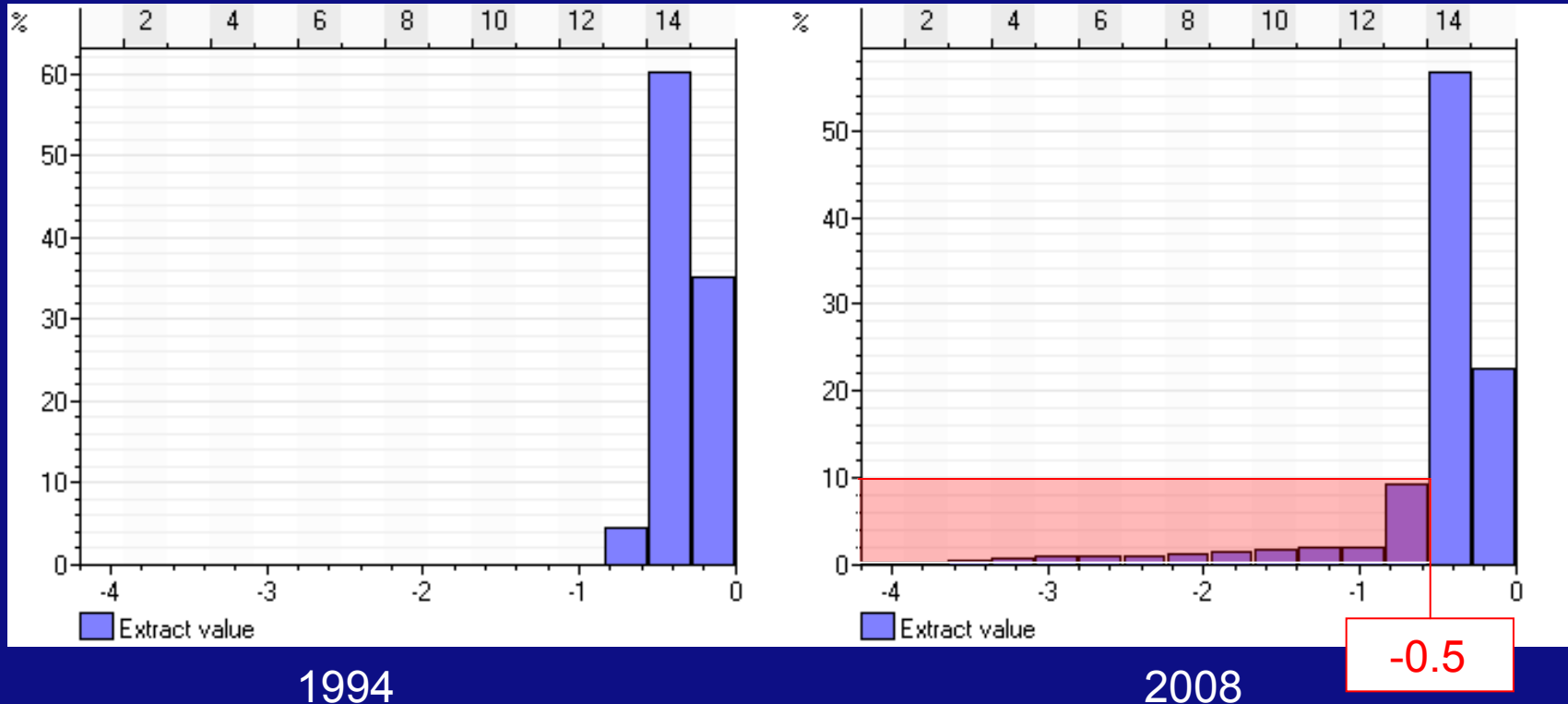
Inline of TL-seismic surveys



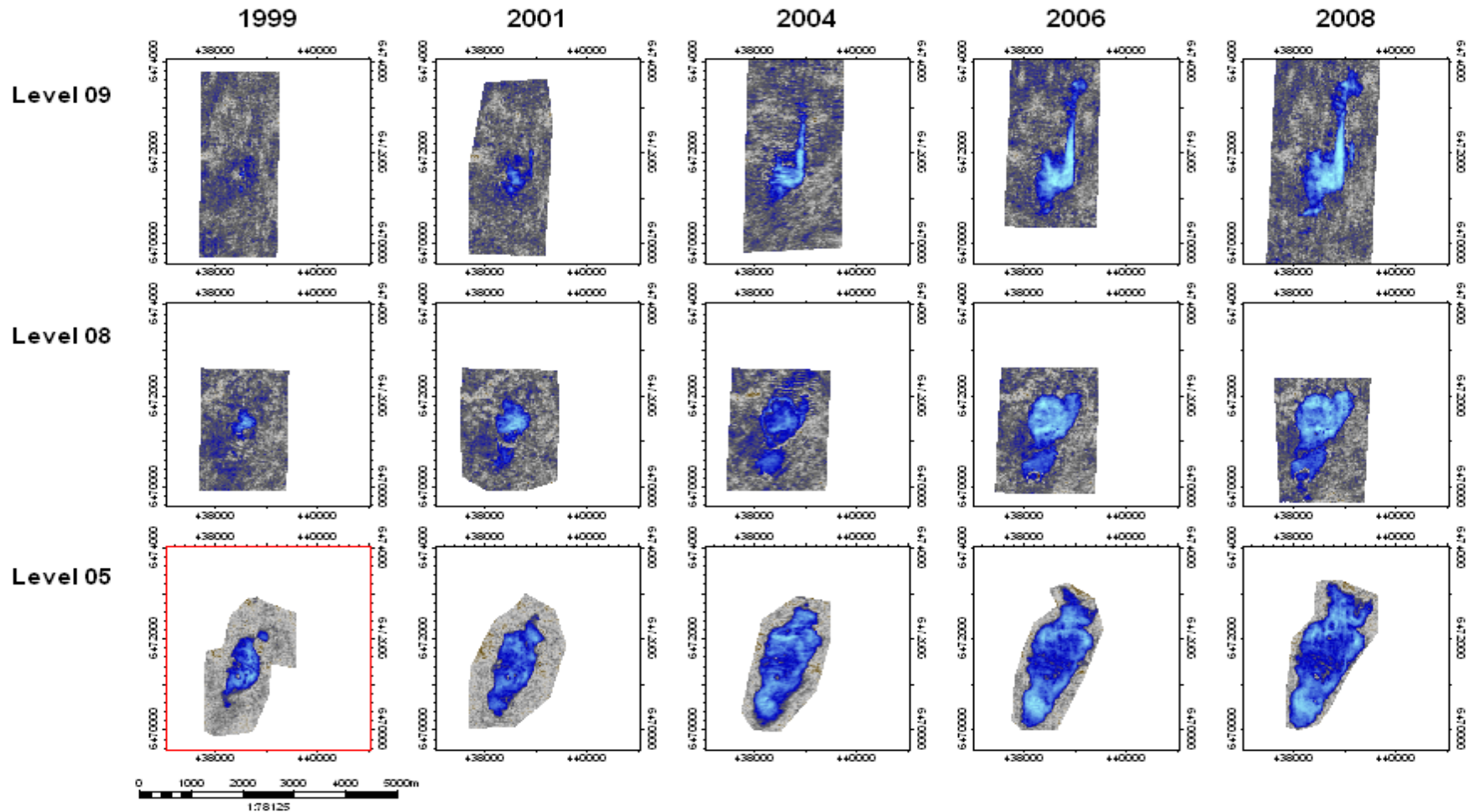
Determination of the pushdown



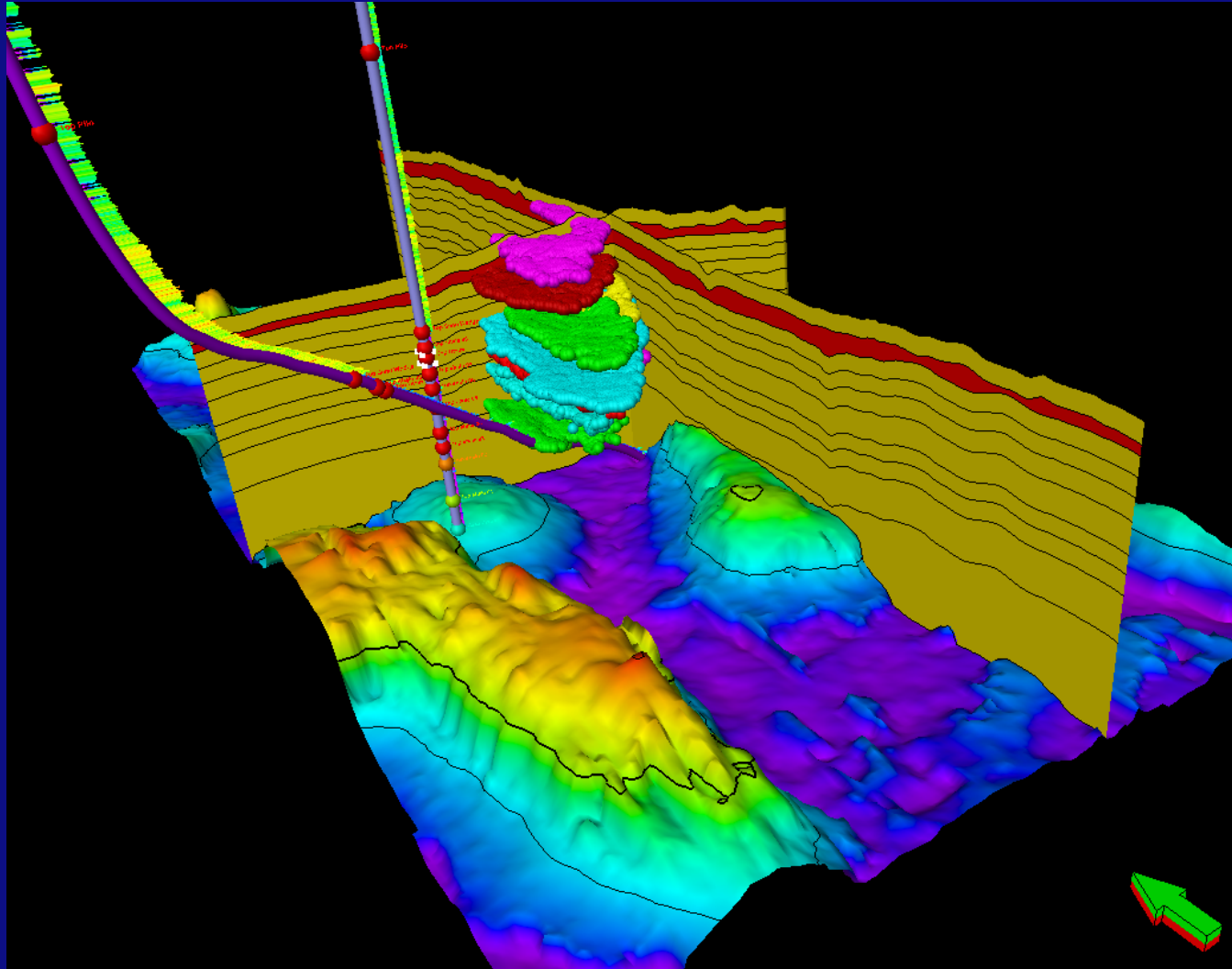
Histogram of the amplitudes: Amplitudes lower than -0.5 suggest presence of CO₂



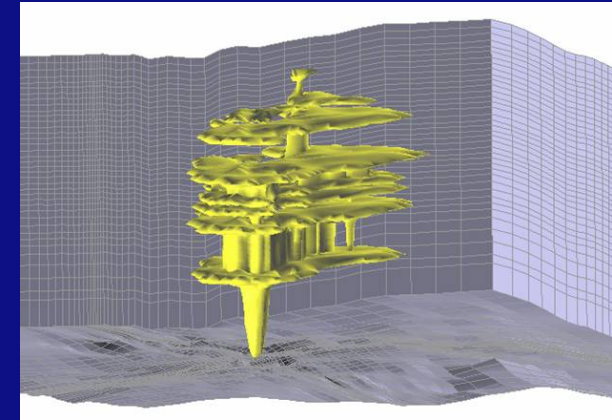
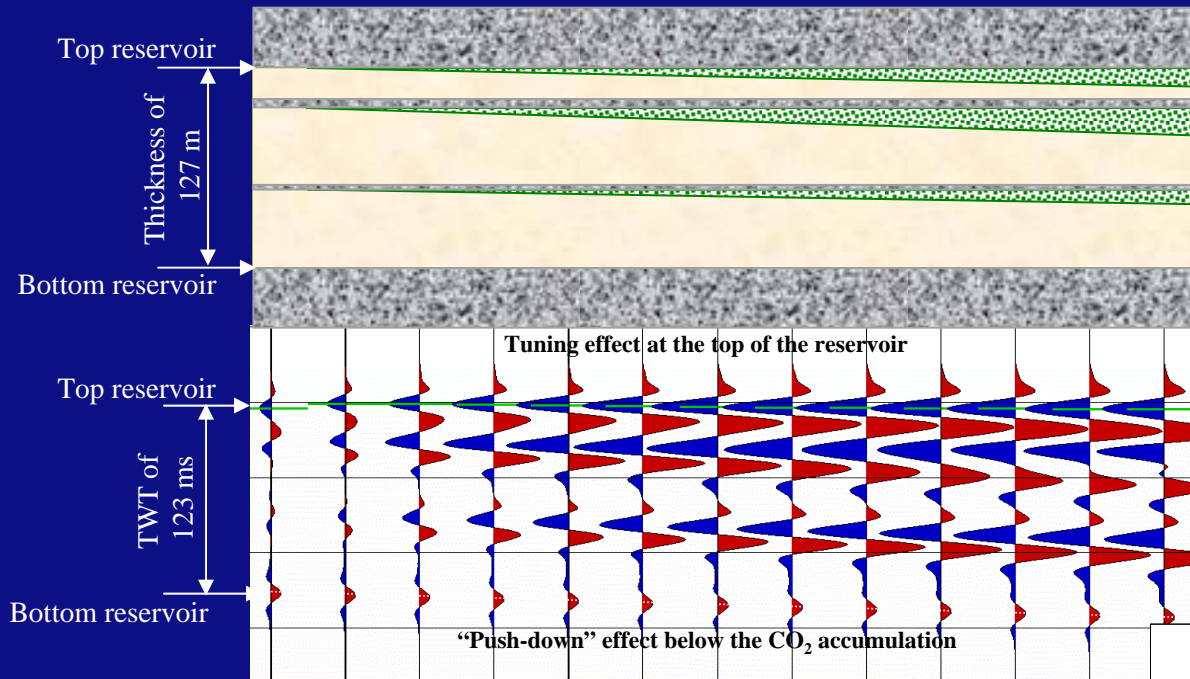
Most important CO₂ amplitude maps from 3D survey



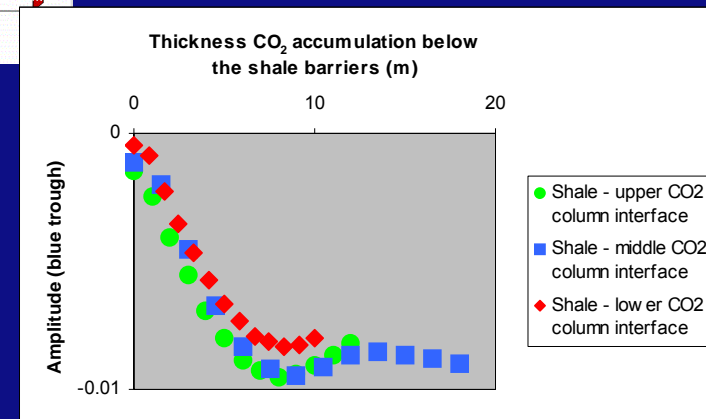
Impression of the 2002 CO₂ accumulations interpreted from the seismic data



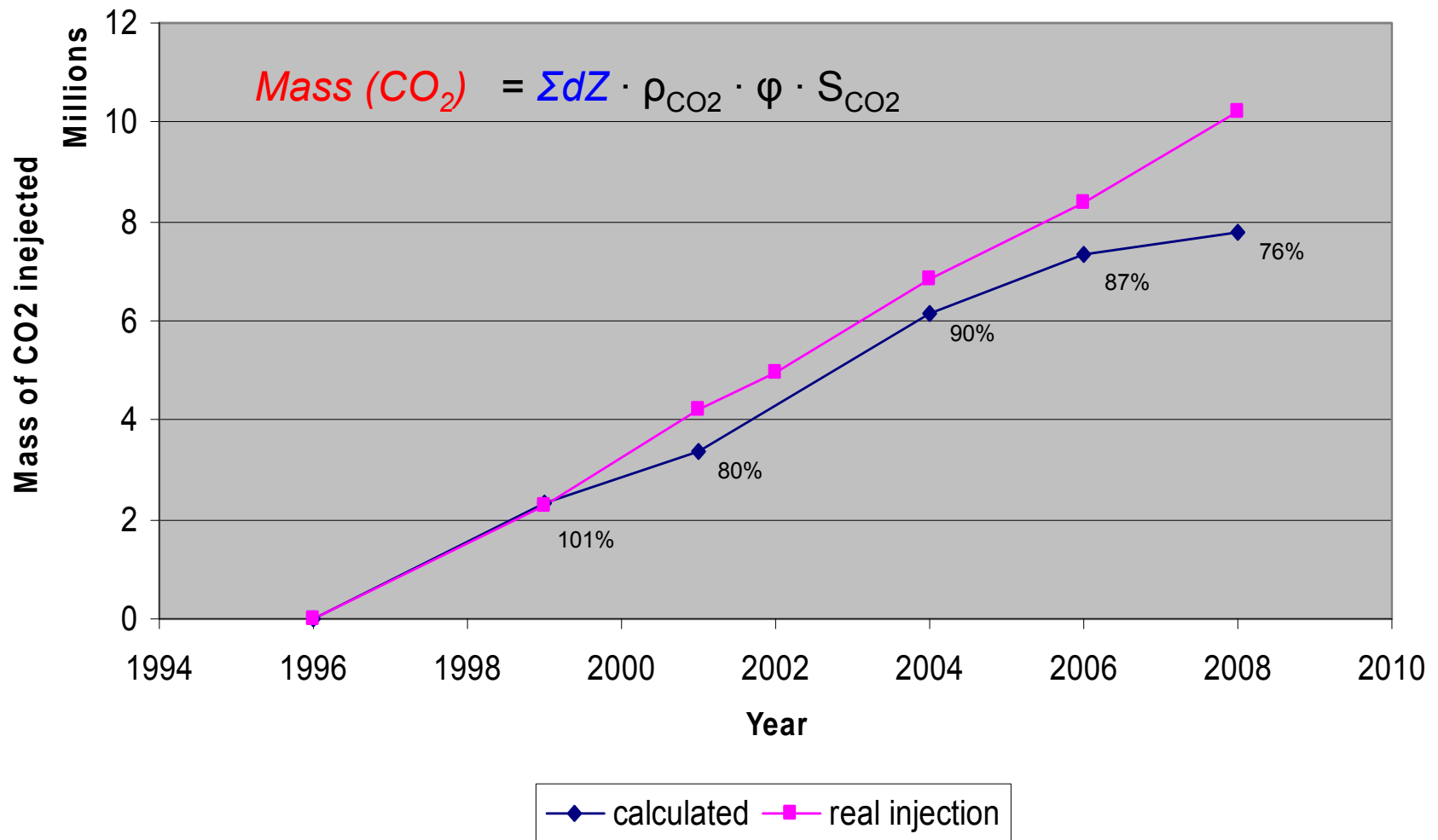
Synthetic modeling of the seismic response



- Sand
- CO₂
- Shale



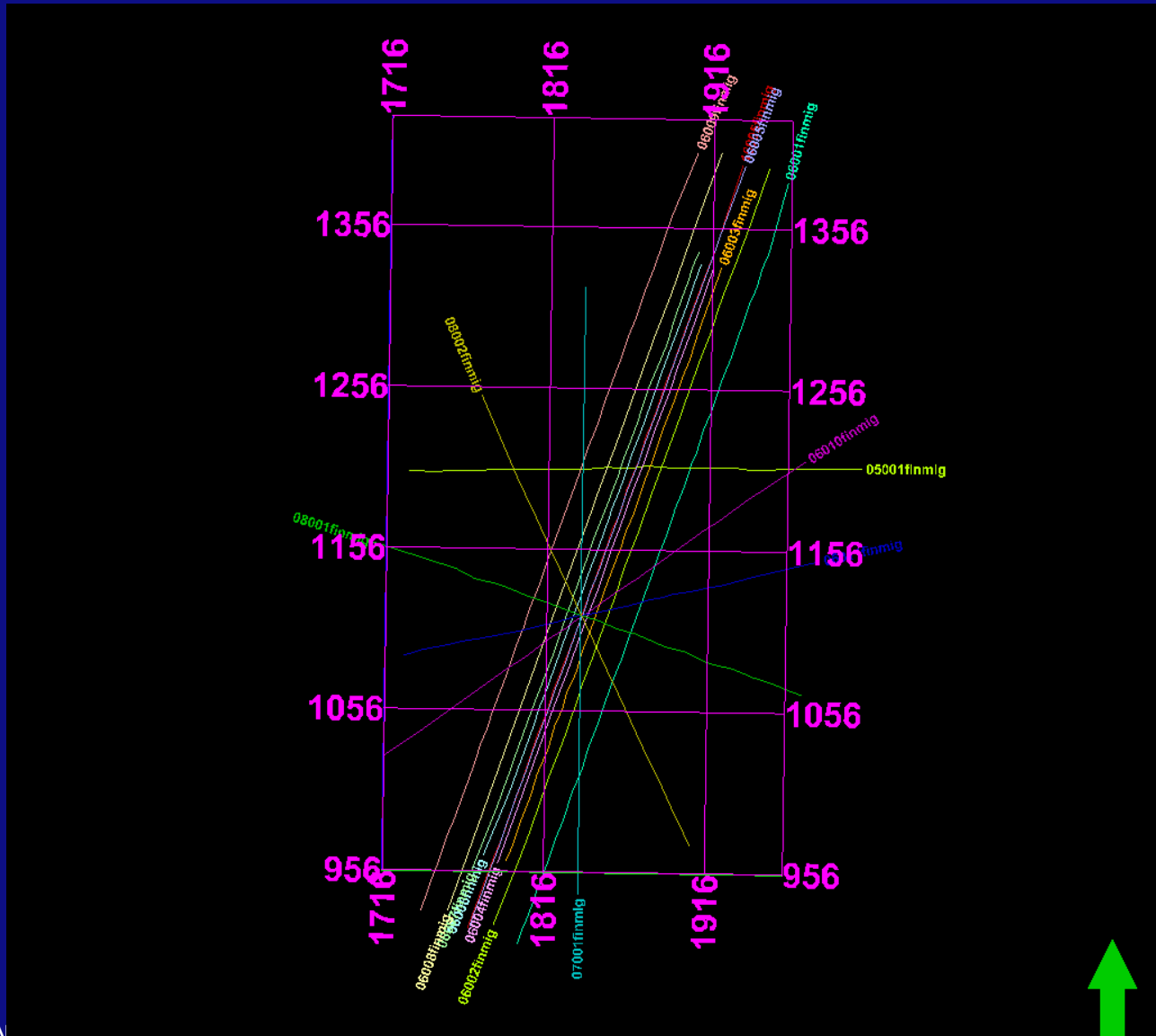
CO₂ in-situ mass verification based on seismic amplitudes



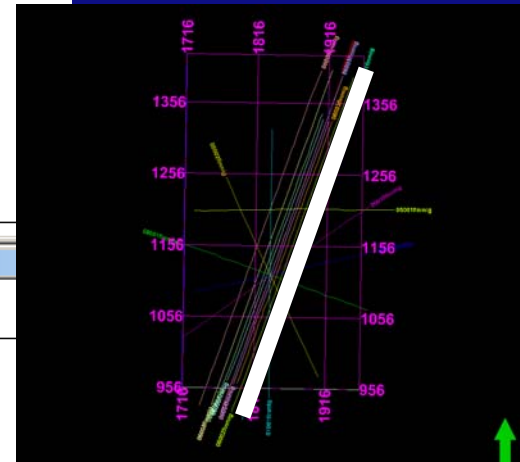
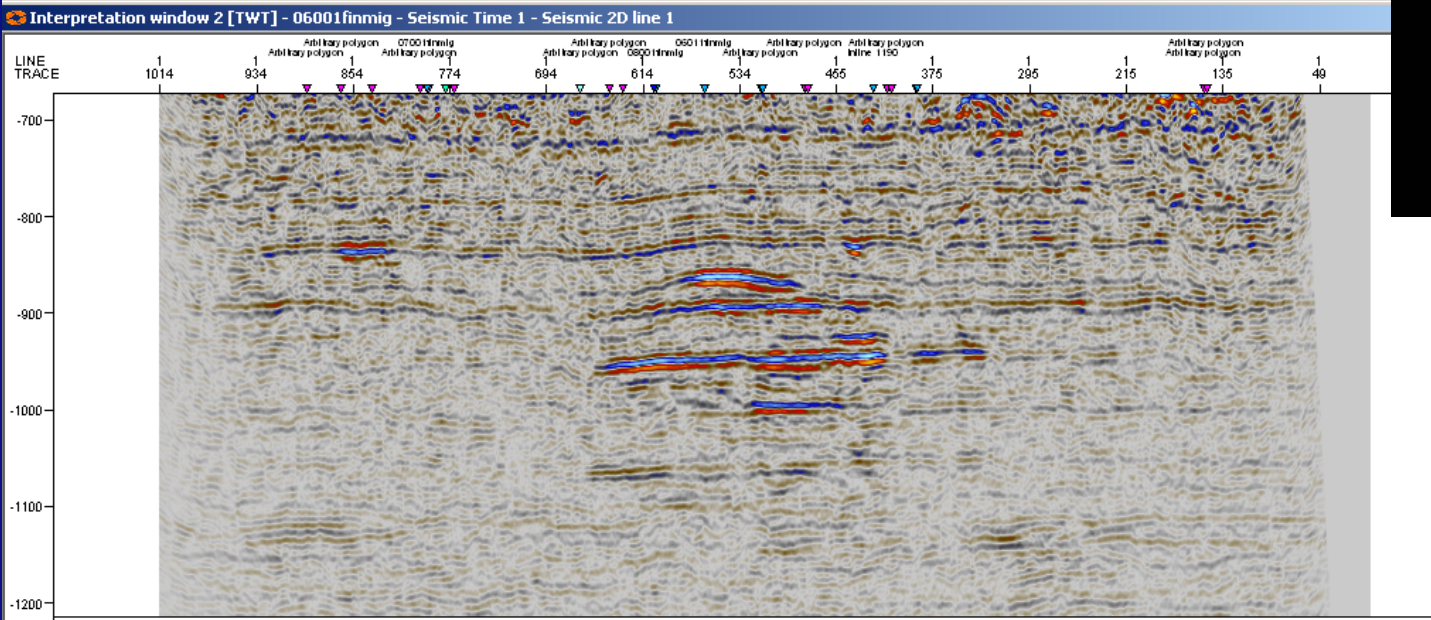
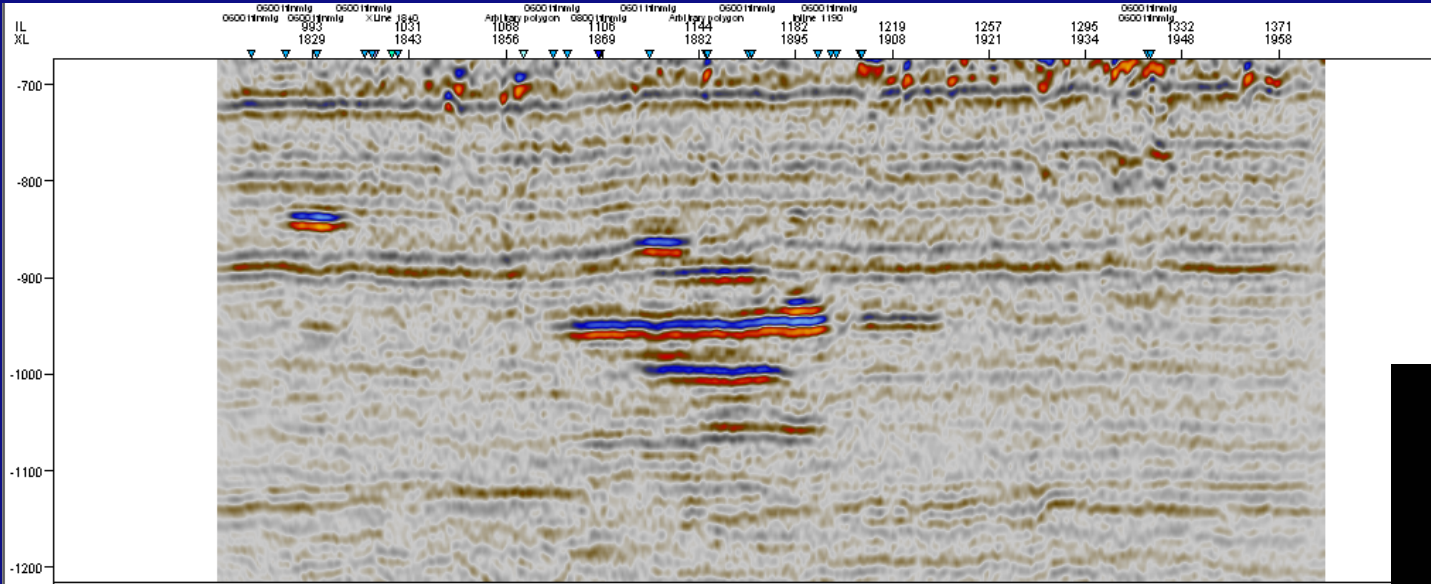
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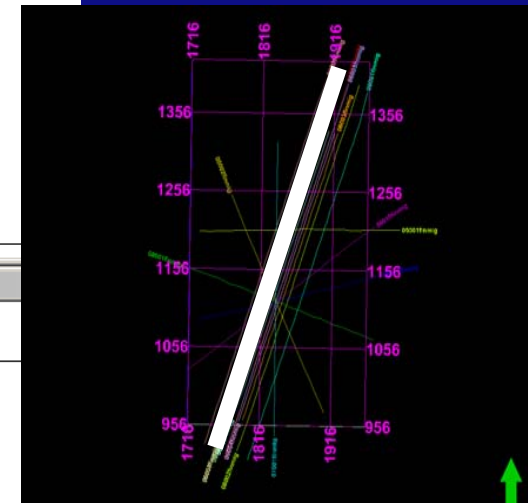
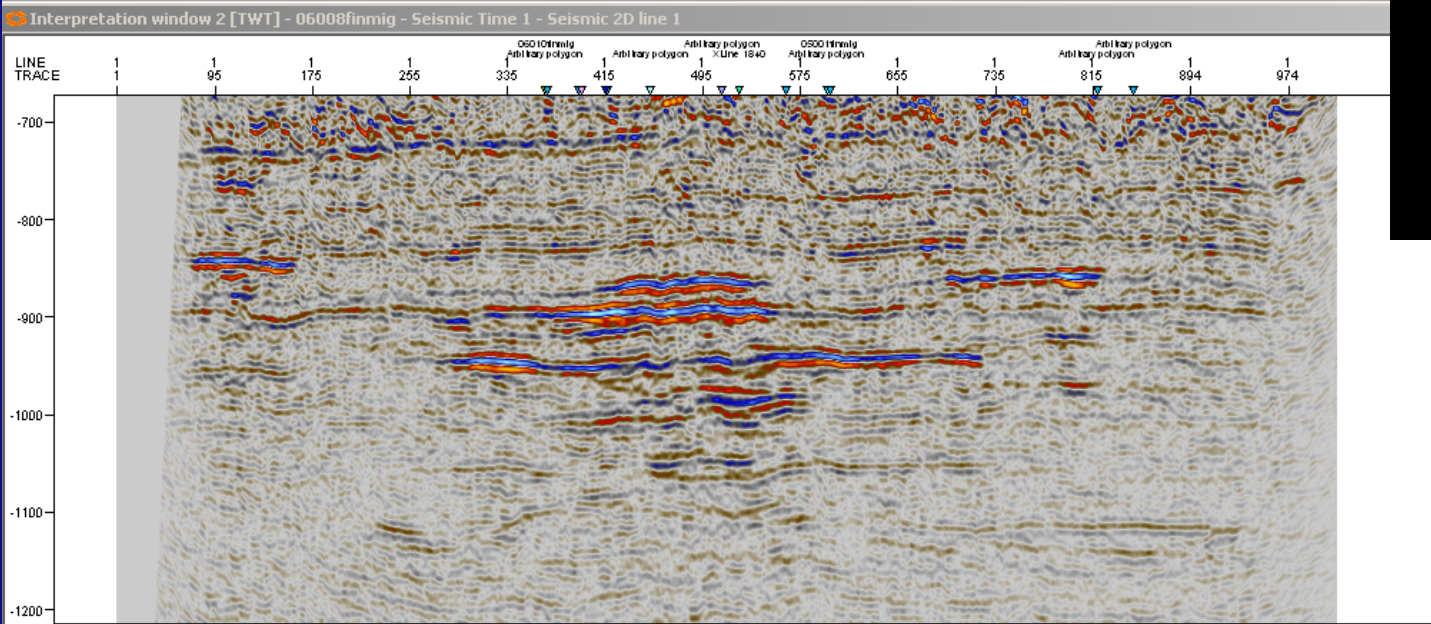
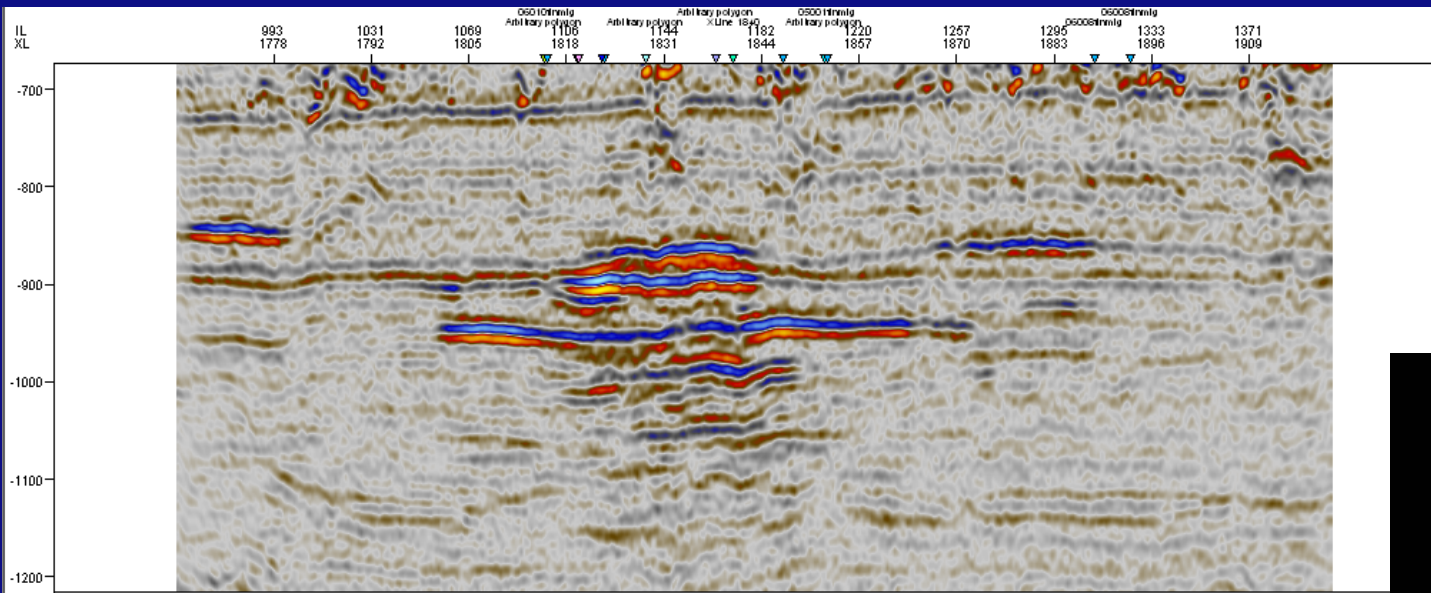
High resolution seismic lines acquired in 2006



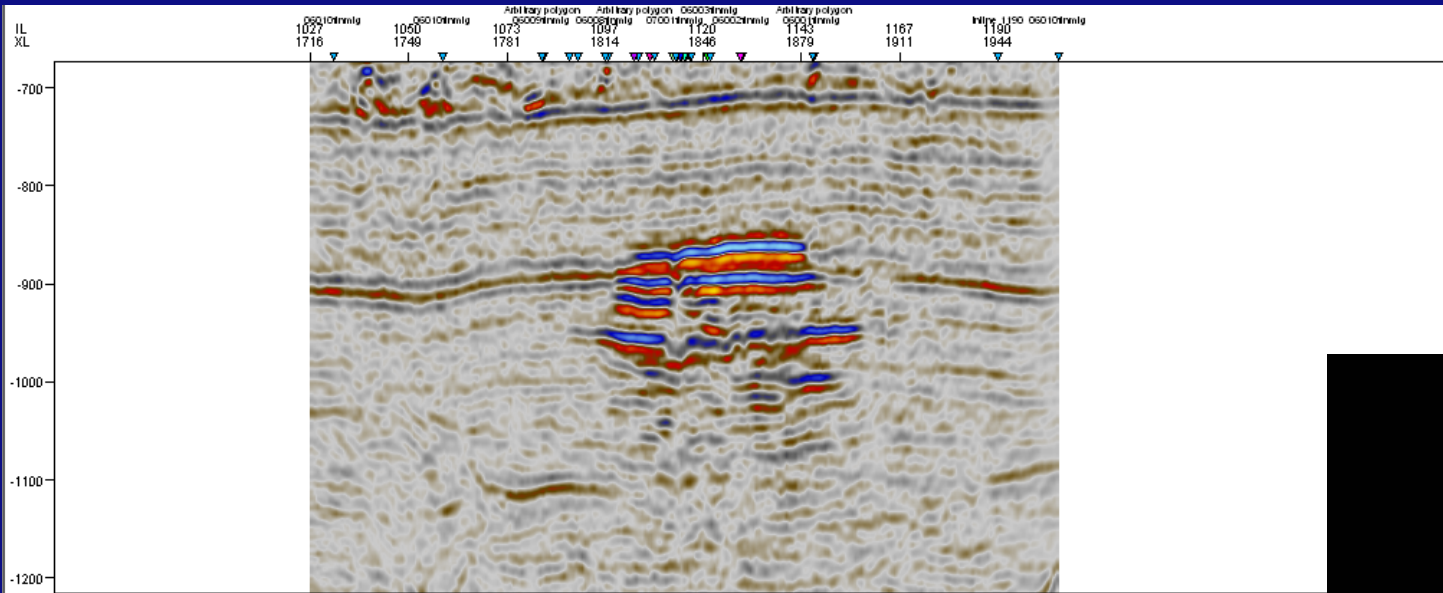
Comparison high-res vs. 3D lines (line 6001)



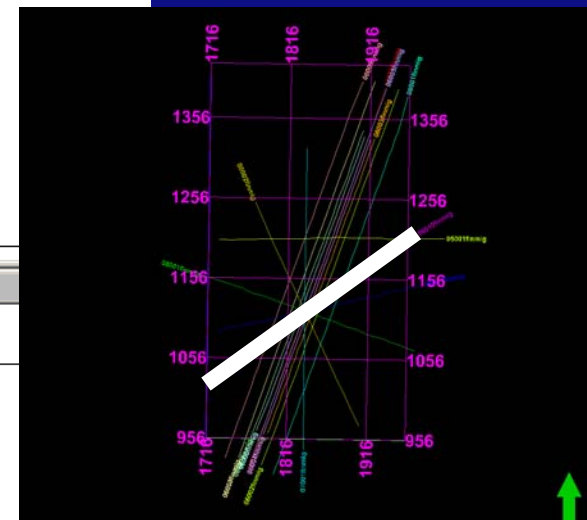
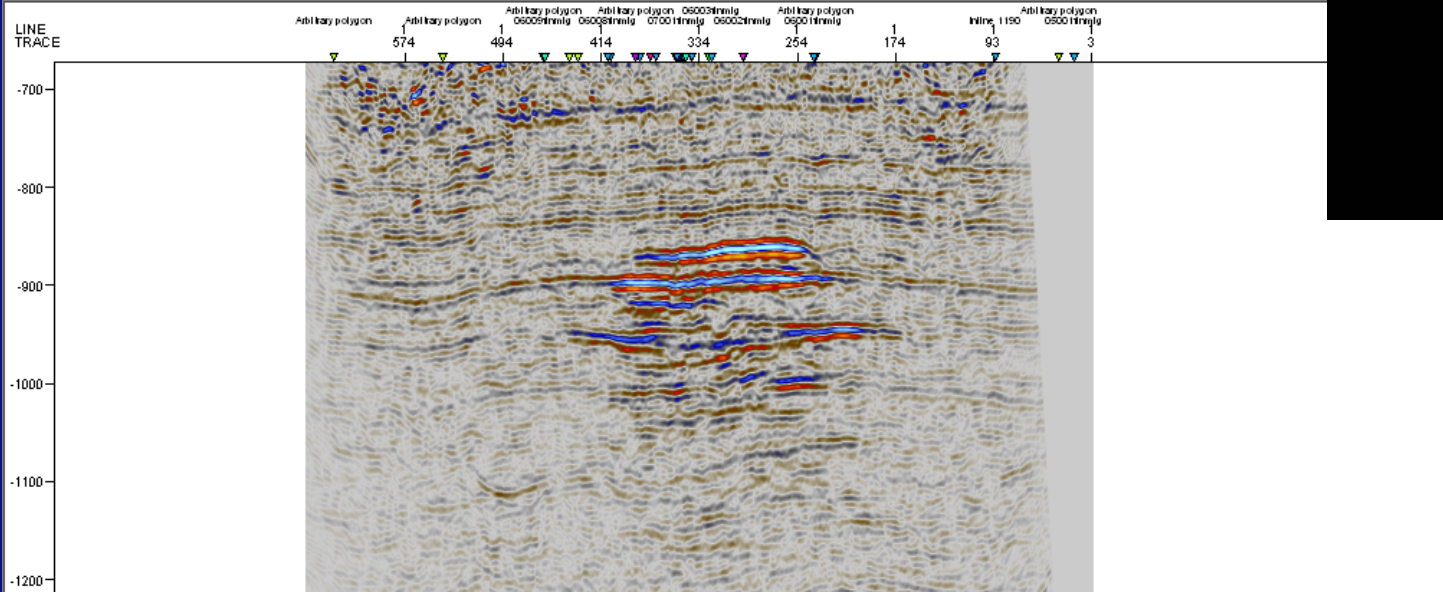
Comparison high-res vs. 3D lines (line 6008)



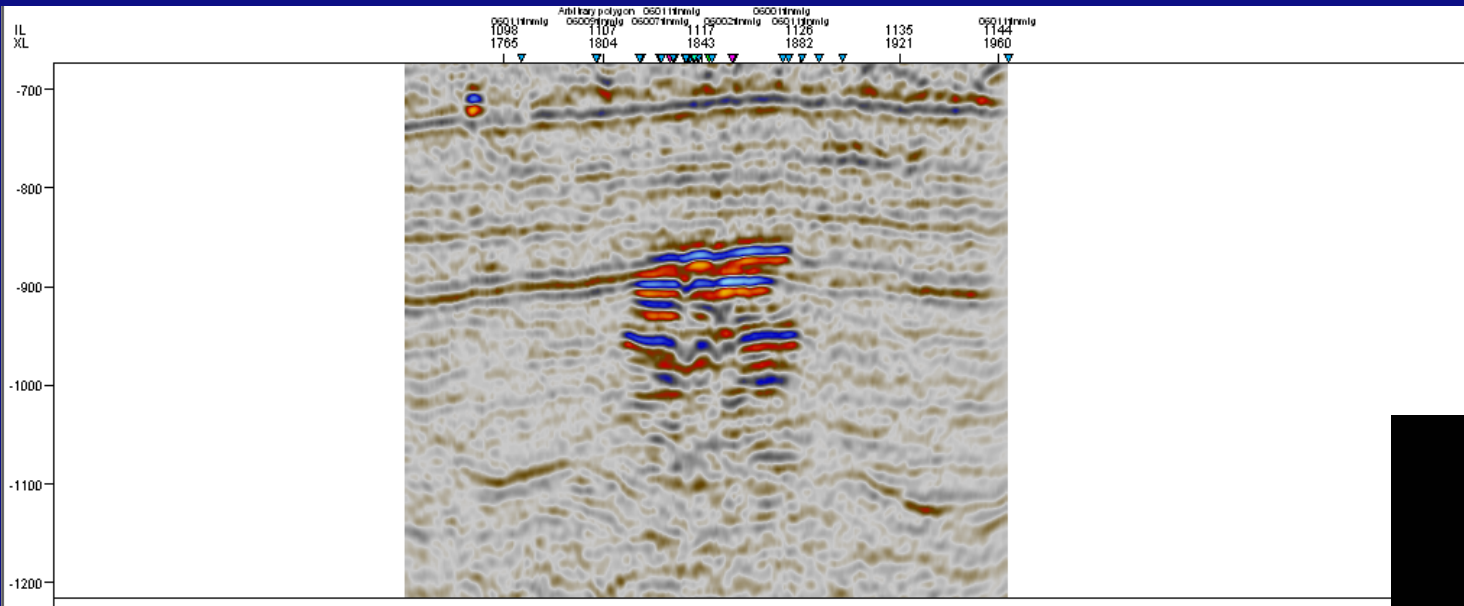
Comparison high-res vs. 3D lines (line 6010)



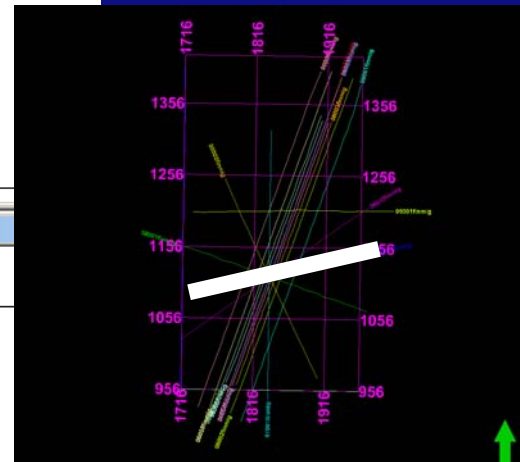
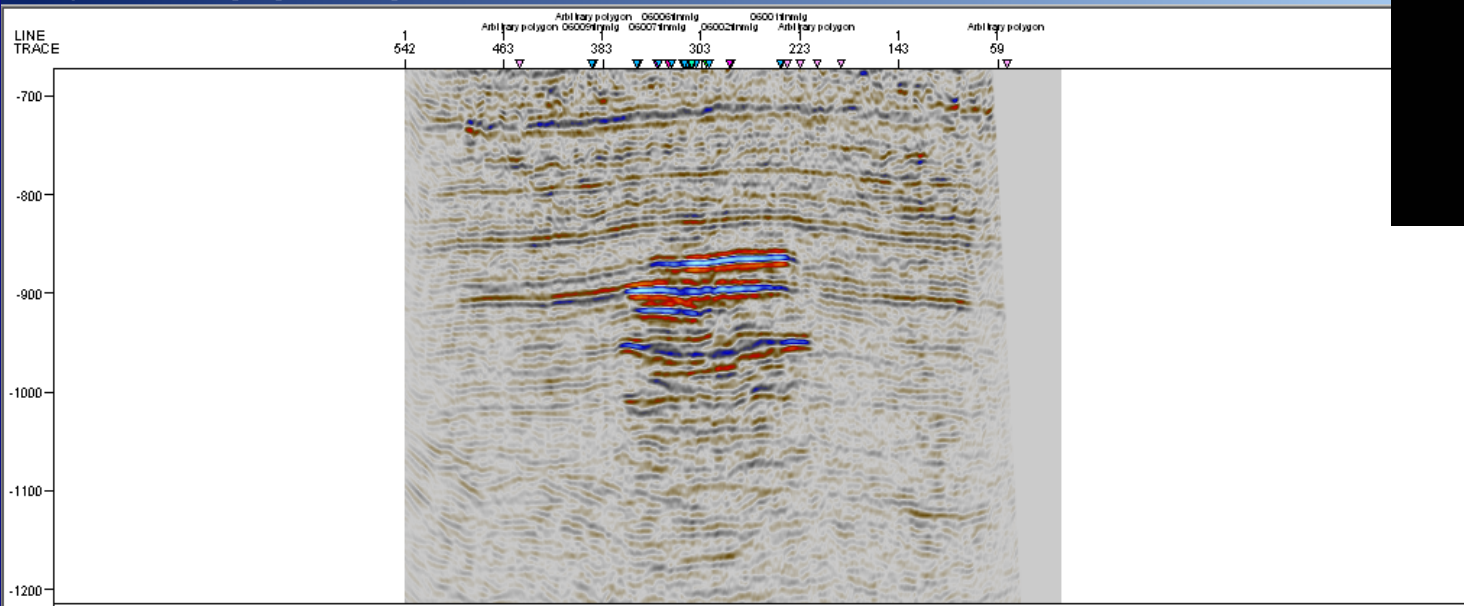
Interpretation window 2 [TWT] - 06010finmig - Seismic Time 1 - Seismic 2D line 1



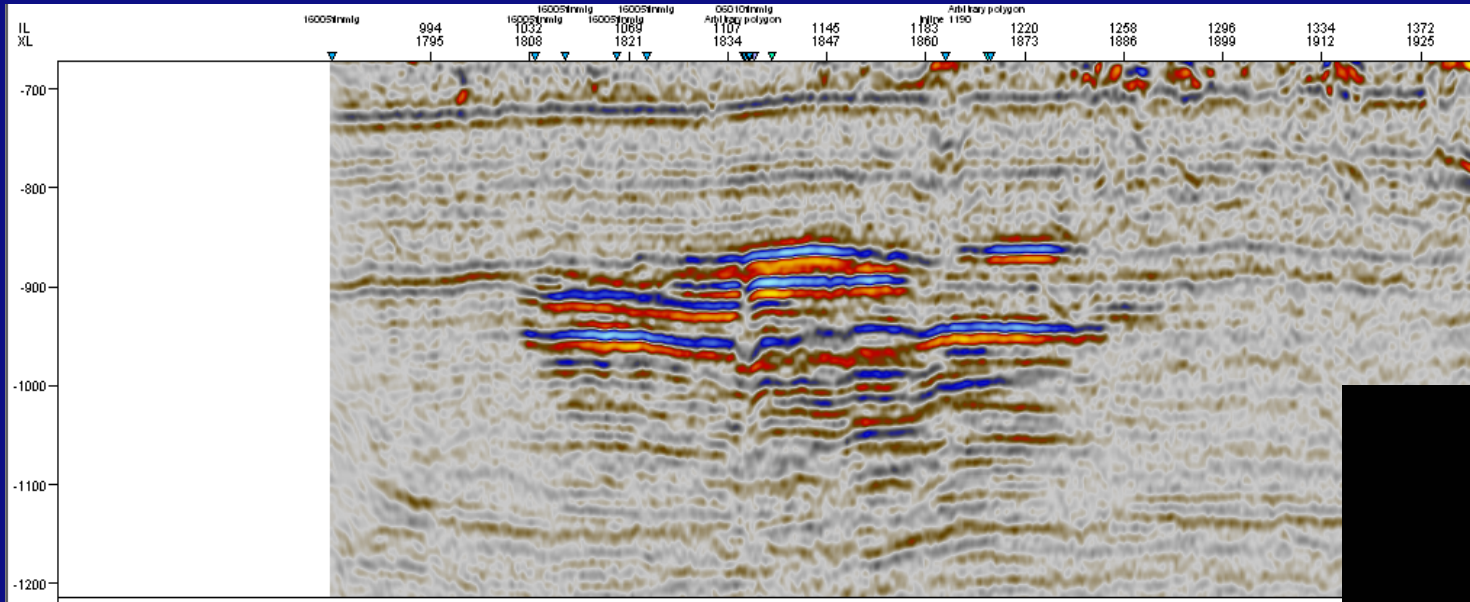
Comparison high-res vs. 3D lines (line 6011)



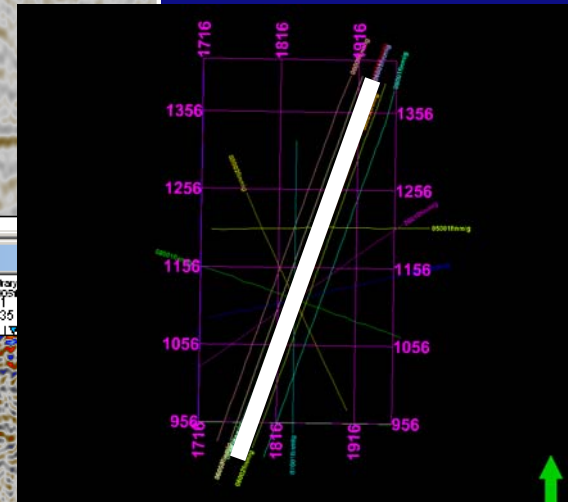
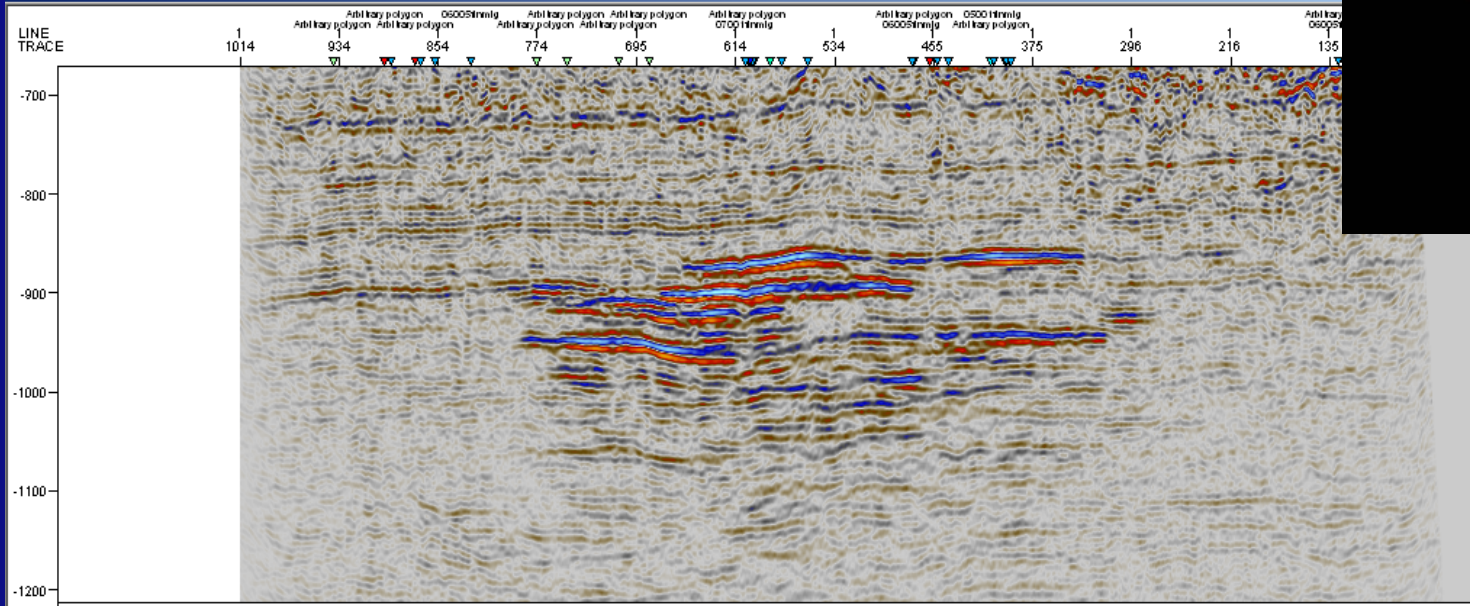
Interpretation window 2 [TWT] - 06011finmig - Seismic Time 1 - Seismic 2D line 1



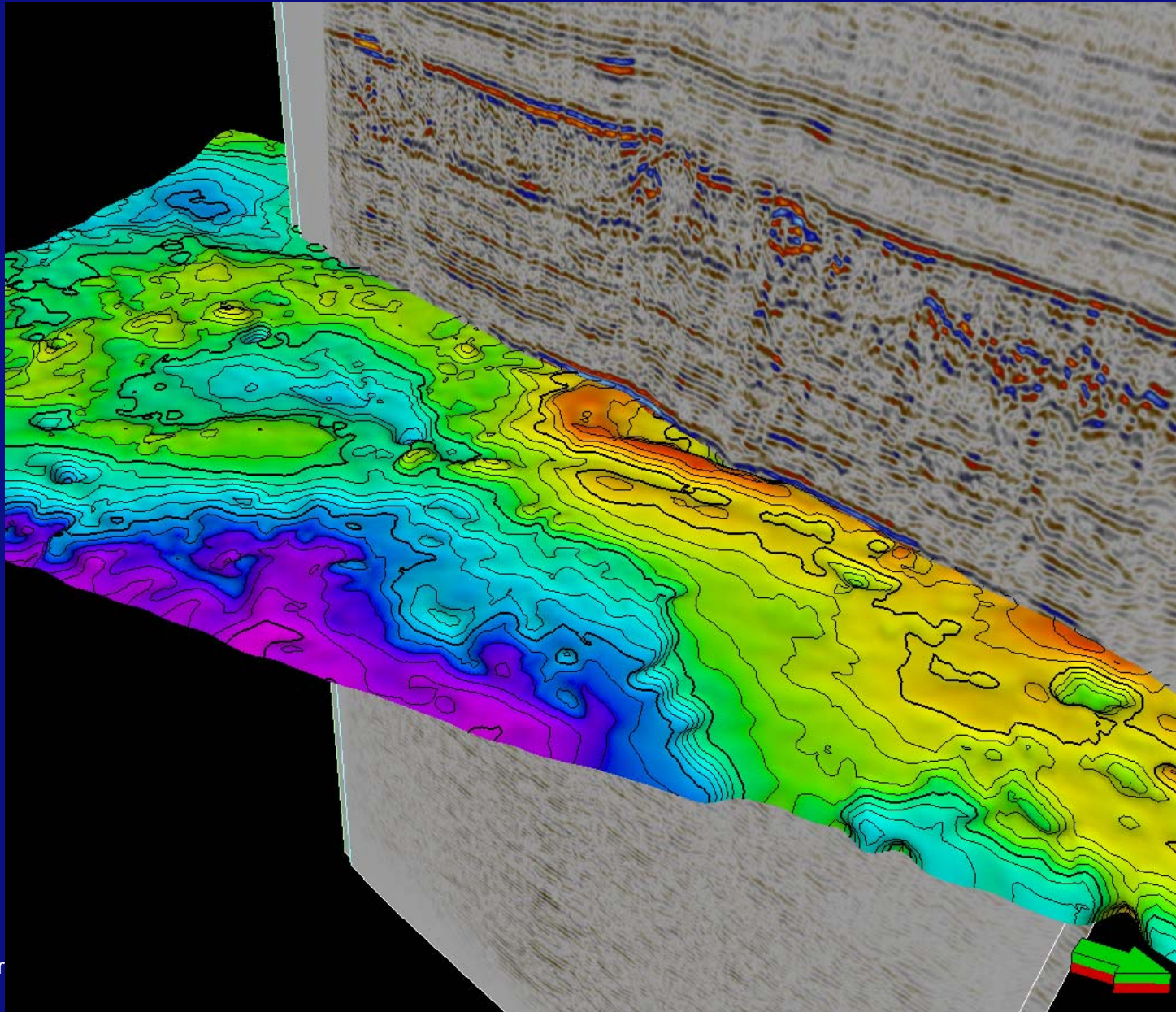
Comparison high-res vs. 3D lines (line 16005)



Interpretation window 2 [TWT] - 16005finmig - Seismic Time 1 - Seismic 2D line 1



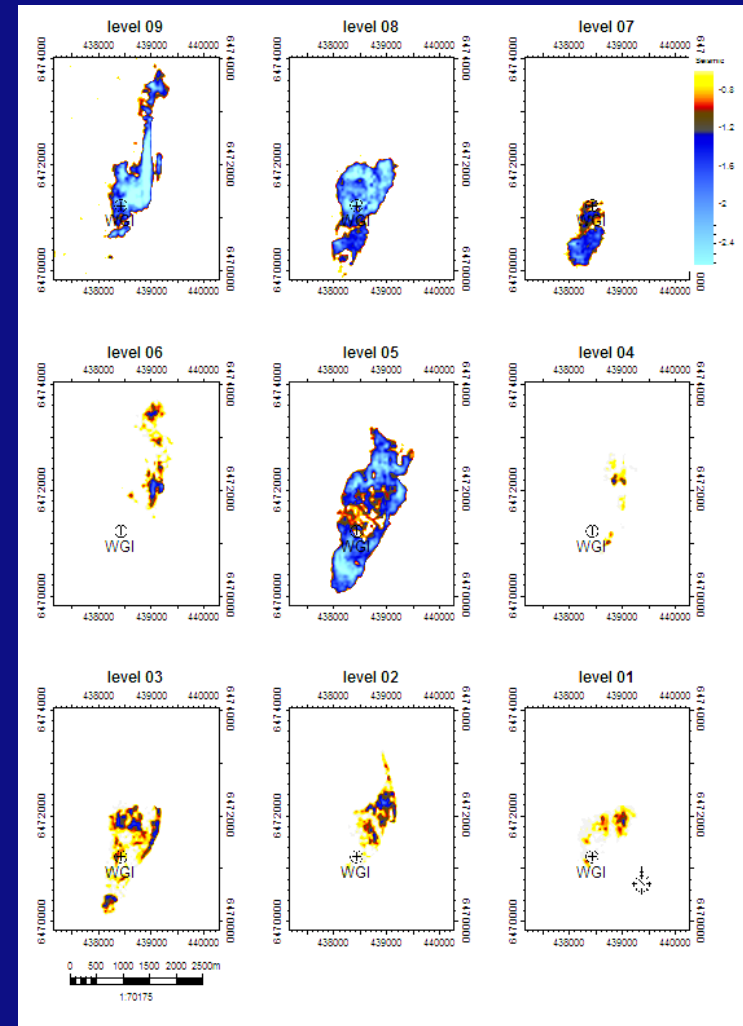
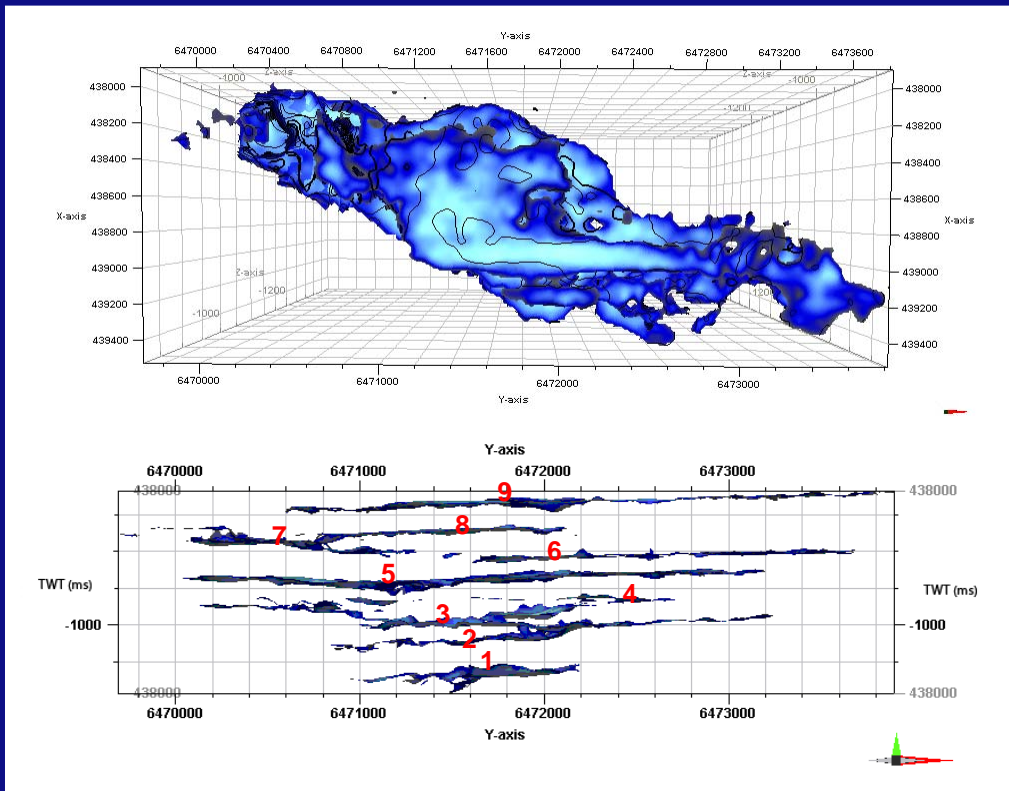
3D interpretation and the high-res lines (line 6006)

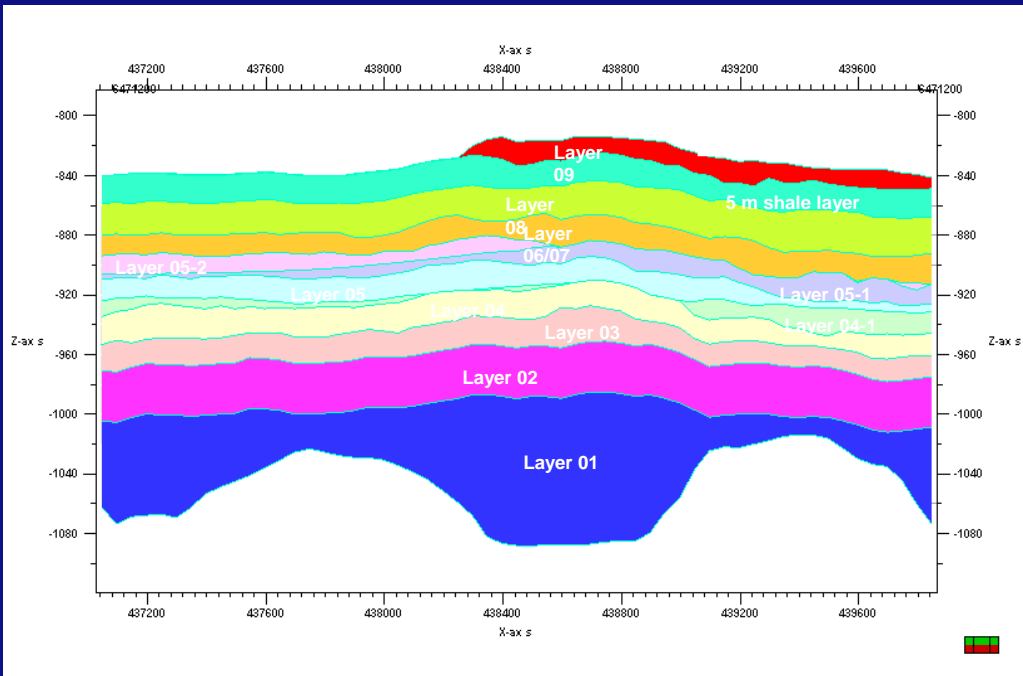


Interpretation of CO₂ levels in 2008

The CO₂ plume:

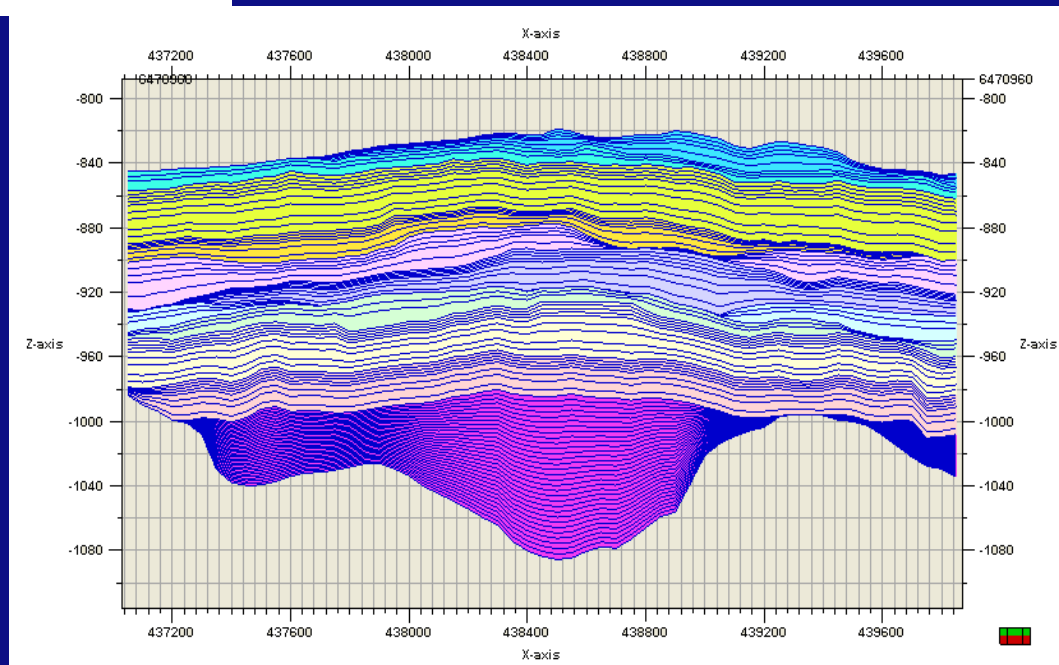
- 1500 m in 1999 - 4000 m in 2008
- Roughly 200 m thick
- Elliptical geometry
- Major levels: 05, 08 & 09



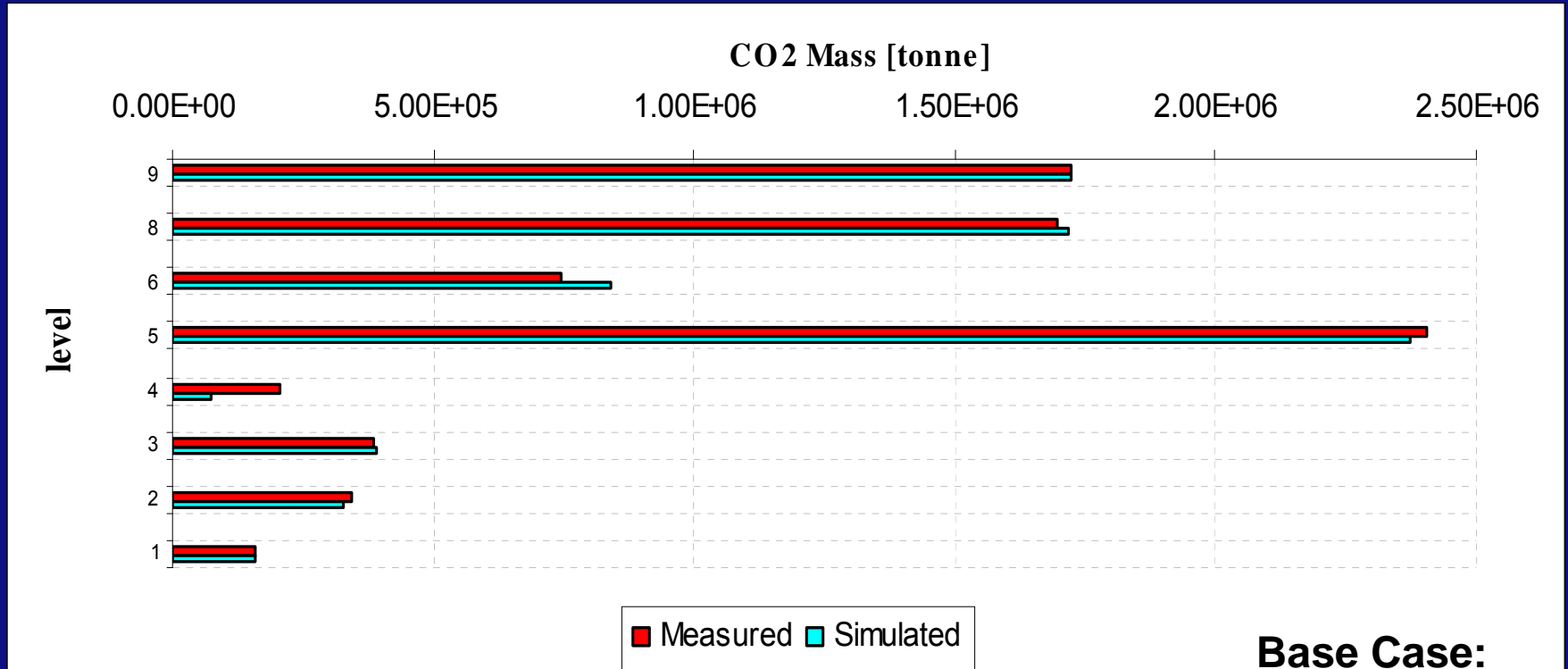


The stratigraphic pattern of the layers in the generated model (around the CO₂ plume).

The resulting reservoir simulation model



History Match of the Sleipner CO₂ Injection, Using 4D Seismic Data: Base case model matched in 2008



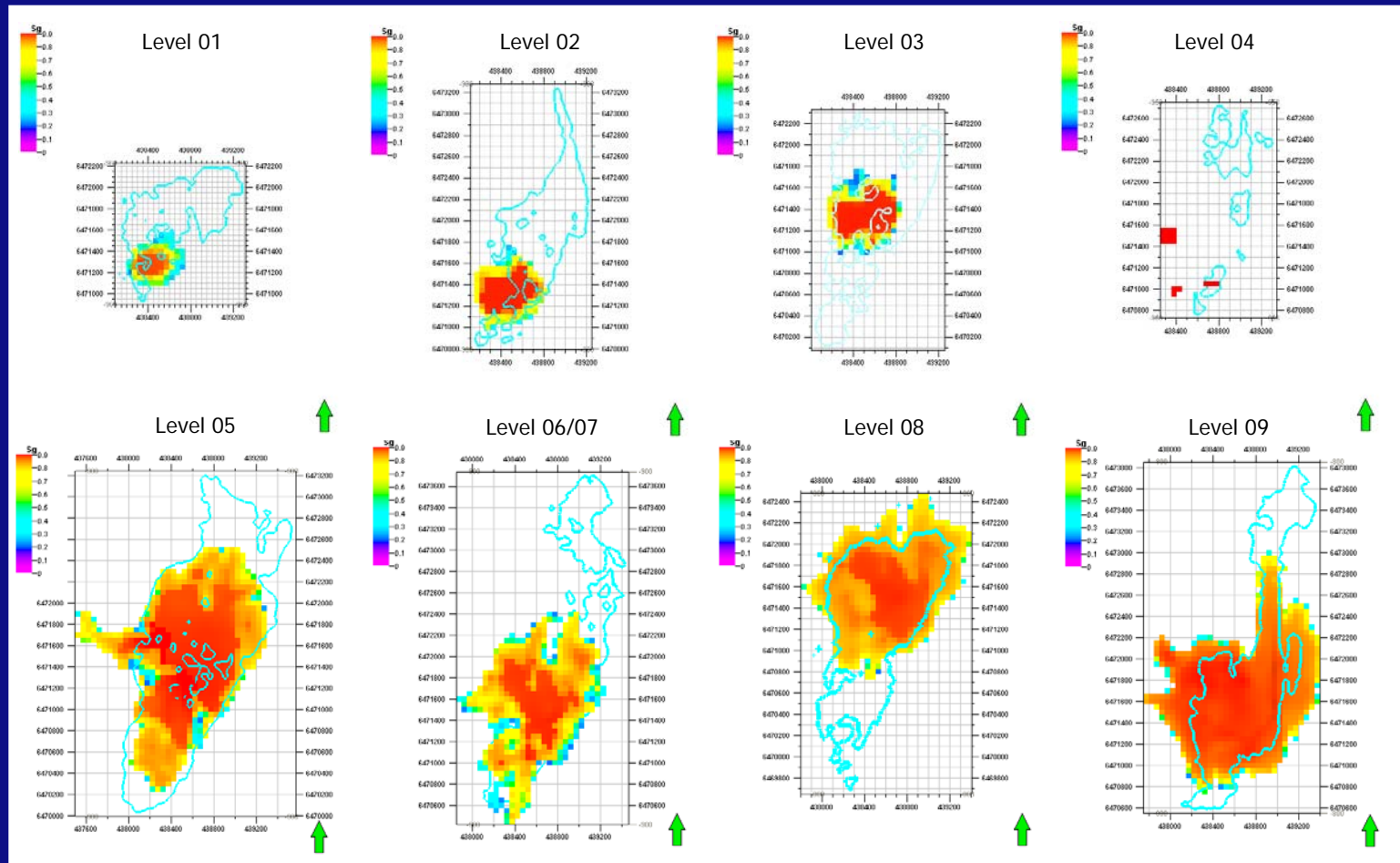
Base Case:

$T_{Res} = 37 \text{ } ^\circ \text{C}$

$K_v = K_h = 2 \text{ Darcy}$

$\Phi = 38 \text{ } \%$

History Match of the Sleipner CO₂ Injection, Using 4D Seismic Data: Base case model matched in 2008

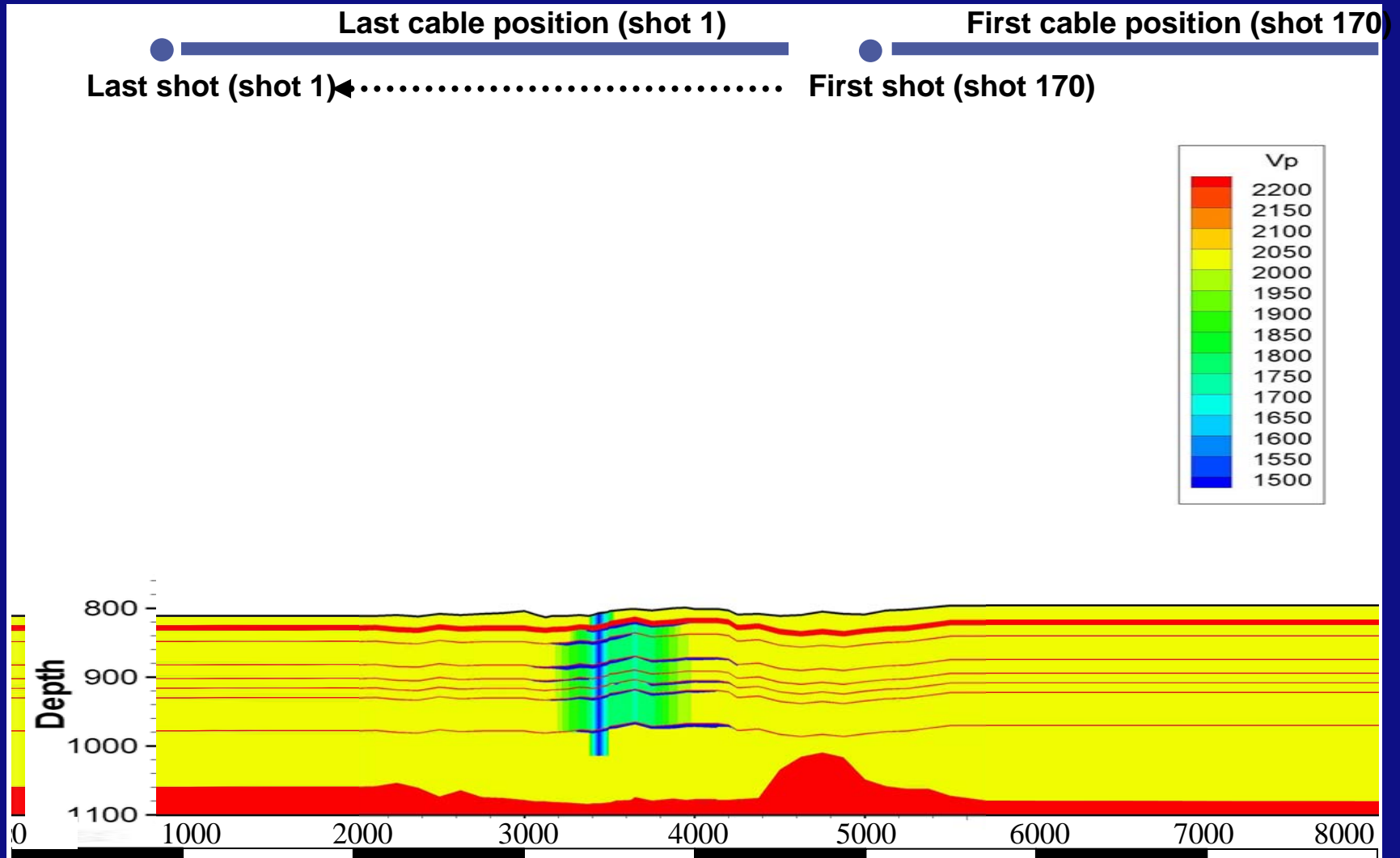


Comparison of the CO₂ anomaly boundary observed of 4D seismic data with the base case simulated CO₂ migration pattern in 2008

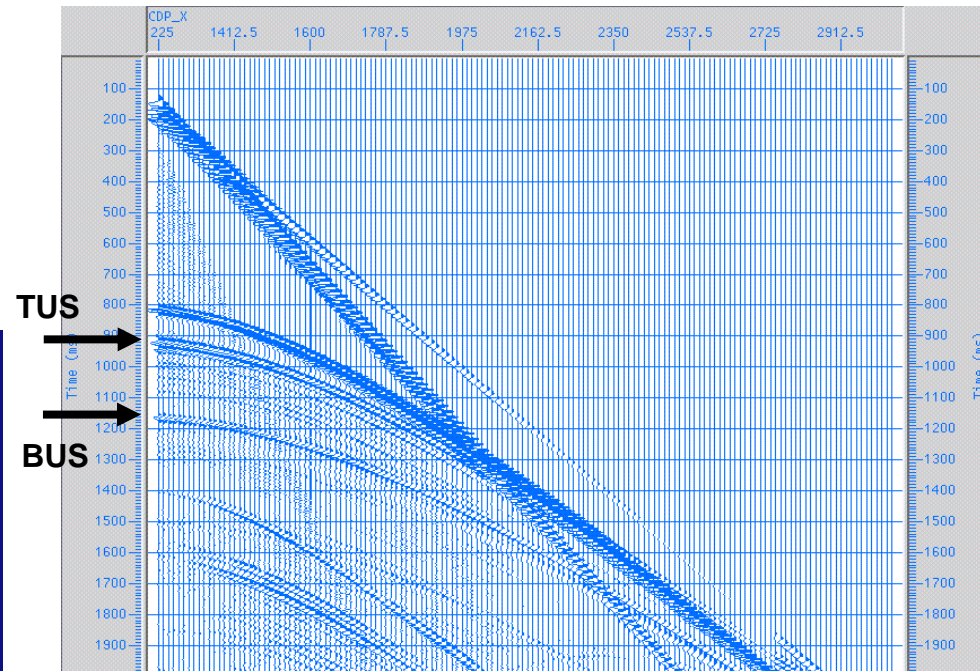
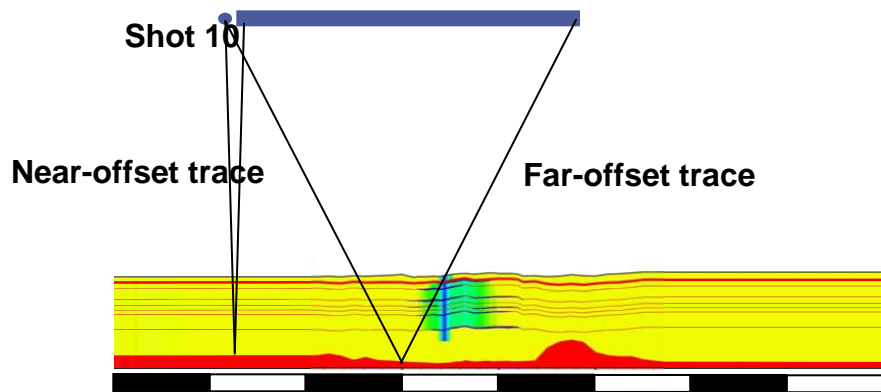
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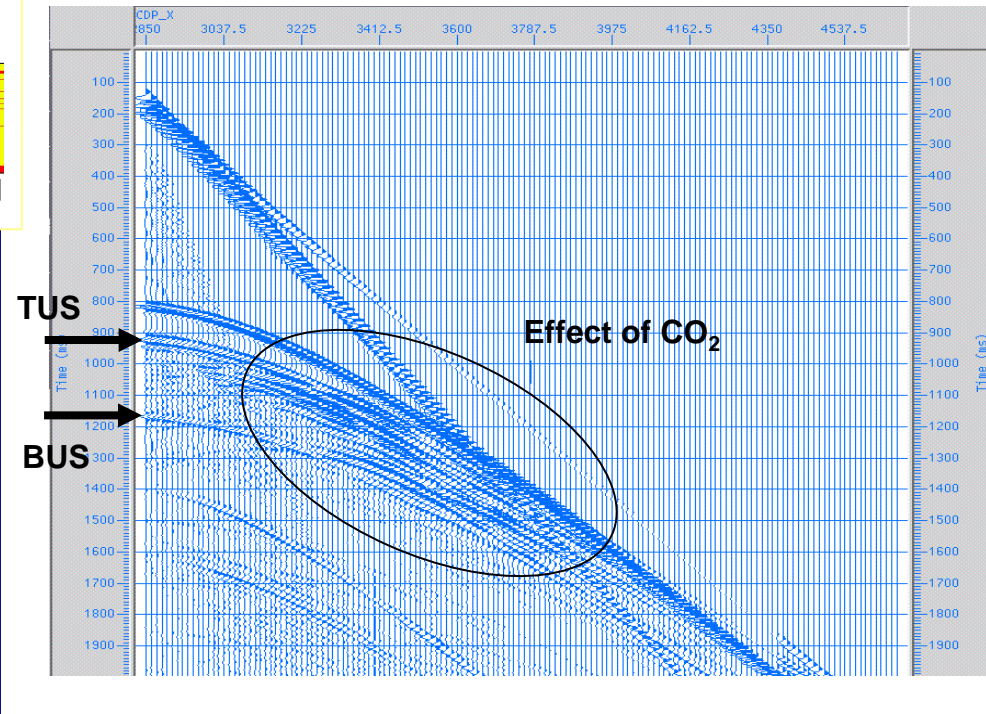
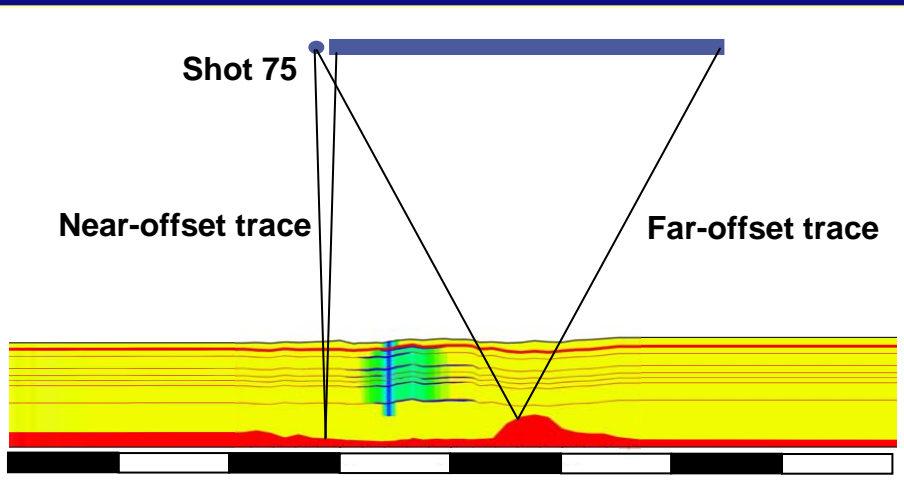
Layout of the (synthetic) acquisition scheme



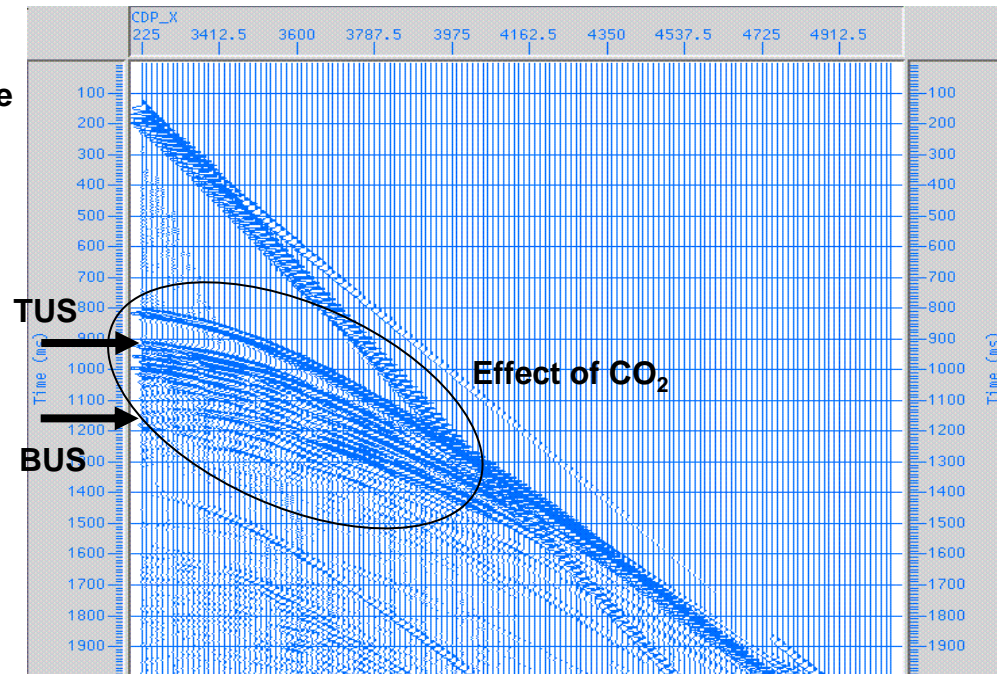
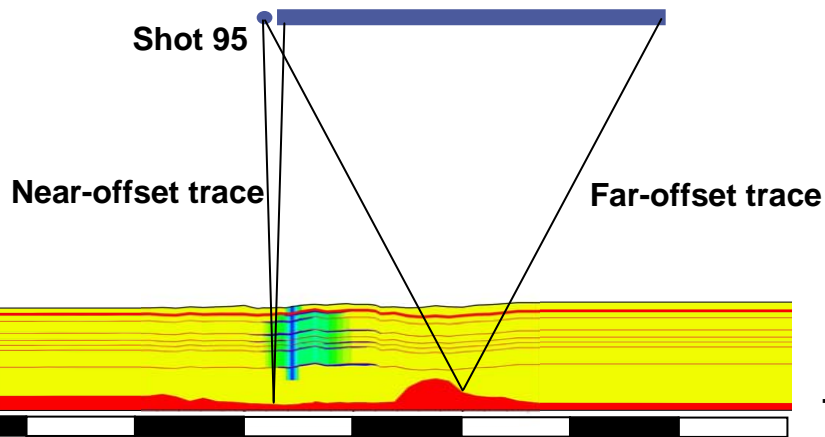
Shot outside the CO₂ plume



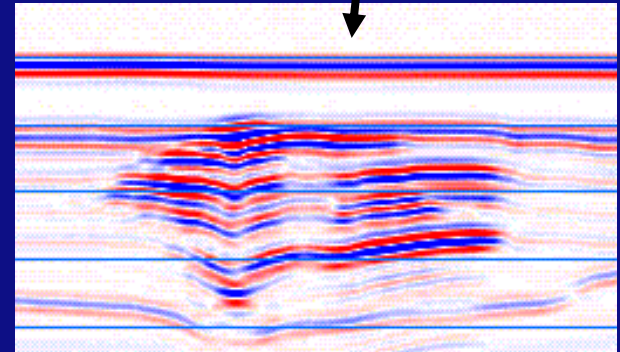
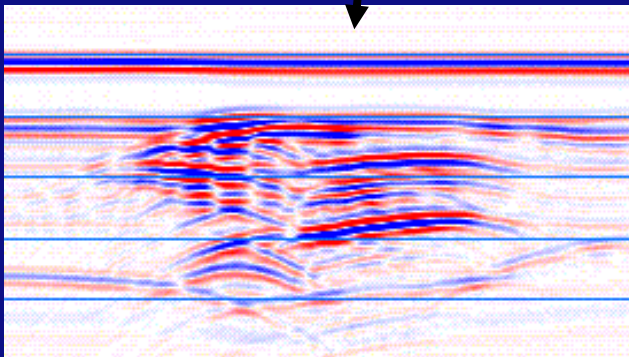
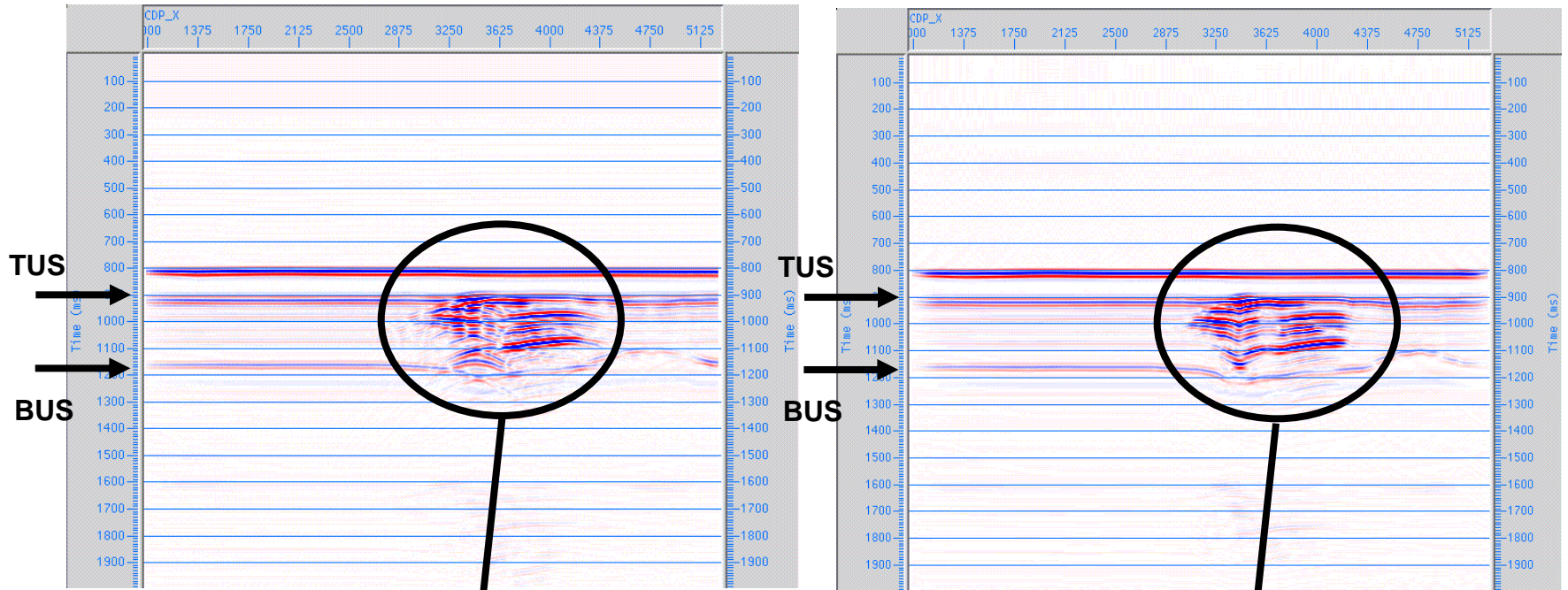
Shot over the CO₂ plume



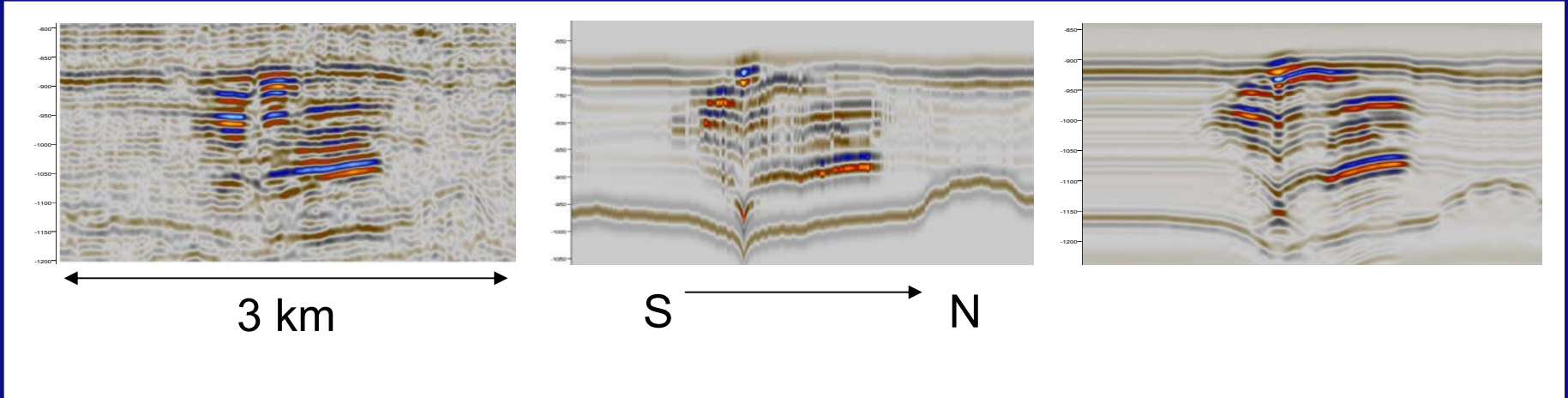
Shot over the CO₂ plume



Stacked section (left) and migrated section (right)



Real seismic data (1999) versus processed seismic data



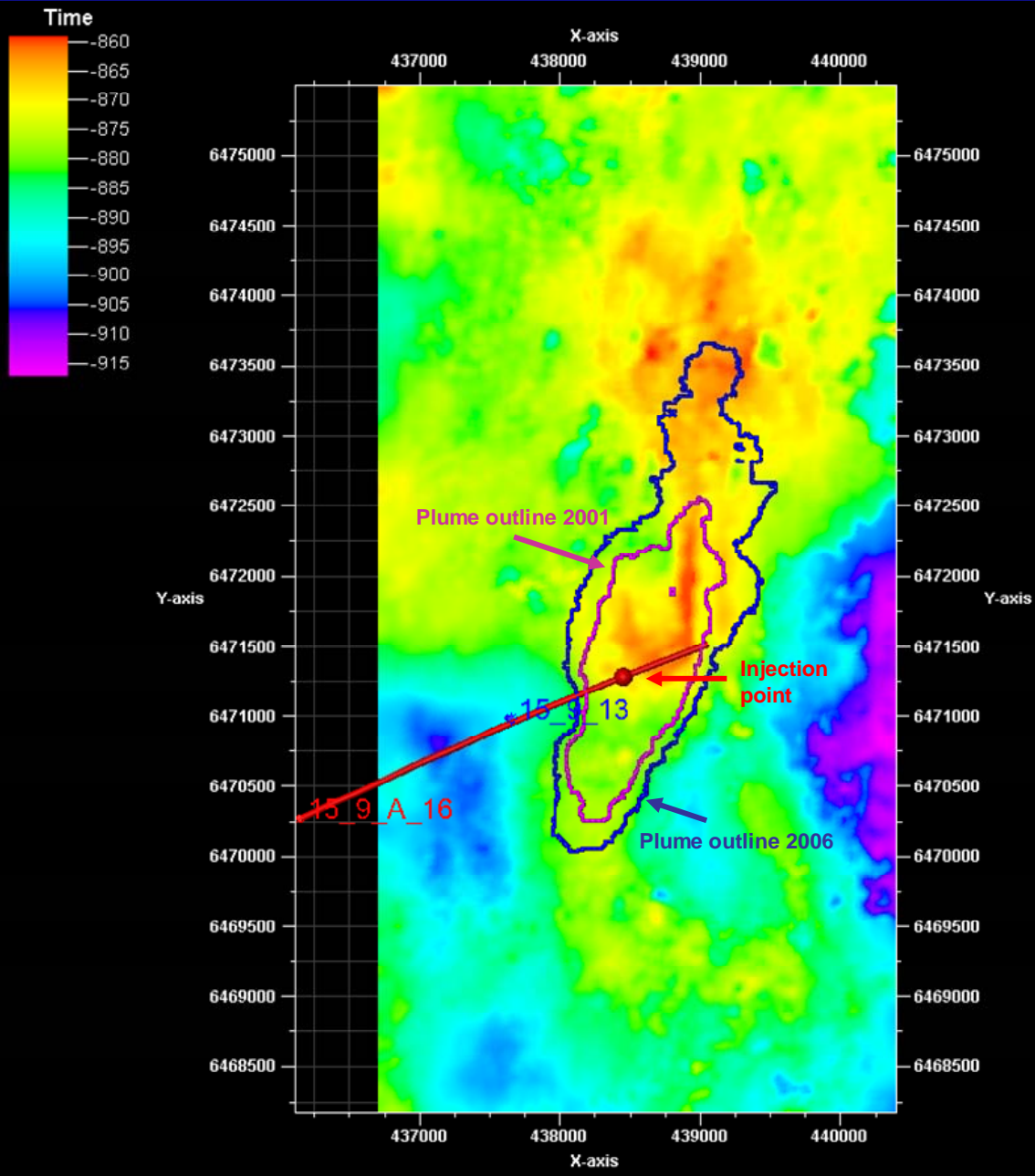
Real data

Synthetic
convolution data

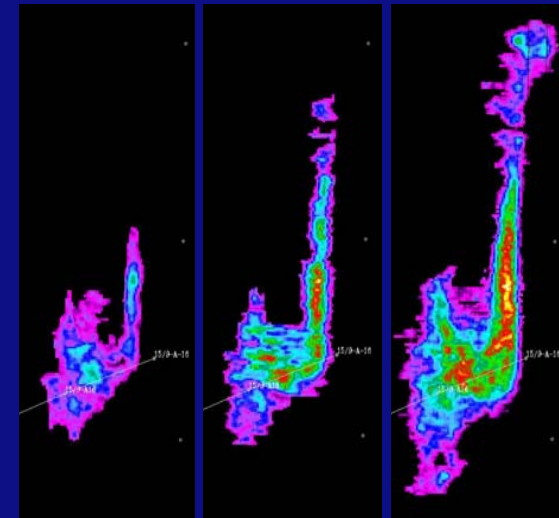
Synthetic Finite
Difference data
after processing

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Growth of top layer



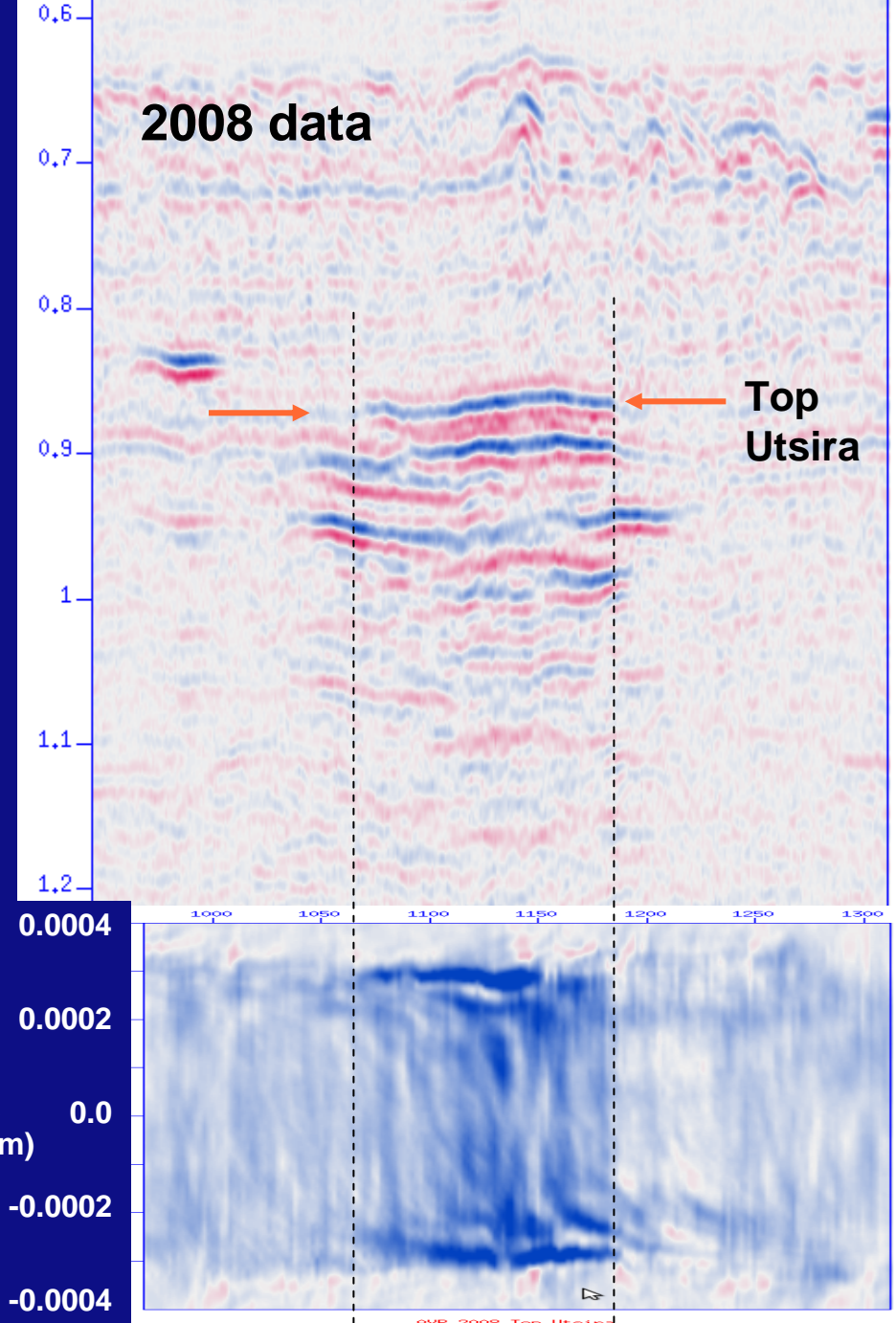
2001

2004

2006

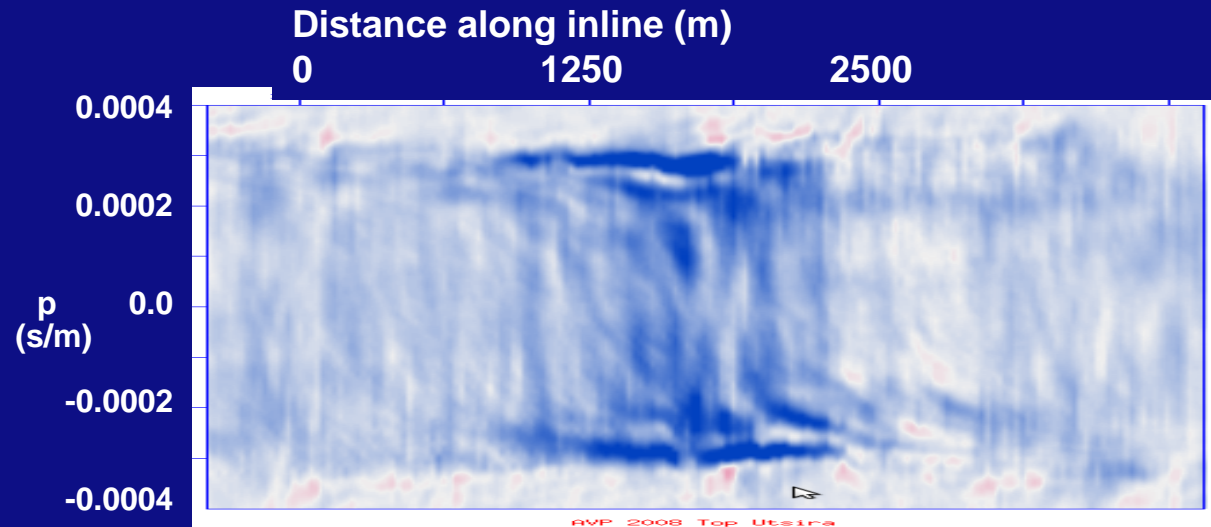
2008 data set

- CFP processing on top Utsira Fm
 - Clear reflection in plume, weak reflection elsewhere

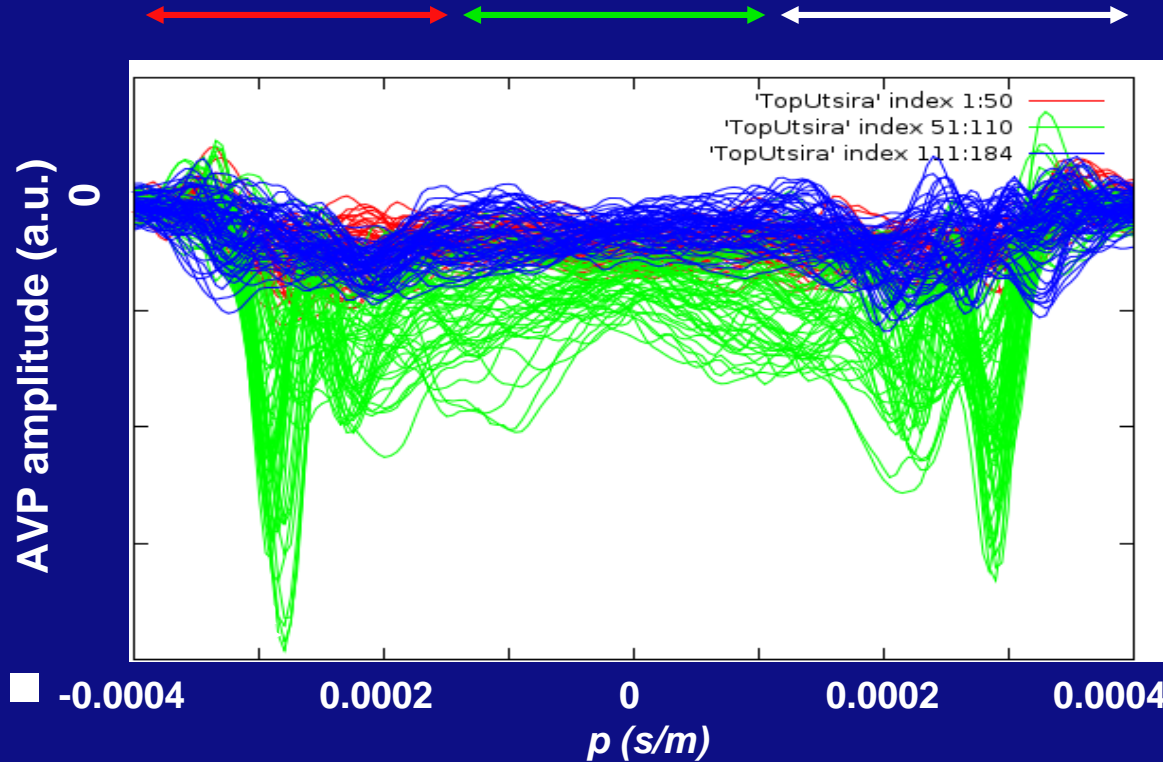


2008 data set AVP Top Utsira

- AVP panel

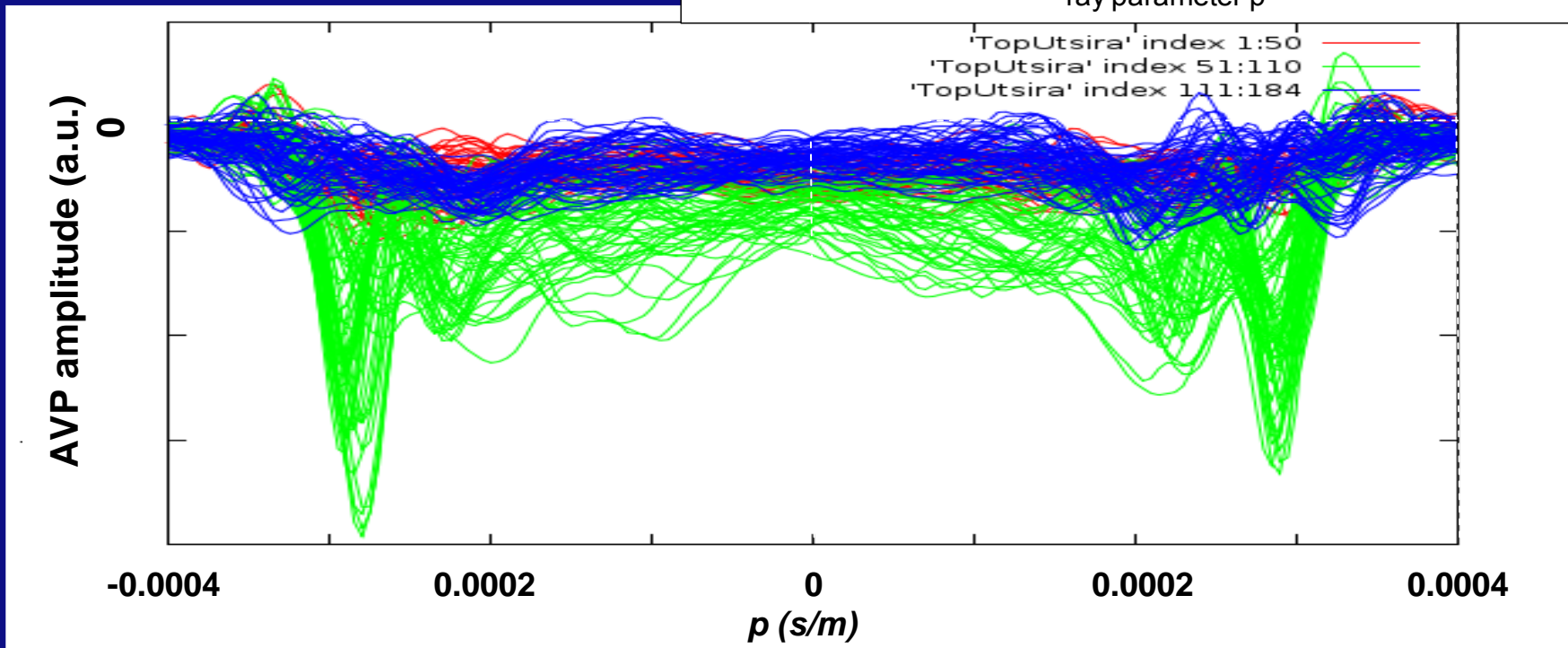
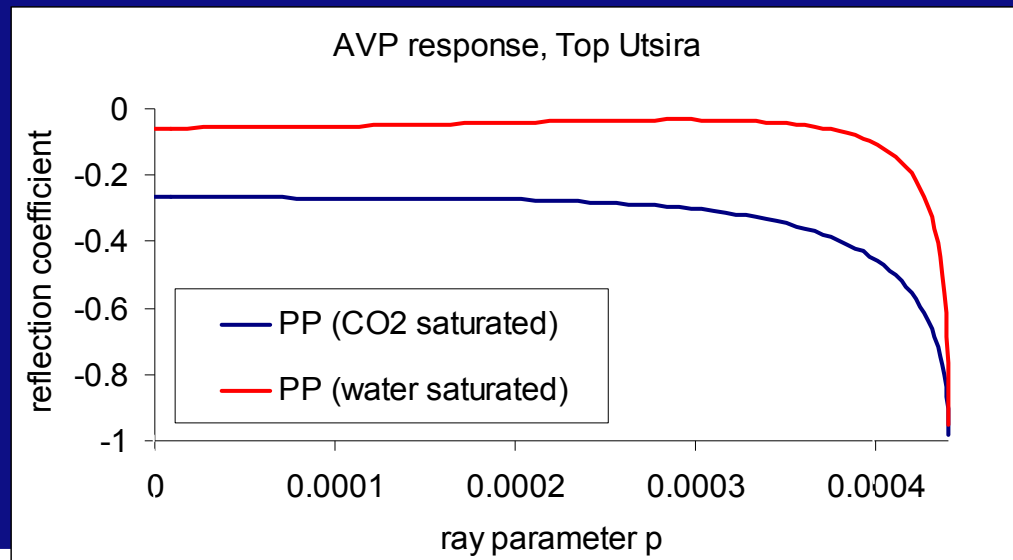


- AVP curves
 - red: 'left' of plume
 - green: 'in' plume
 - blue: 'right' of plume
- Data contain interval $0 < p < 0.0003$



2008 data set Synthetic AVP curves

- Plume zone higher amplitude
- Plume zone higher gradient



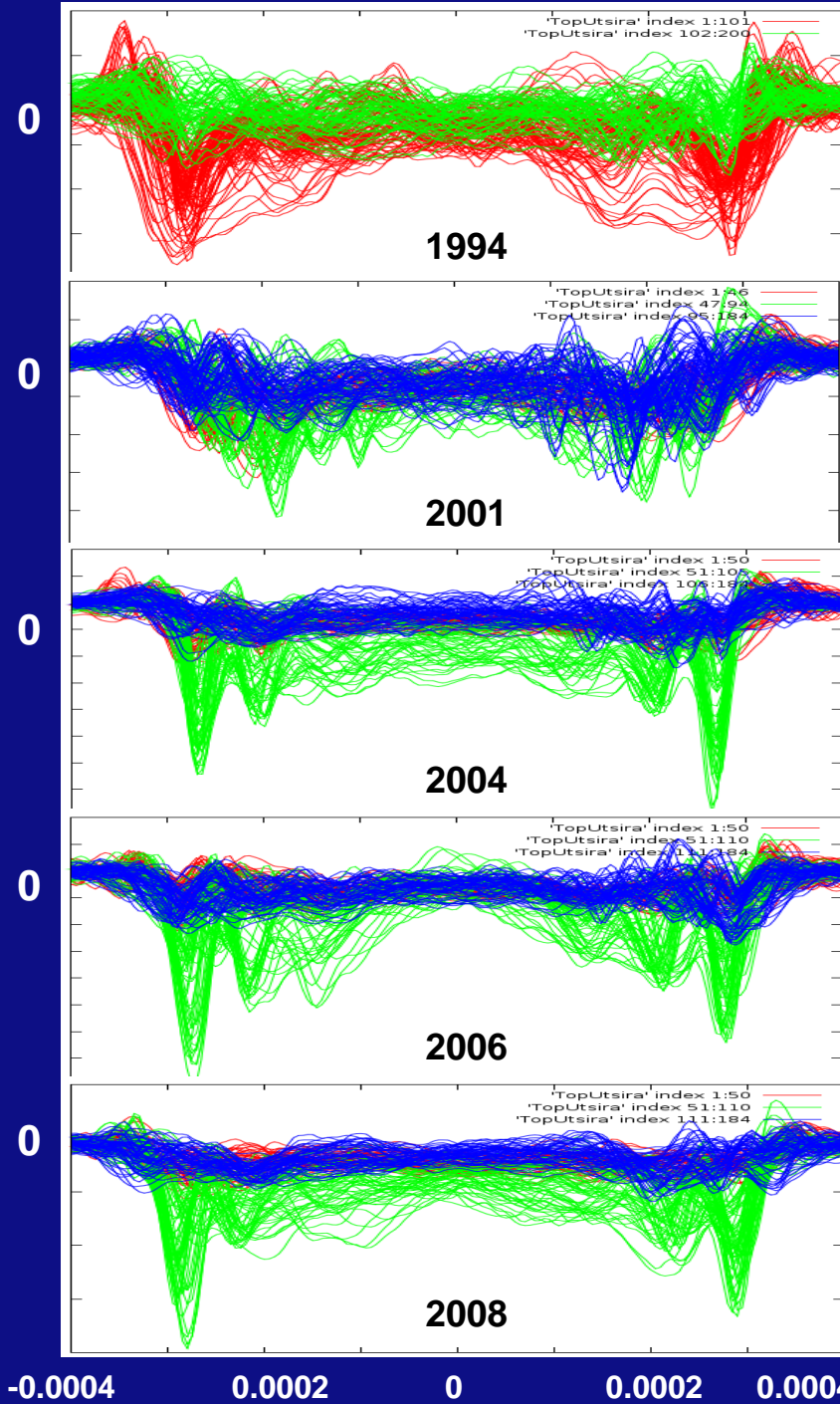
AVP curves

- **Red**: 'left' of plume
- **Green**: 'in' plume
- **Blue**: 'right' of plume

- Data contain interval (approx.)
 $4e-5 < p < 0.0003$
 $7^\circ < \text{incidence angle} < 45^\circ$

- Interference from shallower reflections
 - Restricts validity of results to interval
 $0 < p < 0.0002$ (approx.)

- More far offsets in more recent data sets



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Per station 3 gravimeters and 3 pressure gauges put on a fixed concrete benchmark



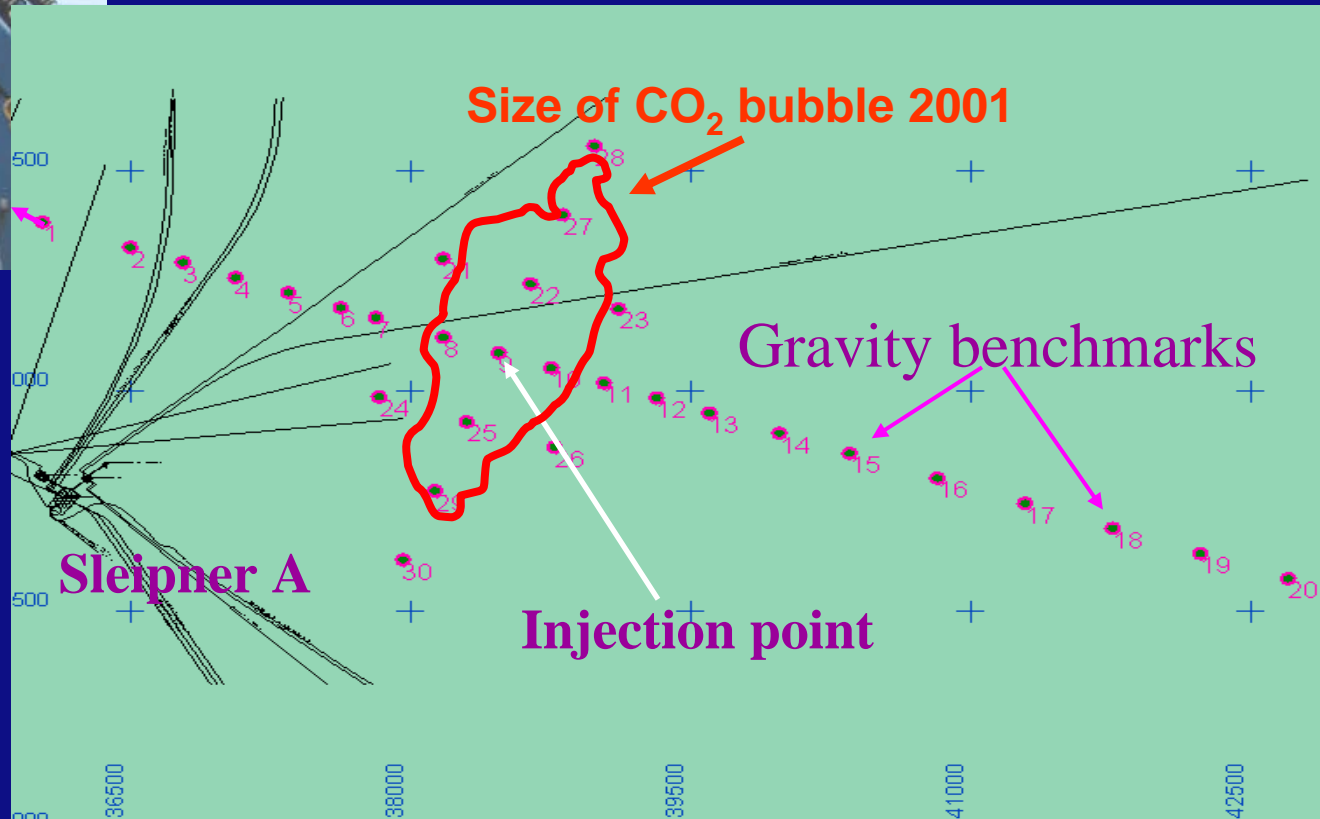
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Kyoto, 9 december 2010

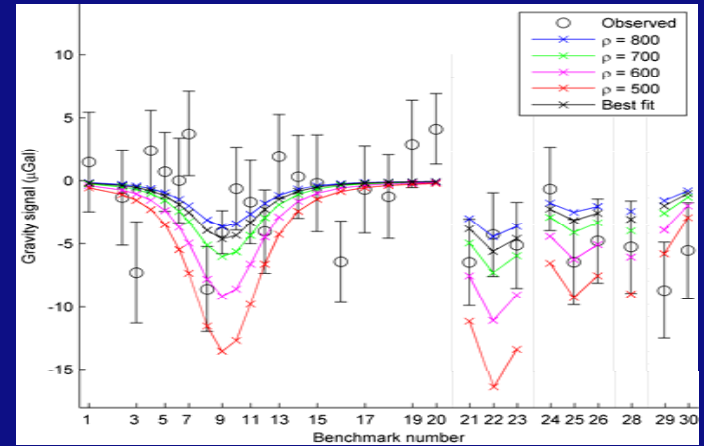
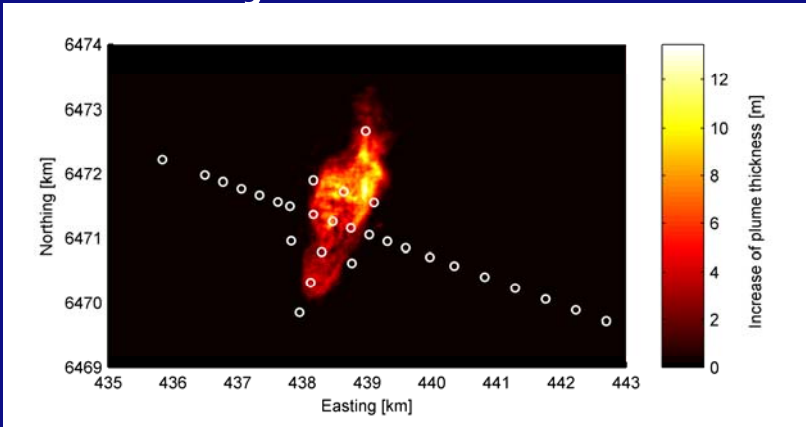


Location of the benchmark stations visited by the ROV

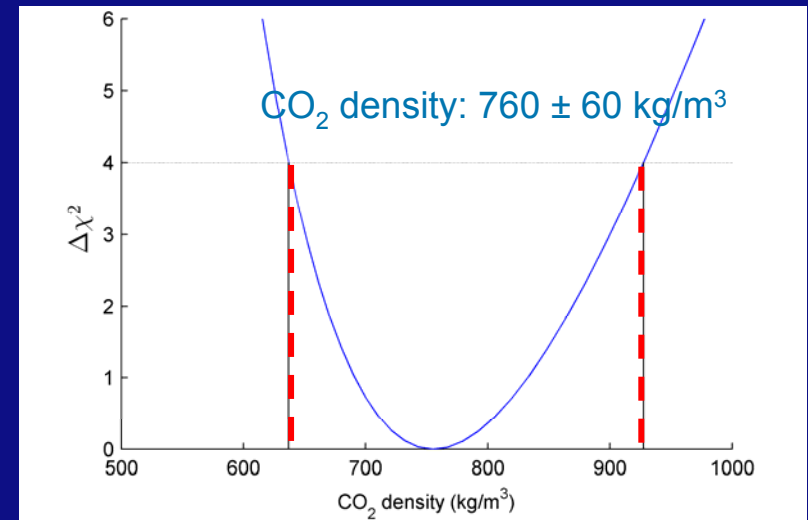
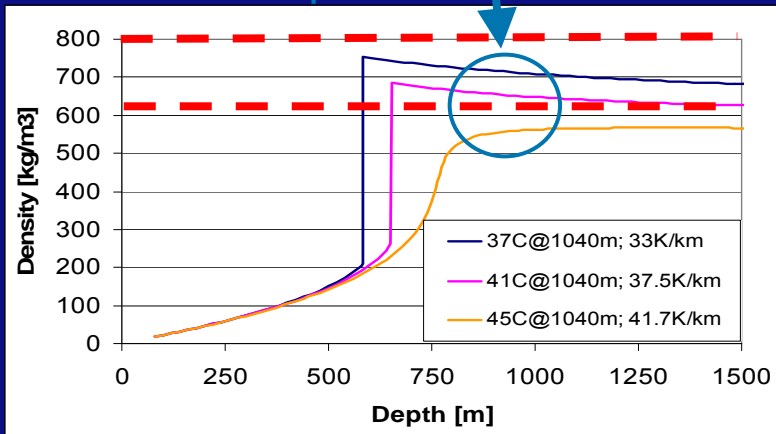




Gravity inversion results



Sleipner/Utsira conditions

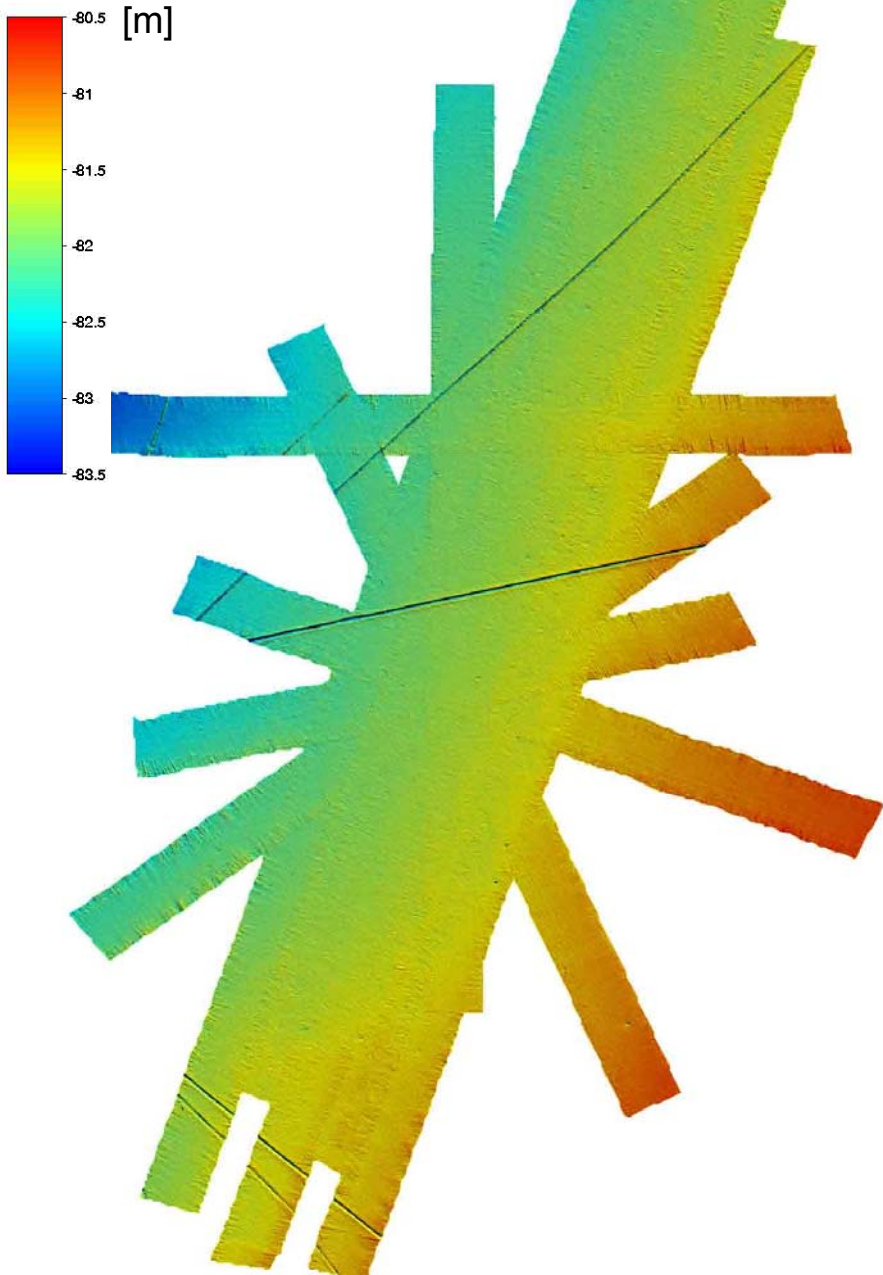


PVT analysis together with gravimetric result give an upper bound of 770 kg/m³ and a lower bound of 640 kg/m³ with 95% confidence.

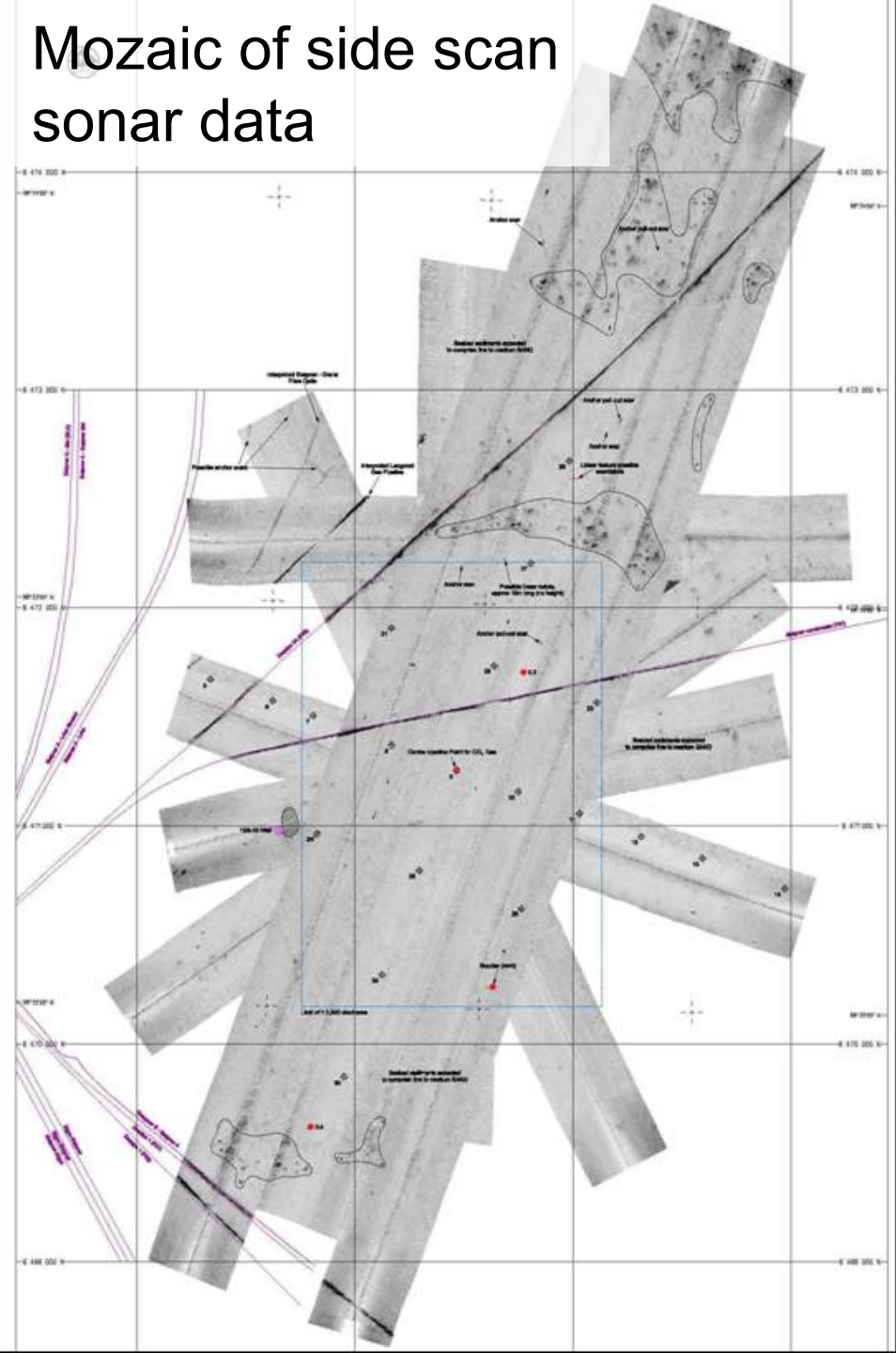
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Seafloor depth, from multibeam echo sounding



Mozaic of side scan sonar data



Overview

- Introduction to the Sleipner CO₂ injection site
- Analysis of the seismic monitoring data
- Gravity monitoring results
- Seafloor imaging
- Concluding remarks

Closing remarks

- No indications for leakage
- Plume development currently in line with expectations at the top reservoir
- Refinement of the characterization of the intra-reservoir behavior still ongoing
- Seismic monitoring and gravity monitoring provide complementary information

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