CSEM data analysis for Sleipner CO2 storage

Joonsang Park
Inge Viken
Tore Ingvald Bjørnarå
Eyvind Aker
Petroleum Geomechanics and Geophysics Division, NGI

6th Trondheim CCS Conference, June 14-16, 2011

Table of contents

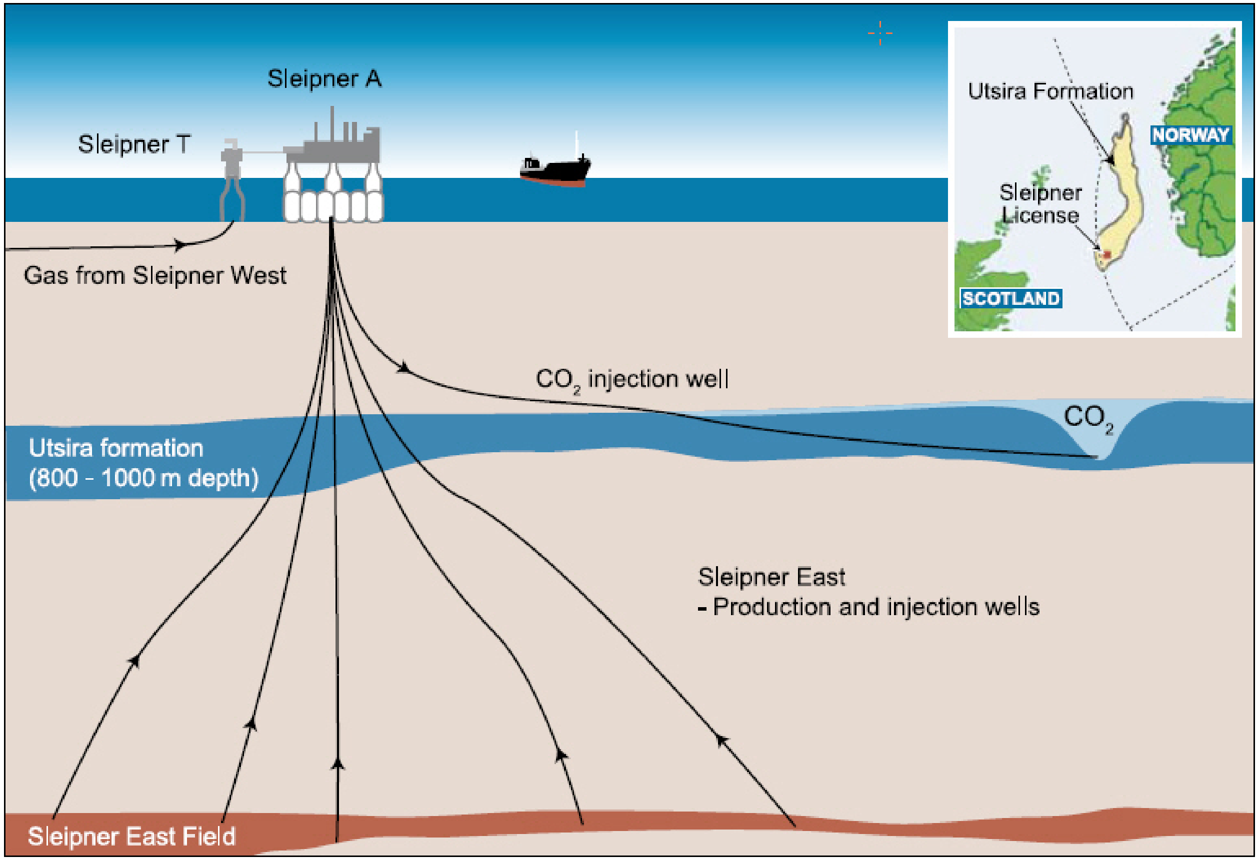
Background

- CO2ReMoVe and Statoil presented the Sleipner CSEM data (collected in 2008) to SUCCESS/Uni Research/NGI. The quality of the data itself is high and processed by means of the state-of-the-art tool. However, the data is known to be highly contaminated by seabed pipes, which makes the interpretation challenging.

- Since 2007, NGI has developed an efficient FE solution with which we can approximate the EM responses due to cased well/seabed pipelines (Statoil supported).

- Through SUCCESS scope of work (WP4.1 in 2010), NGI has been analyzing the data with applying NGI's forward modeling and inversion tools (covering1, 2 and 3D, considering the seabed pipes).

Sleipner/Utsira Field: production and injection



Ref. From a webpage(url?)

Sleipner/Utsira Field:
CO2 plume thin-layers in seismic

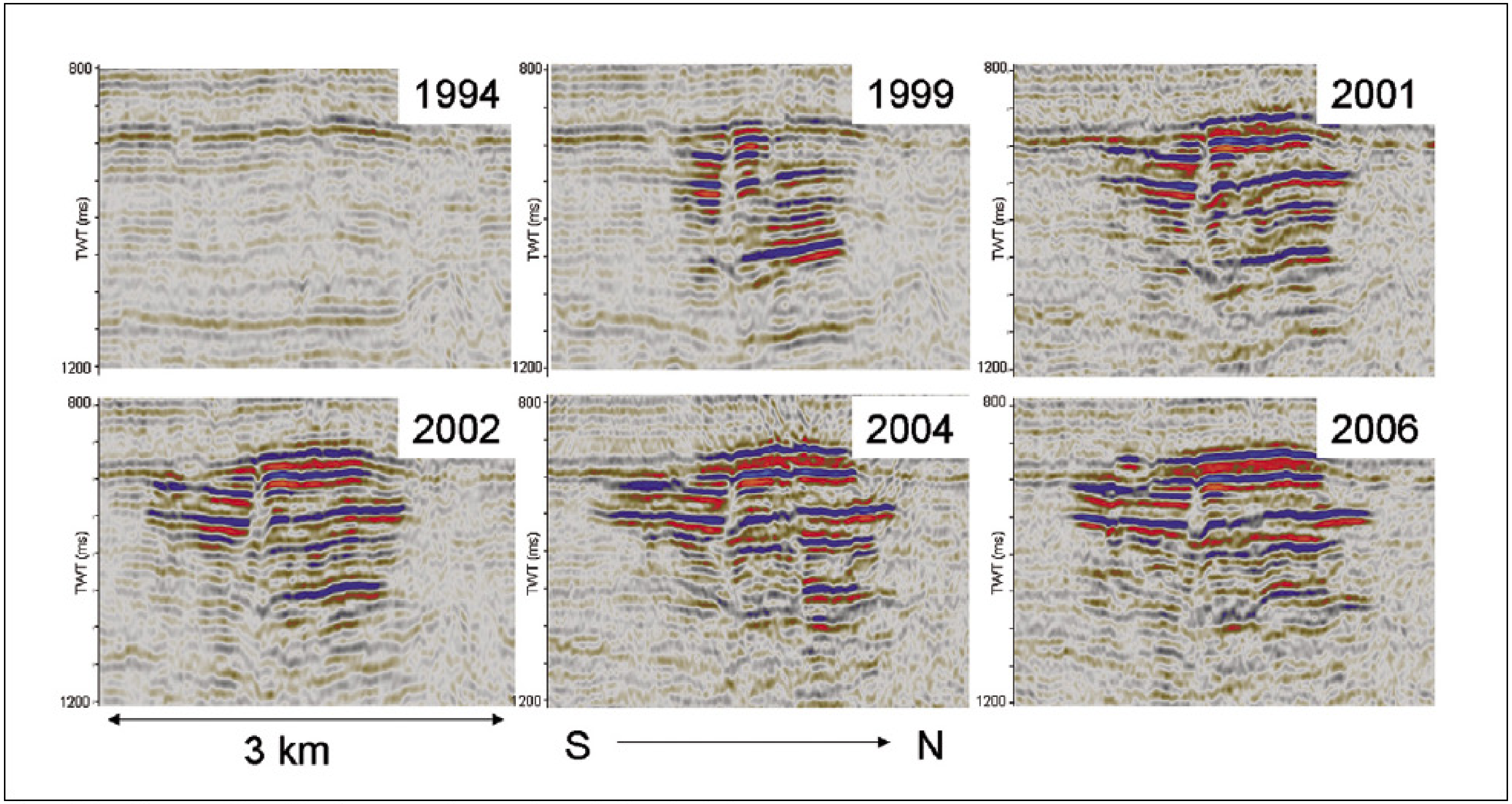


Figure 6 Development of the CO_2 plume over the years imaged with seismic data.

Arts, Chadwick, Eiken, Thibeau, and Nooner (2008) Ten years' experience of monitoring CO2 injection in the Utsira Sand at Sleipner offshore Norway, First Break

Sleipner/Utsira Field:
CO2 plume thin-layers based on seismic

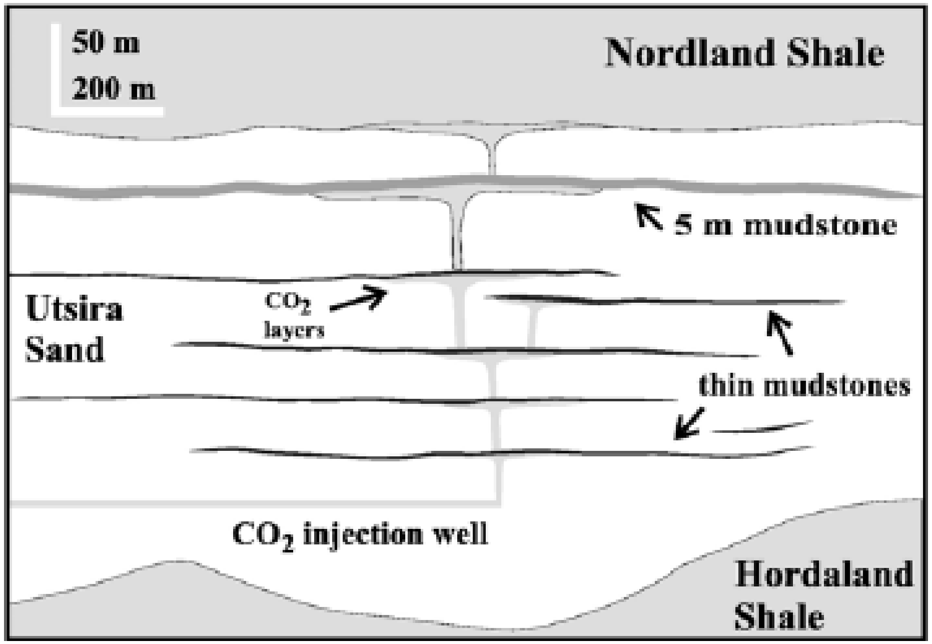


Fig. 1. Schematic illustration of CO_2 injection at Sleipner and rising CO_2 plumes being partially trapped under thin mudstones before reaching Nordland Shale cap rock. Note the vertical exaggeration.

Bickle, Chadwick, Huppert, Hallworth, Lyle (2007) Modelling carbon dioxide accumulation at Sleipner: Implications for underground carbon storage, Earth and Planetary Science Letters

Resistivity measurement via laboratory CO2 flooding : Rothbach sandstone

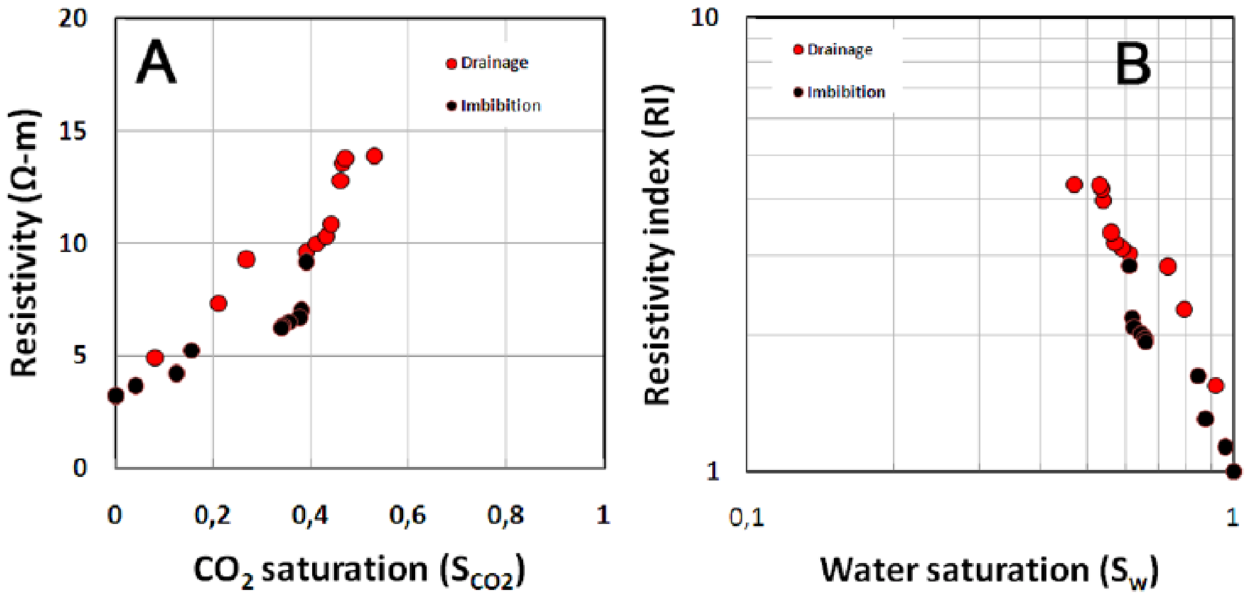
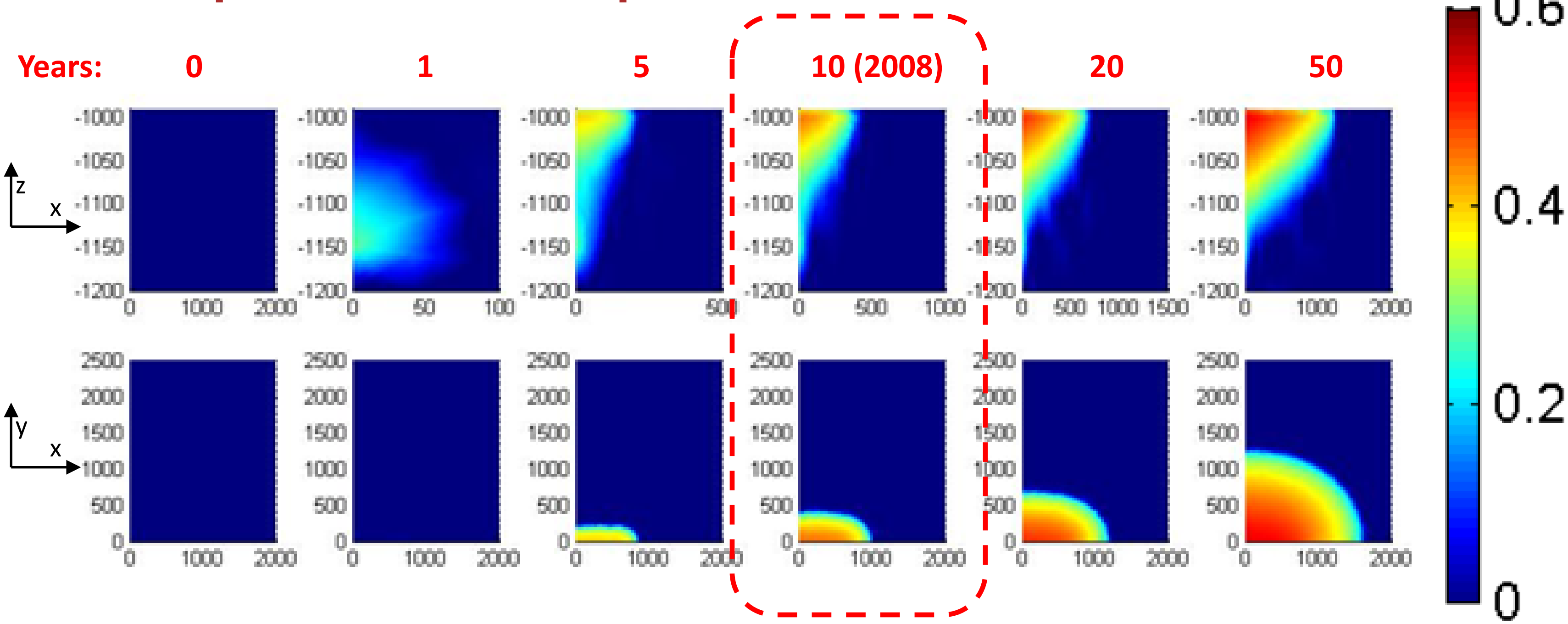


Figure 6: Resitivity measured along the core using electrodes at the top and bottom of the sample against calculated average saturation of the whole sample.

Alemua, Aker, Soldal, Johnsenb and Aagaarda (2010) Influence of CO2 on rock physics properties in typical reservoir rock: A CO2 flooding experiment of brine saturated sandstone in a CT-scanner, Energy Procedia

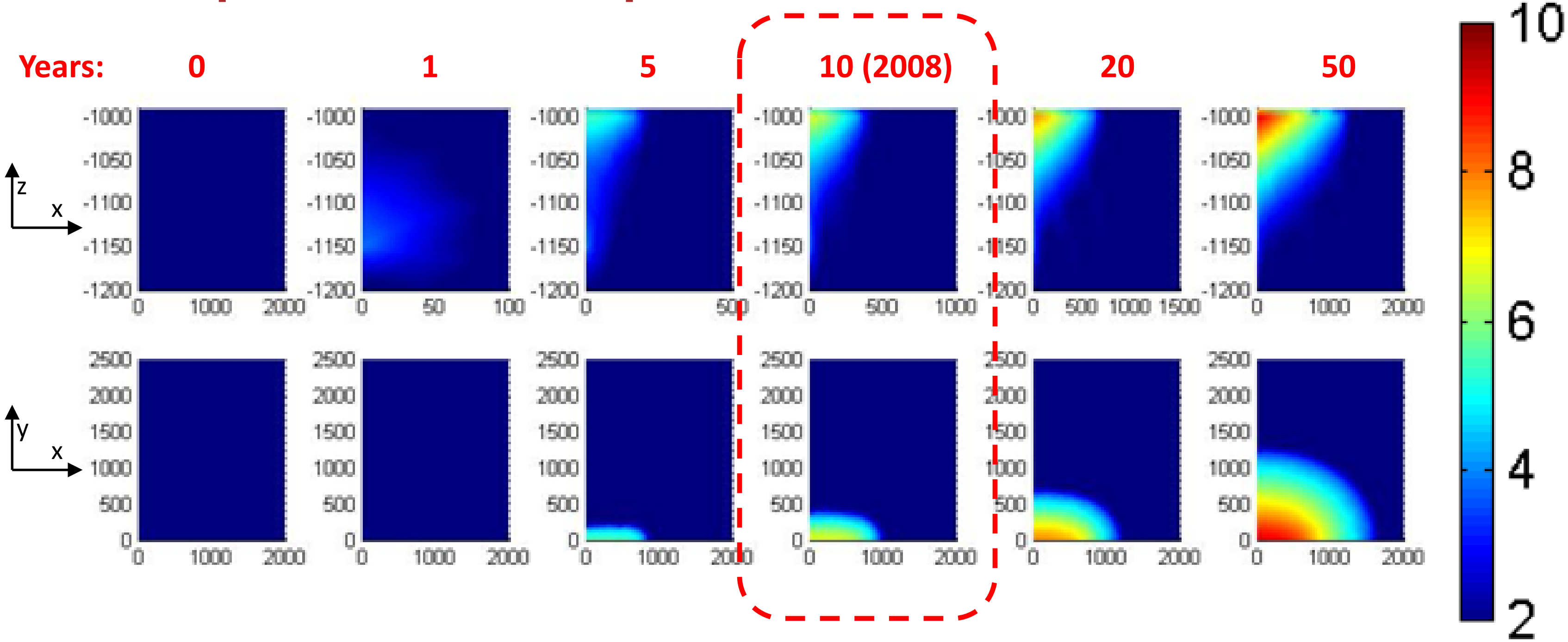
EM monitoring of CO2 injection: EM coupled to two-phase flow



CO2 saturation profiles at various times after injection (from left to right); 0, 1, 5, 10, 20 and 50 years, plotted along the direction of the injection line. **Color scale is from 0 to 0.6 (blue and red, respectively)**.

Bjørnarå and Park (2010) EM monitoring of CO2 injection: EM coupled to two-phase flow, NGI internal report (draft).

EM monitoring of CO2 injection: EM coupled to two-phase flow

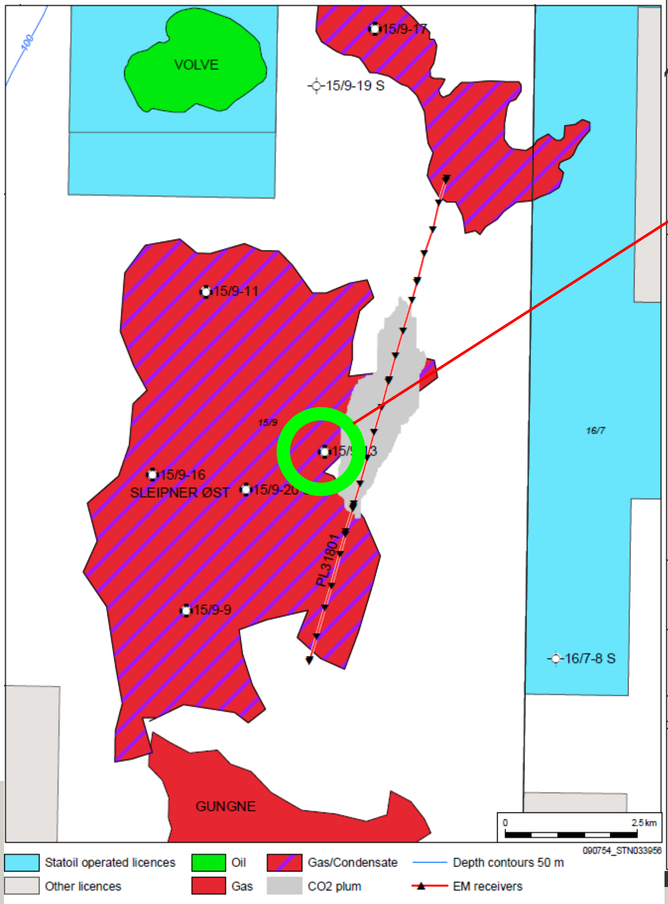


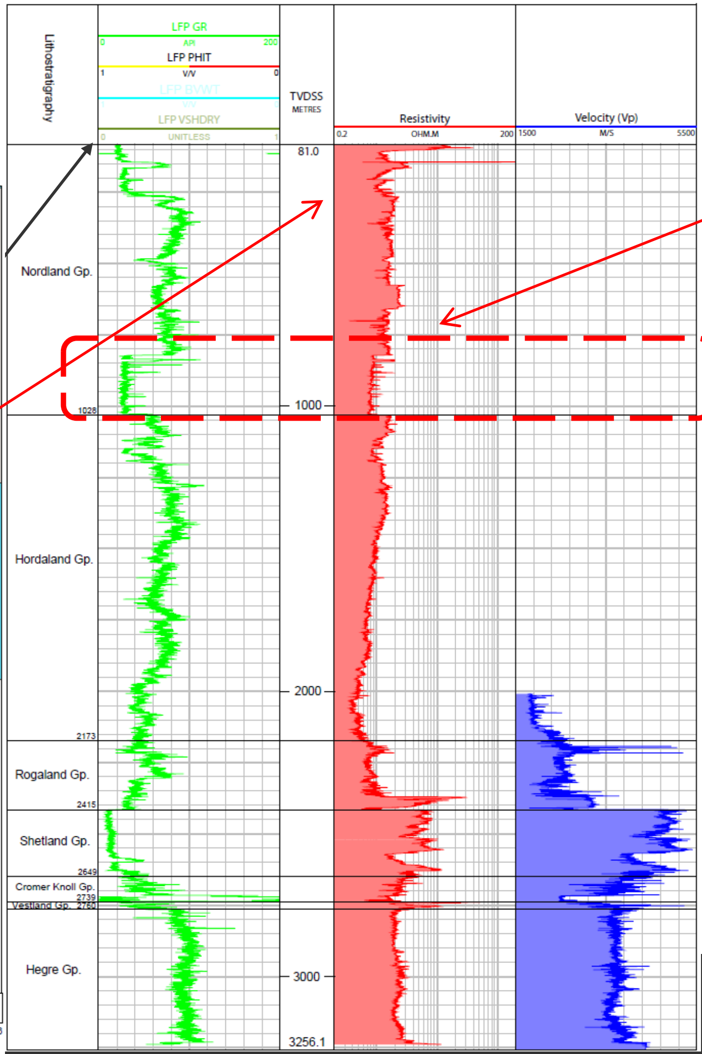
Resistivity profiles (based on Archie's law) at various times after injection; 0, 1, 5, 10, 20 and 50 years, plotted along the direction of the injection line. **Color scale is from 2 Ωm to 10 Ωm (blue to red, respectively)**.

Bjørnarå and Park (2010) EM monitoring of CO2 injection: EM coupled to two-phase flow, NGI internal report (draft).

Sleipner CSEM data and well data

15/9-13 well data

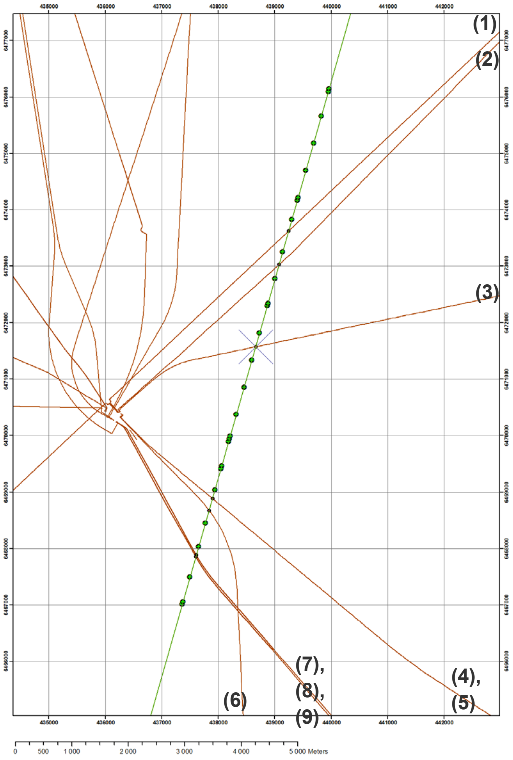




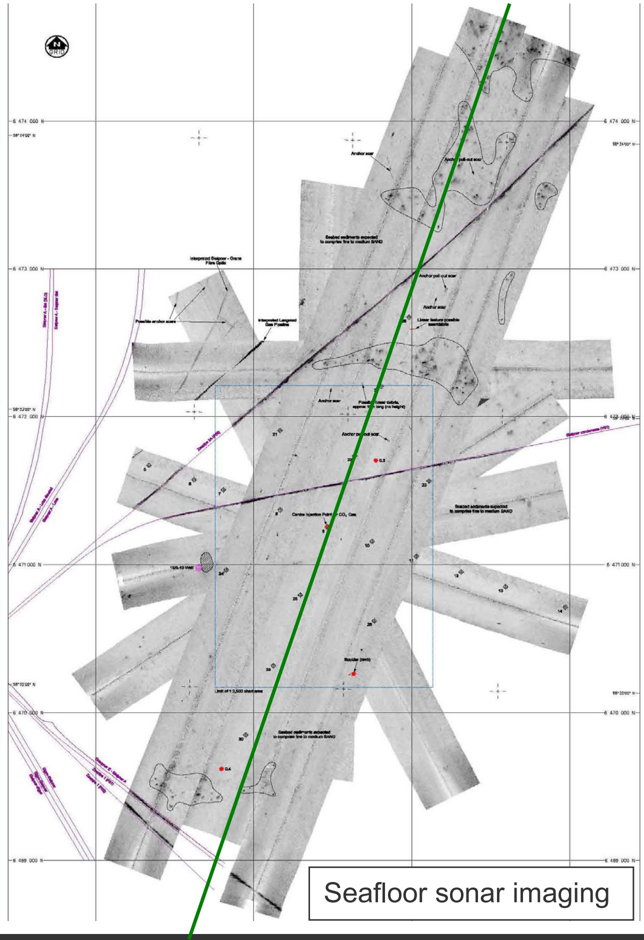
Utsira formation, CO_2 injection region

27 Receivers and 9 seabed pipes

Pipelines Sleipner area



Pipeline location (orange) and EM towline (green)



Seafloor sonar imaging

Statoil

Some remarks on Sleipner/Utsira and CO2 sand reservoir

- Nicely layered background
- Utsira depth: 800-1000m (more or less known position from seismic and injection information)
- Alternating CO2 plume thin-layers (due to thin mudstone beds in Utsira) → anisotropy feature
- Well exists near by (15/9-13)

- 80m deep (shallow) water (most difficult to marine CSEM data intepretation!)
- Relatively low CO2 saturation (~50%) and Relatively low resistivity CO2 plume (e.g. 10~20Ωm) (Bjørnarå&Park, Alemu *et al.*)
- Seabed pipes yet without detailed information
- No CSEM data on ”Day 0”

Marine CSEM: method/principle

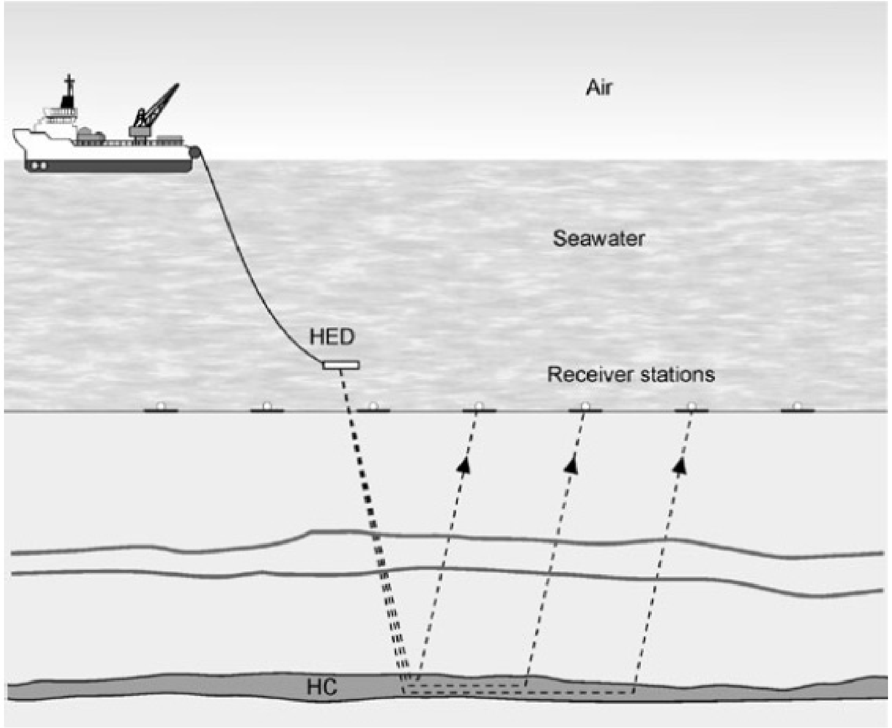
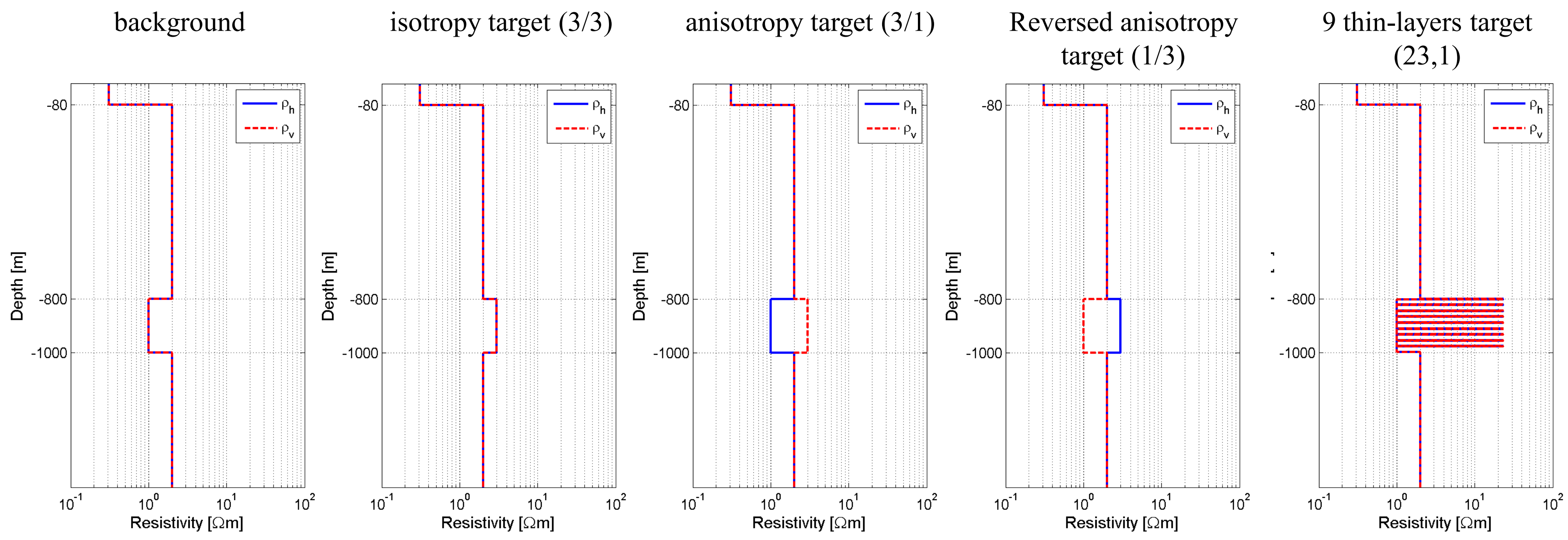


Figure 1 Typical test layout of marine CSEM survey for hydrocarbon (HC) exploration. A horizontal electric dipole is towed by a vessel sending electromagnetic signals with typical frequencies 0.1–5 Hz. The receivers are placed on the sea bed, recording the electromagnetic signal reflected and refracted for a hydrocarbon layer located at a typical depth 1–2 km.

Kong, Johnstad, & Park (2010) Wavenumber of the guided wave supported by a thin resistive layer in marine controlled-source electromagnetics, Geophysical Prospeting.

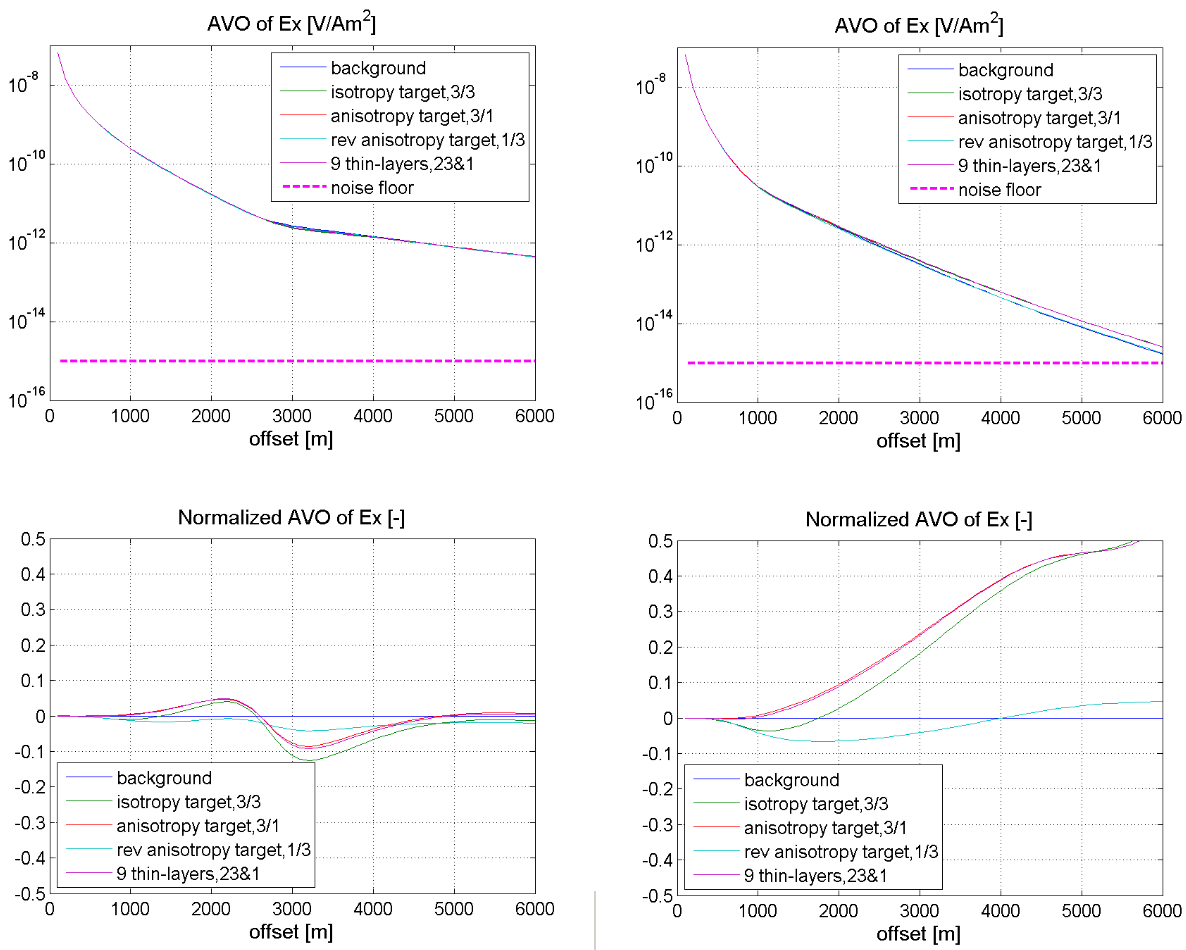
Marine CSEM: Sleipner-like 1D model

- Conceptual 1D layered models that may represent sediments in Sleipner/Utsira field.
- To show potential features of marine CSEM data in Sleipner/Utsira field (next slide)
- Horizontal/Vertical resistivities
- Anisotropy due to alternating thin-layers



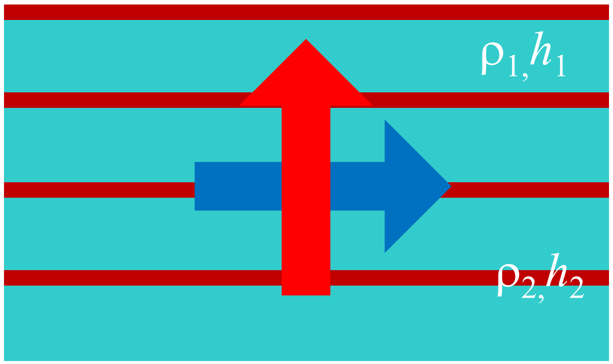
Marine CSEM: Sleipner-like 1D model

Shallow sea (80m; 1Hz) Deep sea (1000m ; 1Hz)



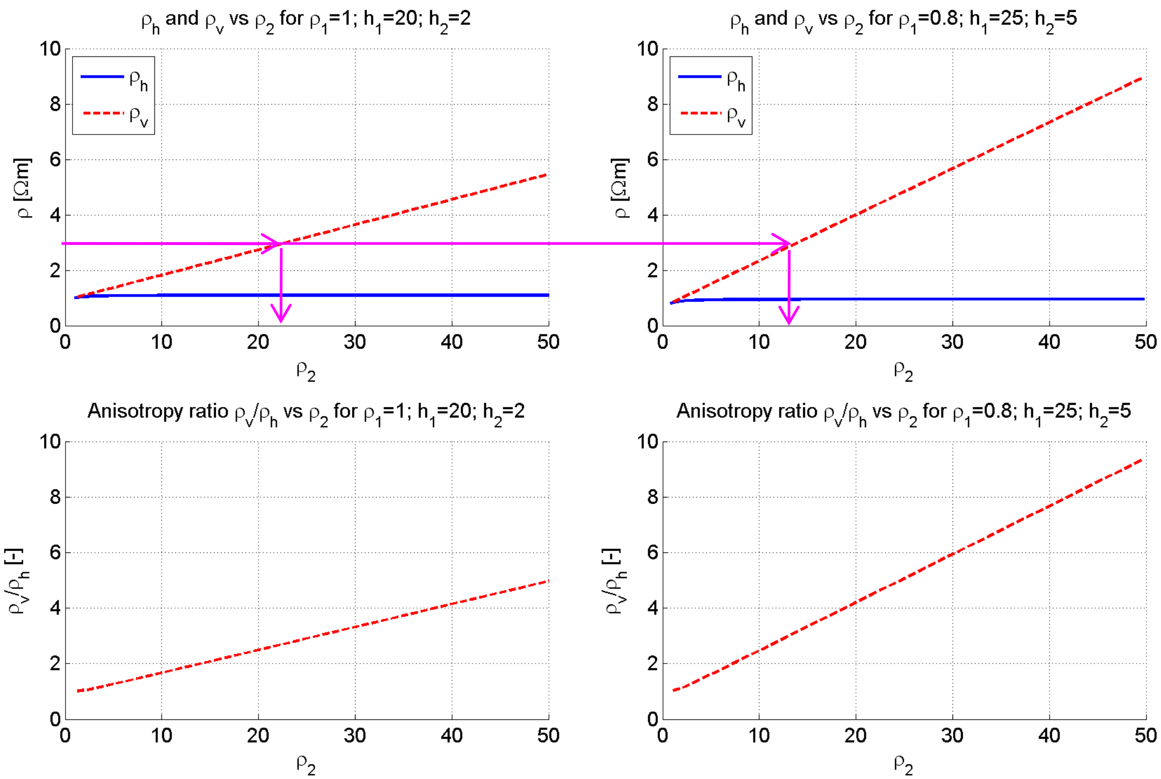
- CSEM data is much more sensitive in deep water than in shallow water.
- Vertical resistivity is more sensitive than horizontal resistivity.
- Alternating thin-layers behave similarly to averaged anisotropy layer.

Anisotropy model



$$\sigma_h = \sum_{j=1}^{N} f_j \sigma_j = \frac{1}{\rho_h}$$

$$\sigma_v = \left[\sum_{j=1}^{N} \frac{f_j}{\sigma_j} \right]^{-1} = \frac{1}{\rho_v}$$



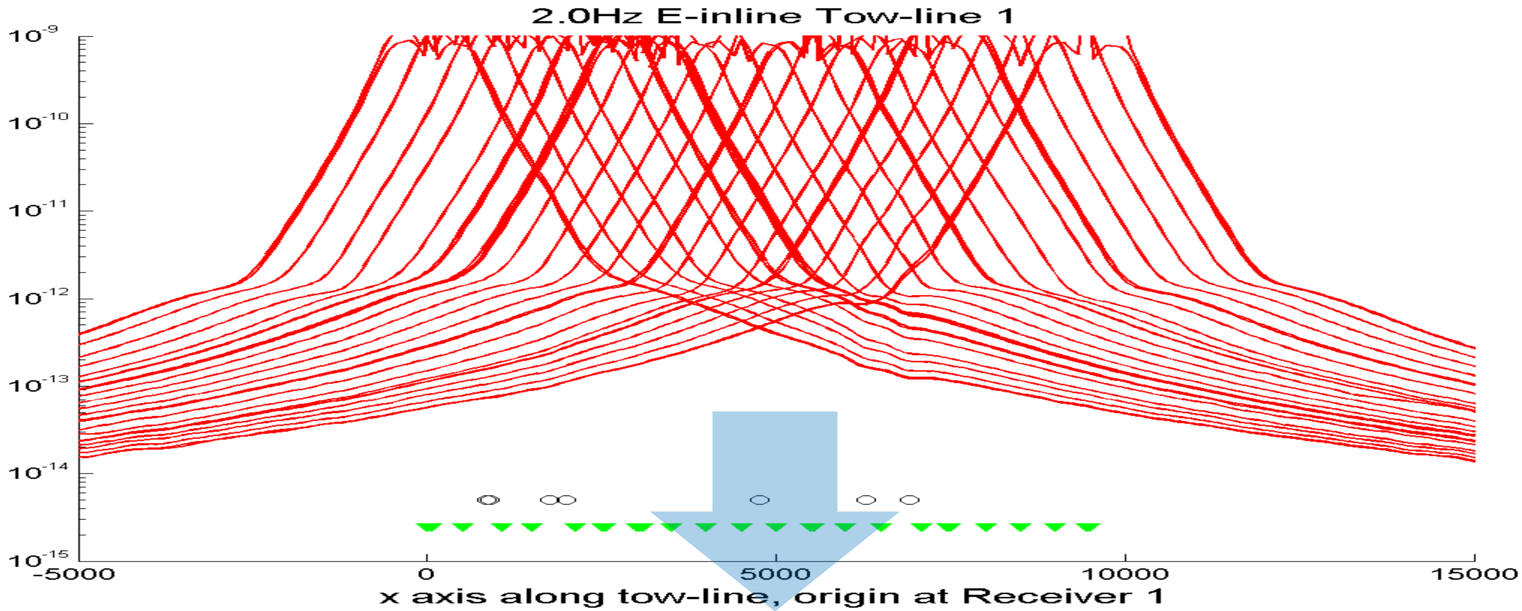
Note that the marine CSEM data may see mostly ρ_h and ρ_v, but not directly ρ_1 and ρ_2, due to its low resolution in depth. On the other hand, the CO2-injected sand reservoir would consist of alternating layers of CO2 plume and Utsira sand.

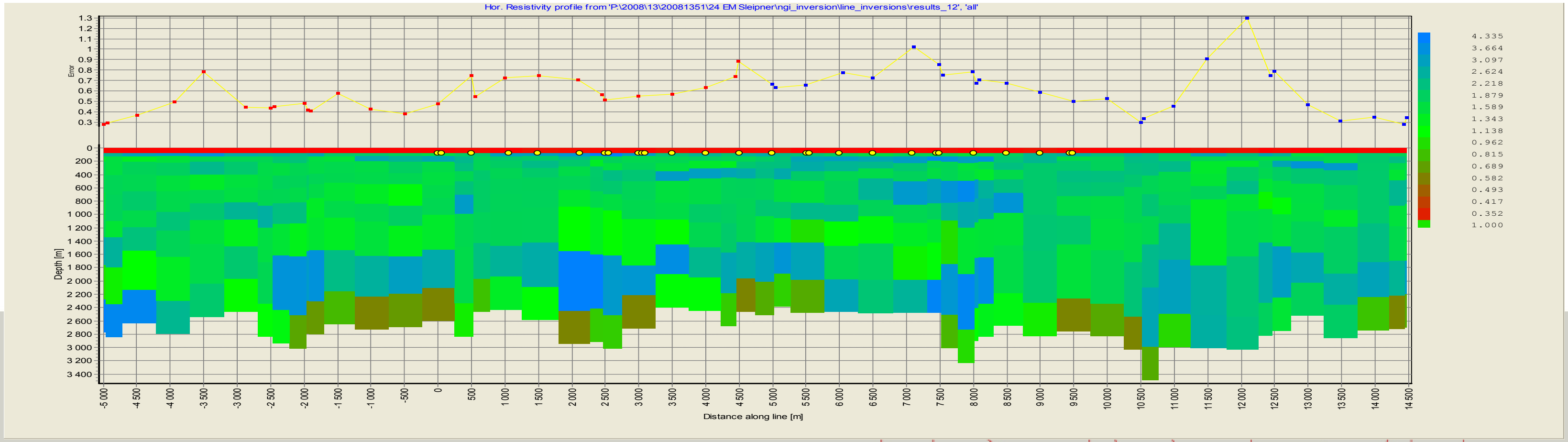
Pseudo 2D Inversion/Interpretation

- Procedure (iterated):
  1. Run line-inversion or pseudo 2D inversion;
  2. Import inversion results (2D resistivity profiles!) into 2.5D (without seabed pipe) and 3D (with all 7 seabed pipes) FE modeling;
  3. Evaluate the inversion results in comparison with the measured data.

- Inversion via line-/pseudo2D inversion codes (emsea1d_interface, Pseudo-2D forward modeling).
- Interpretation/Evaluation via 2.5D and 3D forward modeling tools (CSEM123/COMSOL Multiphysics)

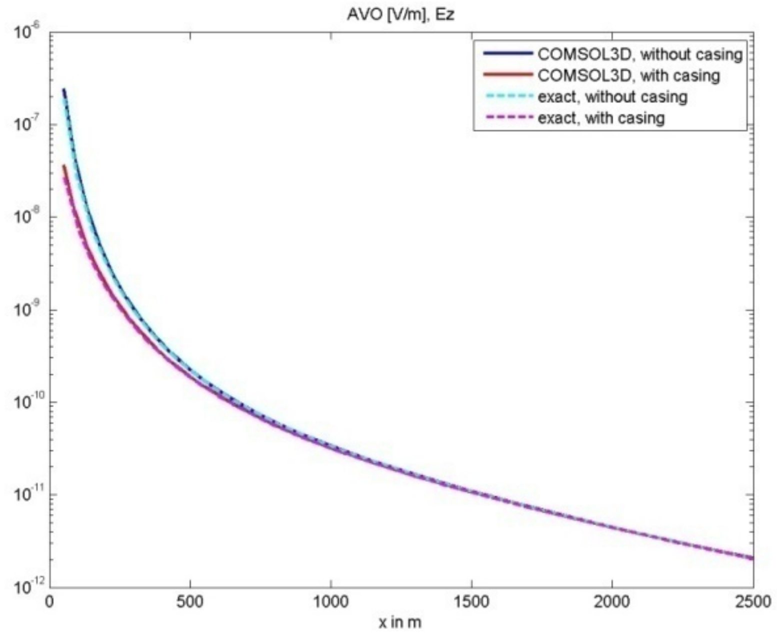
Pseudo 2D inversion (line-inversion)





Line/edge approximation for pipe/casing

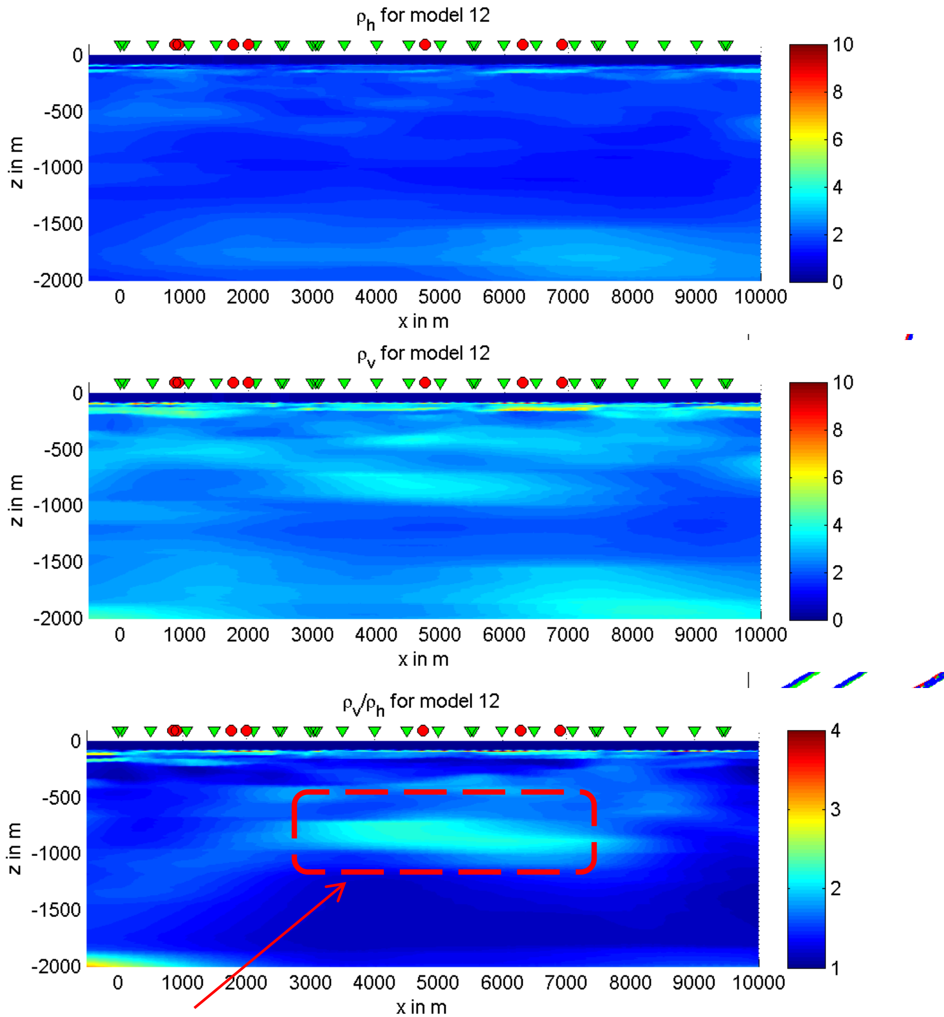
- We approximate the finite-volume seabed pipe (or casing well) by using a line/edge version of 3D EM equation by using an equivalent cross-section area parameter.
- The method is simple and efficient in the FE framework, because we represent the seabed-pipe by means of only line-segments/curves in 3D space.
- On the left, we present an example where we can see the performance of the edeg approximation in comparison to a referenece solution.
- Currently, we are developing it further and planning to publish in the near future.

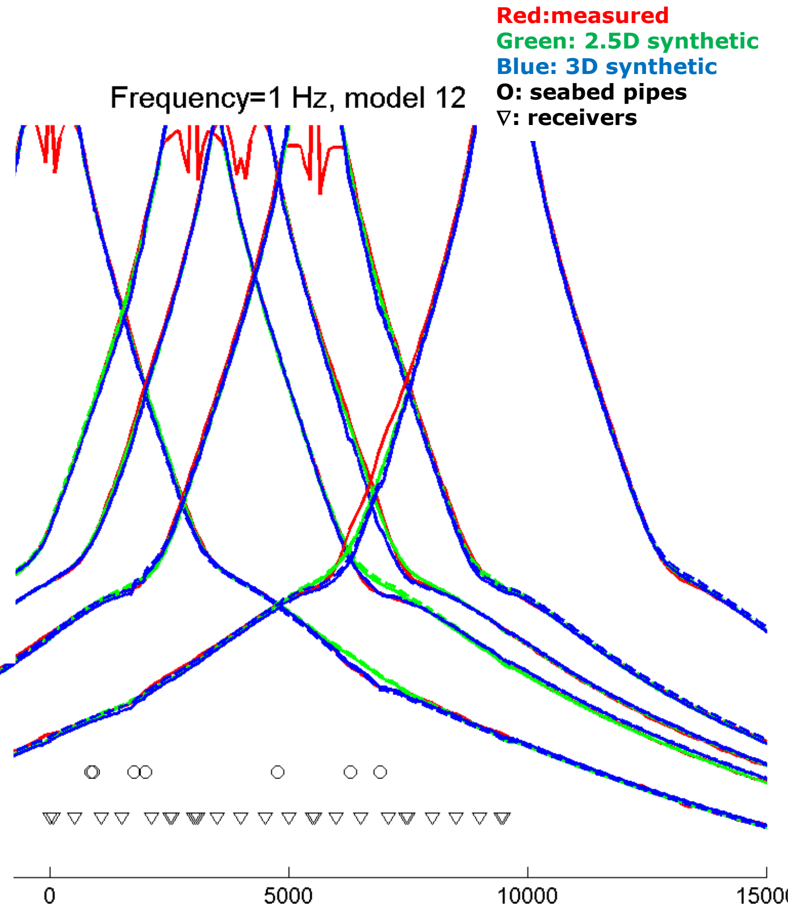


Vertical electric field (Ez) outside casing generated by a vertical electric source (Jz) inside casing

NGI report, 20071514-1 (2009) *Approximate FE solution for borehole casing*, Statoil supported.
NGI report 20091693-00-20-R, *CSEM 3D modeling via COMSOL Multiphysics,* , Statoil supported.

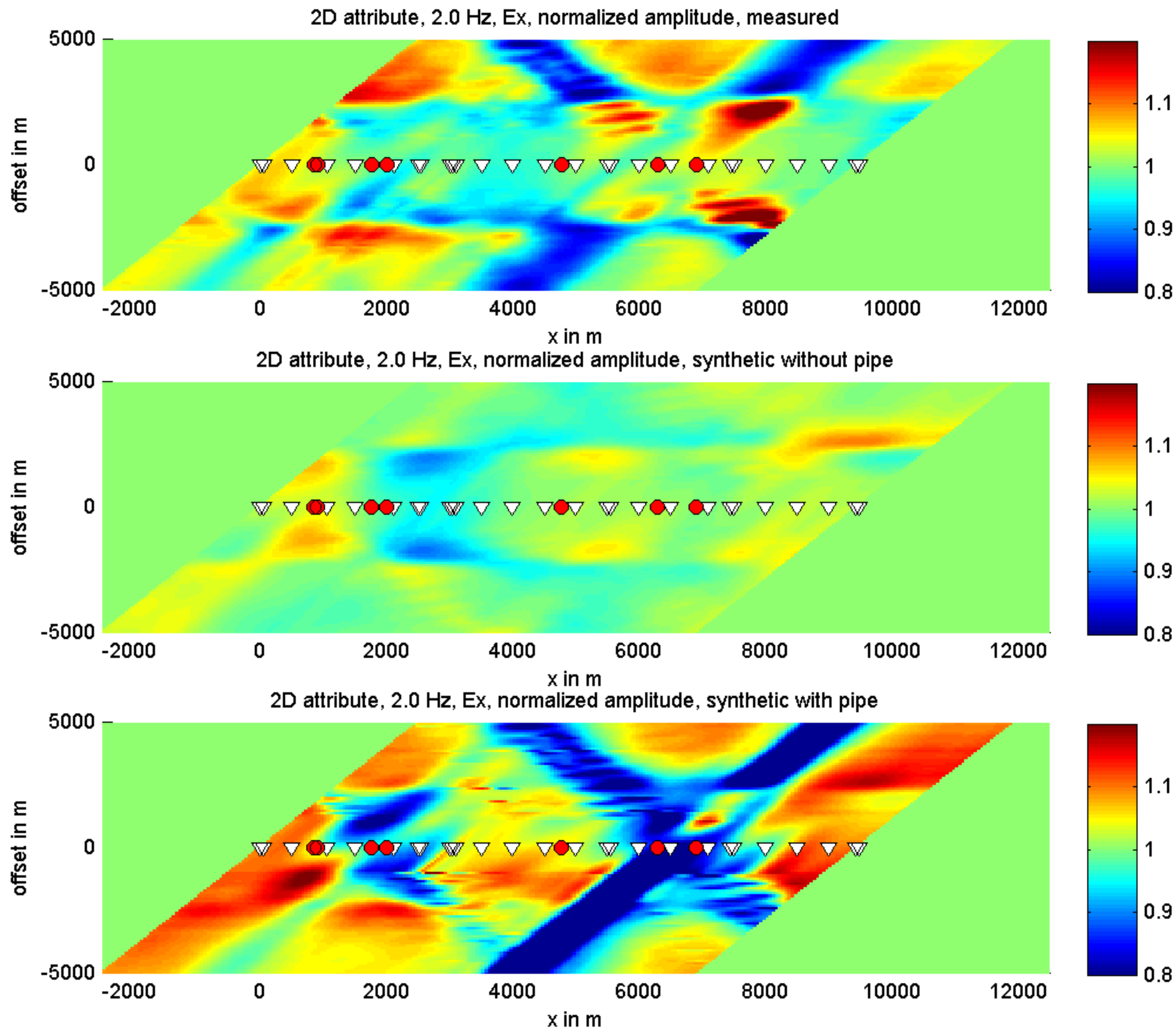
Line-inversion result and synthetic data





Relatively high anisotropy, indicating
CO_2 plume region

Attribute 2D plot, 2Hz



Summary and Future work

- It is confirmed once more that the CSEM application to Sleipner/Utsira is a challenging task, probably mainly due to the super shallow seawater as well as seabed pipes.
- Nevertheless, some promising inversion results are obtained from line-inversion and pseudo-2D-forward-modeling inversion.
- Anisotropy feature due to alternating CO2 plume thin-layers in Utsira can be an important parameter inversion (or indicator).
- The synthetic data with modeling pipes show some similar features to the measured data. However, there is still quite much difference, which might be due to either or both of 1) inaccuracy of inverted resistivity profile and 2) inaccuaracy in seabed pipe modeling.

Summary and Future work

- We will need to improve furthermore the (background) model in order to provide a good input to further inversion (e.g. Feasible to produce ”Day0” CSEM model).
- 2.5D inversion with or without seabed pipe effects (e.g. manually removing data points) but with constraints/initial models resulting from Pseudo2D/line-inversion of 2010.
- 3D inversion with seabed pipe effects but with constraints/initial models resulting from all the previous studies (Pseudo2D/line-inversion, 2.5D inversion, etc.)
- Coupling CSEM with CO2 multiphase flow simulation (extending NGI FoU work)

Acknowledgement

We thank

- CO2ReMoVe project
- Statoil
- SUCCESS center (NFR/FME)
- NGI and NGI colleagues (Inge, Tore, Eyvind)

for supporting and permission to present the study at the conference.