Electrical Resistivity Tomography Concept for CO_2 Injection Monitoring at the Svelvik CO_2 Field Lab

Tobias Raab[1], Wolfgang Weinzierl[1], Dennis Rippe[1], Bernd Wiese[1], and Cornelia Schmidt-Hattenberger[1]

1: GFZ German Research Centre for Geosciences, Potsdam, Germany

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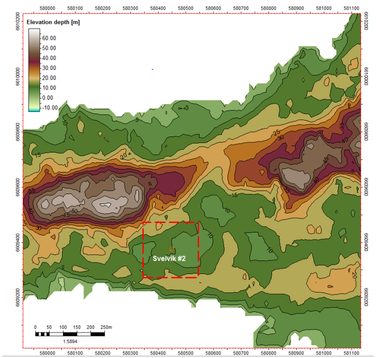
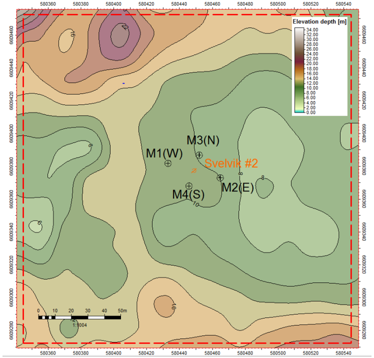
Summary

- Within the ERA-NET co-funded ACT project Pre-ACT (Pressure control and conformance management for safe and efficient CO_2 storage - Accelerating CCS Technologies) a brine- and CO_2 injection experiment was performed at the Svelvik CO_2 Field Lab. The field lab consists of four 100 m deep monitoring wells surrounding an injection well.
- In a first phase ≈60 tonnes of brine were injected in the target horizon at approximately 65 m depth. In a second phase ≈1.5 tonnes of CO_2 were injected. This represents a significantly smaller amount of CO_2 than was originally planned (22 tonnes), made necessary by operational constraints.
- The main goal of the experiment was to discriminate pressure- and saturation effects on the response of monitoring systems. Among others, Electrical Resistivity Tomography (ERT) monitoring systems were installed in the four monitoring wells. Complementary seismic cross-well measurements were carried during both phases of the experiment.
- To select suitable ERT measurement schedules prior to the experiment, we performed numerical ERT modeling. We use ECLIPSE reservoir simulations in combination with Archie's second equation to generate electrical resistivity models of the injection site. All possible measurement configurations are simulated and sub-sets are selected based on different criteria. The sub-sets are evaluated by inverting the simulated data with different error levels.
- Due to the small amount of injected CO_2, ERT has so far failed to image the CO_2 plume in the sub-surface. A small increase in electrical resistivity ($\approx 1\%$) can be observed in individual configurations. We perform a post schedule analysis with modified reservoir models using the full Archie equation. The adjusted reservoir models better represent the measured data.

The Svelvik CO_2 Field Lab





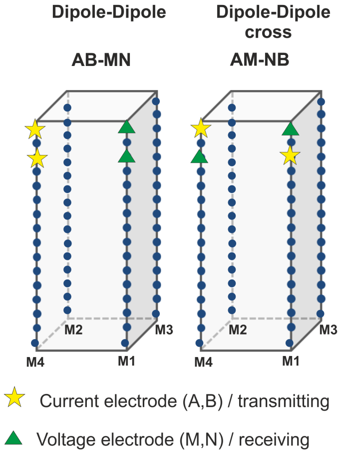
The Svelvik CO_2 Field Lab is located on the Svelvik ridge at the outlet of the Drammensfjord in Norway. The geology in the target depth ($\approx$ 65 m) is classified as glaciofluvial-glaciomarine terminal deposits.

The Svelvik CO_2 Field Lab

The Svelvik field lab consists of four 100 m deep monitoring wells, drilled in July 2019, surrounding an existing well used for brine and CO_2 injection. Each monitoring well is equipped with state of the art sensing systems including five types of fiber-optic cables, conventional and capillary pressure monitoring systems, as well as 16 ERT electrodes with a spacing of five meters installed from 23 to 98 meters depth.

Electrical Resistivity Tomography - Introduction

- Established technique for monitoring resistivity sensitive processes, e.g. due to CO_2 related saturation changes.
- Measured in four-point configurations, current injection between two electrodes (AB), potential measurement between the second pair (MN).
- Large number of possible configurations.
- $\text{Num}_{configs} = N_{el}(N_{el}\text{-}1)(N_{el}\text{-}2)(N_{el}\text{-}3)/8$
- 64 electrodes $\rightarrow$ 1906128 configurations (excluding reciprocal measurements).



Schedule Selection - General Considerations

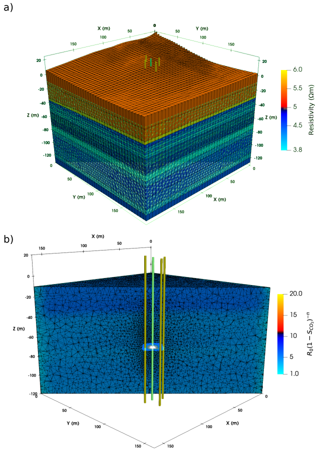
- Schedule selection: Trade off between temporal $\leftrightarrow$ spatial resolution
- Geometric factor
  - $rhoa = R * k$ [Ohm * m]
  - k is called the geometric factor, determined by the measurement geometry.
  - k can become very large ($> 10^5$) Small positional errors/point approximation of electrodes $>>$ Measurement signal.
- Error estimation (reciprocal measurements)
- Maximum response
- High sensitivity in target area

Pre - Experiment - Schedule Selection

- Forward simulation of all possible configurations where two electrodes are located in the same well (am - bn, ab - mn) for all well combinations ((well 1, well 2), (well 1, well 3) ...)
- Selection criteria for am - bn configurations $max(^{\Delta R}/_{k})$ (geometry optimized)
- Selection criteria for ab - mn configurations $max(\Delta rhoa)$ (response optimized)
- Schedule optimized for sensitivity in the target area utilizing Jacobi matrix of individual configurations (sensitivity optimized)
- All am - bn configurations selecting every 1500'th configuration with reciprocal measurements. Error estimations over a large range of configurations (overview)

Electrical Resistivity Tomography - Simulation Workflow

- Coupling of ECLIPSE reservoir modeling, with open-source packages Gmsh and pyGIMLI, PHREEQC, and mayavi
- Workflow:
  - ECLIPSE reservoir simulation of CO_2 injection with a priori information (well logs (resistivity, sonic), petrophysical models ...).
  - Automatic mesh generation with well placement, mesh refinement around electrodes.
  - Conversion of structured reservoir model data to electrical resistivity data on unstructured grid using Archie's laws.
  - Forward simulation and schedule selection.
  - Inversion of simulated data with different error levels. Back-interpolation to structured, Petrel readable format.



Pre - Experiment Schedule Evaluation

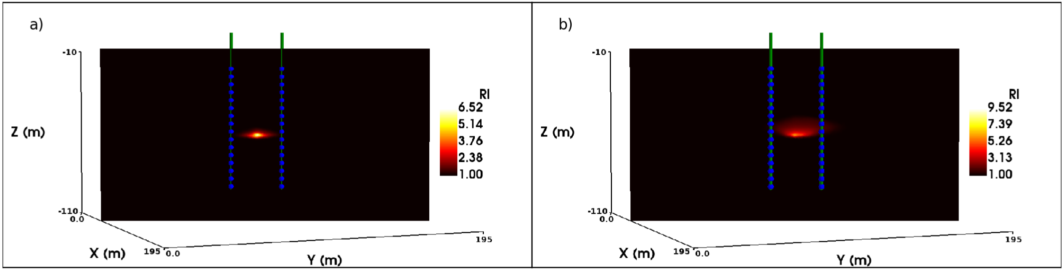
In the following we will show the simulated performance of the applied selection criteria and their advantages and disadvantages. For each criterion, the top-ranked 1000 measurement configurations are selected. Originally it was planned to inject 22 tonnes of CO_2. The simulations injecting 1.5 tonnes of CO_2 were performed after the experiment, to investigate their potential to image the smaller amount of injected CO_2.

Geometry- and response optimized schedules show similar behavior, resolving the spatial extension of the plume well. The peak value in RI is resolved less well compared to the other two schedules. The two criteria show the least numerical artifacts and are less prone to increased data errors.

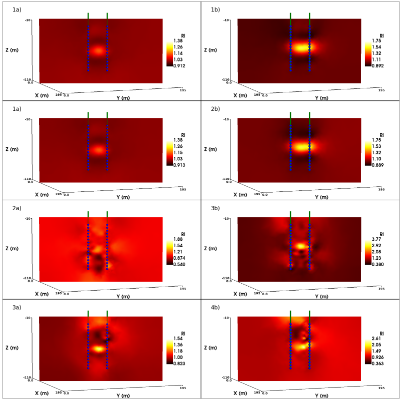
The sensitivity optimize schedule resolves the peak RI value the best. The spatial extent of the plume is resolved. Considerable numerical artifacts are produced, especially in the 1.5 tonnes injection case.

The overview schedule also resolves the plume. Especially for the originally 22 tonnes injection, it produces the most inversion artifacts.

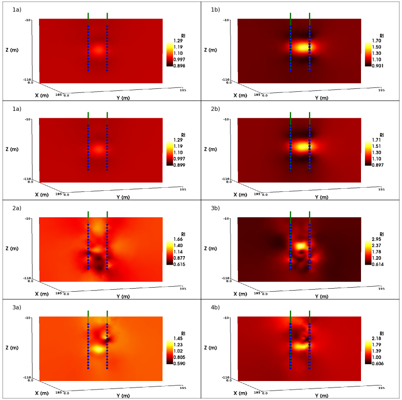
Pre - Experiment Schedule Evaluation



NW-SE slice through the pre - injection model for a) 1.5 tonnes and b) 22 tonnes of CO_2 injection, in terms of the resistivity index (RI). Blue spheres indicate the position of the electrodes. RI is calculated according to Archie's second law as $R/R_0 = RI = (1 - S_{CO_2})^{-n}$, where S_{CO_2} is the CO_2 saturation. The saturation exponent n is assumed to have a value of 2.



0% Data Error

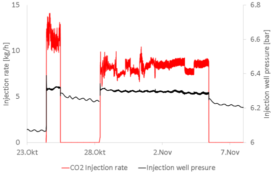


8% Data Error

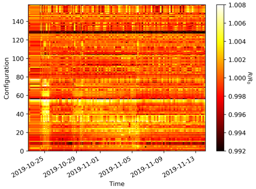
Slices through the 3D inversion result on the NW-SE diagonal for the resistivity models shown on the previous slide. Sub-plots show the inversion results for selected schedules and different data errors. 1) 1.5 tonnes of CO_2 injection. 2) 22 tonnes of CO_2 injection. a) Geometry optimized criterion. b) Response optimized criterion. c) Sensitivity Optimized, d) Overview Schedule

Post - Experiment Schedule Evaluation

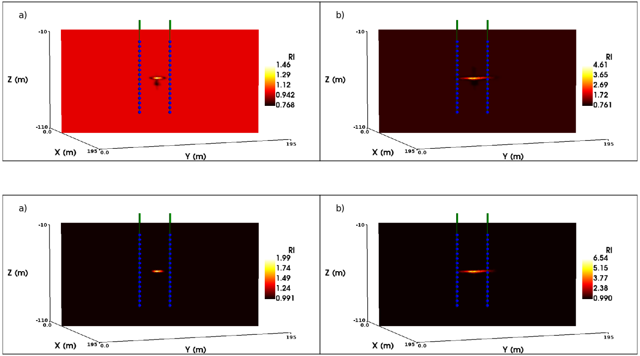
- The CO_2 injection took place between 24.10.2019 and 05.11.2019.
- Approximately 1.5 tonnes instead of originally planned 22 tonnes of CO_2 were injected.
- So far, we where not able to image a potential CO_2 plume using ERT inversion. Individual configurations show maximum RI of 0.012. The majority, where changes are detected, show increases below 1 % however. This represents a considerably lower response than predicted by the models used prior to the experiment, even for the reduced injection volume. This lead to adjustments of the reservoir model (consideration of CO_2 solubility, adjusted permeability and injection procedure) as well as the application of the full Archie equation to generate the resistivity models.
- The full Archie equation is given as $R_{Rock} = R_{Brine}\Phi^{-m}(1 - S_{CO_2})^{-n}$, where R_{Rock} is the bulk resistivity, Φ is porosity, S_{CO_2} is the (gaseous) CO_2 saturation, R_{Brine} is the resistivity of pore filling fluid, and m is the cementation exponent.
- Since the relevant geology is glacio-marine we consider the possible presence of $CaCO_3$ in the formation, which can be dissolved by CO_2 in solution increasing the brine conductivity. We performed PHREEQC simulations for different CO_2 pressures in the reservoir and complementary increase in brine conductivity with and without the presence of $CaCO_3$.



CO_2 injection rate during the experiment.



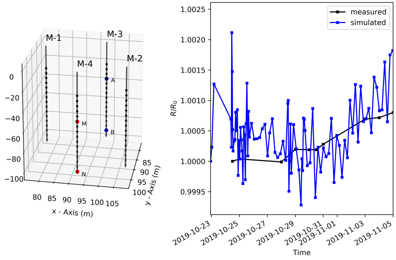
Resistivity Index of individual configurations measured on the NS diagonal between well M-3 and M-4.

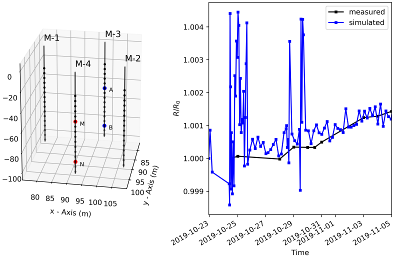


Saturation exponent n = 2, cementation exponent m = 2.

Slice through the adjusted reservoir model in the NW-SE direction for the simulation time step with maximum gaseous CO_2 (05.11.2019). The simulation mimics the real injection procedure with operations paused at the weekend. a) 1.5 tonnes injection b) 22 tonnes injection. Top with increased brine conductivity due to solution of $CaCO_3$. Bottom brine conductivity only increases due to solution of CO_2 (small effect).

Post - Experiment Schedule Evaluation





Comparison for between measured- and modeled data for two individual configurations. The model used assumes no $CaCO_3$ solution. The dynamic evolution in the first phase of the injection (around 25.10.2019) is not resolved, also due to a lack of resolution in the reservoir simulation. Later trends appear to broadly agree. The time series also demonstrate the dynamic resistivity evolution, with fast changes particularly in the first phase of the injection.

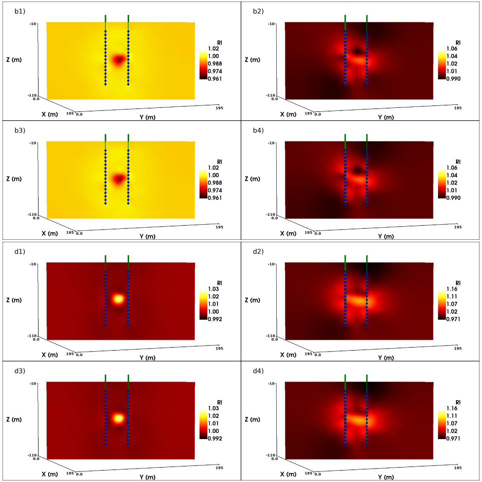
The figures show the inversion results for the modified resistivity models shown two slides before.

The top four sub-plots (b) show the case for $CaCO_3$ dissolution. The bottom four sub-plots (d) show the case without $CaCO_3$ dissolution.

Shown are inversion results for the maximum response- (1, 2) and optimized sensitivity schedule (3, 4).

The first column shows the case of 1.5 tonnes CO_2 injection, the second column shows the case for 22 tonnes of CO_2 injection.

The smaller spatial extent and lower magnitude of the CO_2 induced resistivity anomaly makes it difficult to resolve the plume.



Post - Experiment Schedule Evaluation

From the numerical experiments the following observations can be drawn:

- The resolved resistivity index is considerably lower than indicated by the models used in the pre-experiment phase, inline with field observations.
- Adjusted reservoir models appear to better explain the measured data.
- With the low resolved resistivity index both schedules will likely fail to image the CO_2 plume in the real field experiment.
- Temporally finer reservoir simulations needed in the first phase of injection.
- Since a small increase in the resistivity index is measured over all, $CaCO_3$ is likely not present in sufficient quantities to completely mask the resistivity effect of gaseous CO_2, but might be present locally.

Conclusions

- Numerical results indicate that ERT measurement schedule selection based on the presented selection criteria can be beneficial in the context of CO_2 injection monitoring.
- Accurate reservoir modeling will further support the understanding of potential and limitations of ERT imaging techniques in the context of CO_2 storage.
- Although difficulties were encountered, the presented study helped to further the understanding of the Svelvik test site, leading to more accurate reservoir models with potential benefits for future experiments.

Acknowledgements:

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