Evaluation of **Geoelectrical Crosshole** and **Surface-Downhole** Measurements

presented by

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Outline

I. Our Motivation

II. Site specifics

III. Work-Flow & Results

   Crosshole Measurements

   Surface-Downhole Measurements

IV. Summary & Lessons learned
I. Motivation

**Geophysical monitoring** of the migration of injected CO₂ by using **seismic** and **geoelectrical** measurements

- at intermediate and high gas saturation (above 20%) geoelectrical methods are more sensitive than seismic methods
- geoelectrical measurements are relatively easy to deploy
- higher repetition rates and cost-efficiency, **but**: lower structural resolution

![Graph](image.png)

**P-wave velocity** and **resistivity** versus CO₂ saturation - measured at Nagaoka test site (Japan), X. Zue et al., SPE 126885, Nov. 2009, - theoretical derived in: Wilt & Alumbaugh, 2006

→ **investigation of the feasibility** of the geoelectrical monitoring of the CO₂ migration into the saline aquifer in Ketzin

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II. Site specifics – measurement concept

VERA

<table>
<thead>
<tr>
<th>VERA</th>
<th>June 21, 2008 baseline</th>
<th>daily</th>
<th>twice a week until December 2008</th>
<th>weekly further on</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-S / S-D</td>
<td>Pre-Injection Phase</td>
<td>Start Injection Phase</td>
<td>Regular Injection Phase</td>
<td></td>
</tr>
<tr>
<td>Operational Work</td>
<td>June 30, 2008</td>
<td>July 15, 2008</td>
<td>March 20, 2009</td>
<td></td>
</tr>
<tr>
<td>Facility Testing</td>
<td>Start of Injection</td>
<td>Arrival of CO₂ at Ktzi200</td>
<td>Arrival of CO₂ at Ktzi202</td>
<td></td>
</tr>
</tbody>
</table>

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III. Work-Flow and Results

Major phases:

(1) Operational Phase
- Design of VERA (modeling, expertise for technical layout)
- Borehole installation, organizing data recording and handling
- Development of suitable large-scale surface-downhole measurement concept

(2) Start Injection Phase
- Preliminary results (instable states based on the small amount of CO₂)
- Tool optimization (Software, Data-readout, Pre-Processing demands)

(3) Regular Injection Phase
- Ensuring of data-quality
- Consistency of models and parameters
- Alternative or improved evaluation schemes

(4) Start of data integration and joint interpretation

still in process...

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Design of Crosshole Measurements

VERA
Vertical Electrical Resistivity Array

45 permanent electrodes
15 electrodes per well
electrode spacing ~ 10 m
installation depth ~ 590 to 735 m

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Technical Layout Cross-hole ERT

**VERA** - **Vertical Electrical Resistivity Array**

- **Steel electrode**
- **Taper pin**
- **Insulated casing**
- **Electrical cable**
- **Electrical cable**
- **Electrical cable**
- **Electrical cable**
- **Electrical cable**

- **used current: 2.5 A max.**
- **used channels: 15**
  (for potential registration)
- **measured voltage: 50 μV to 100 mV**

**ZONGE measurement equipment**

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Electrode Configurations

Selection of the electrode configurations of the main VERA acquisition schemes

[Bergmann et al., 2009]
Resistivity Logging

Logging results at injection well Ktzi201

Cap rock

Reservoir

100 % brine: 0.75 Ωm
50 % brine, 50 % CO₂: 2.0 Ωm

[Ref: Norden et al., 2007]

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Laboratory Experiments

Results from laboratory flow-through experiments of WP3.1

Available lab data indicate a bulk CO₂ saturation of 50% which corresponds to a resistivity increase of about 200%.

### Table: Lab data before and after CO₂

<table>
<thead>
<tr>
<th></th>
<th>Lab data before CO₂</th>
<th>Lab data after CO₂</th>
<th>difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ktzi202_B2-3b</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ρ [Ωm]</td>
<td>0.53</td>
<td>1.71</td>
<td>+223%</td>
</tr>
<tr>
<td>Ktzi202_B3-1b</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ρ [Ωm]</td>
<td>0.46</td>
<td>1.26</td>
<td>+174%</td>
</tr>
</tbody>
</table>

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Forward Modeling

Synthetic resistivity models and corresponding time-lapse results

homogeneous CO₂ distribution  small CO₂ plume  very thin layer with CO₂  composite model

[H. Schütt, 2008]
First Results of Time-Lapse Difference Inversion

[Kießling et al., IJGGC, accepted 2010]

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First Results from Field Data

Difference inversion:
(3D-EarthImager, AGI / USA)

THOUGH2, V2: homogeneous aquifer,
homogeneous permeability,
circular migration

Top reservoir

Bottom reservoir

08.09.2008: 1750 t CO₂

Resistivity change (%)

CO₂ gas saturation

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Quality Control of Field Data

Examples

[Bergmann, 2009]

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Sensitivity Studies

Resistivity models used for forward modeling

- Forward modeling with BERT [Rücker et al., 2006]
- 2D models with electrode geometry (6 km x 4 km)

[Bergmann et al., 2009]

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Sensitivity Studies

Evaluation of the crosshole measurement configurations

- The Bipole-Bipole configuration shows most significant alteration for vertical shaped anomalies.
- The Dipole-Dipole cross configuration shows most significant alteration for horizontal shaped anomalies.
- The Dipole-Dipole configuration does not show a distinct preference towards the shape of anomalies.
- For Bipole-Bipole and Dipole-Dipole cross data, magnitudes of synthetic and field data match.

[Reference: Bergmann, 2009]
Relating Resistivity and CO$_2$ Saturation

Multiphase fluid flow modeling of migration scenarios in the simplified injection formation model with varying reservoir permeability

\[ \rho(S_{CO2}) = \frac{A \rho_w}{\phi^m(1 - S_{CO2})^n} \]

Resistivity saturation relation derived from Archie's equation (black line) for $\rho_w=0.037 \ \Omega m$, $A=1$, $m=n=2$, $\Phi=23 \%$. The grey line depicts the discretized resistivity saturation relation utilized in forward modelling.

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Relating Resistivity and CO₂ Saturation

Step 2: Comparison with field data

Examples of electrode configurations

Synthetic resistances
True reservoir data \((T,p)\)
Field data

Conclusion:
Comparison of field data and modeled data allows analysis of potential CO₂ induced alterations and noise sources in the pre-inversion domain.
But the reservoir model needs to be refined to improve the fitting of both datasets.

[Bergmann, 2009]
Error Analysis and Dataset Optimization

Synthetic three-layer model with noise ~3% + 50μV/1A

Removal of data with noise > 30%

\[ \frac{\delta \rho_i}{\rho_i} = p\% + \left( \frac{\delta U}{U_i} \right) \times 100\% \]

Processed with BERT
– Boundless Electrical Resistivity Tomography

[Rücker, 2009]

<table>
<thead>
<tr>
<th>Measurement configuration</th>
<th>BB</th>
<th>DD</th>
<th>DD_lateral</th>
<th>Any (BB+DD+DDc+user defined)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data of sufficient quality</td>
<td>100%</td>
<td>20%</td>
<td>60%</td>
<td>57%</td>
</tr>
</tbody>
</table>
Crosshole-ERT Inversion Results

[C. Rücker, 2010]

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Crosshole-ERT Inversion Results

2D Inversion with BERT / cross section Ktzi200-Ktzi201: $\lambda = 100$ (regularization strength), $\rho_{\text{min}}^a = 0.05 \, \Omega \cdot m$, $\rho_{\text{max}}^a = 3 \, \Omega \cdot m$, error approximation: $3\% + 50 \, \mu V / 1 \, A$, amount of model cells: 702 (grid-model),
distribution of inverted resistivity (above), distribution of resistivity ratio (below)

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Field data: June 4, 2009

3D Inversion with BERT:

\( \lambda = 100 \)
(regularization strength),

\( \rho^{a}_{\text{min}} = 0.05 \ \Omega \text{m}, \)
\( \rho^{a}_{\text{max}} = 3 \ \Omega \text{m}, \)

error approximation: 3% + 50 \( \mu \text{V} / 1 \text{A} \)

Isosurfaces with resistivity ratios >2

\( \rightarrow \) arrival of \( \text{CO}_2 @ \)
Ktzi202 appears in the inverted data

[C. Rücker, 2010]
Large-scale geoelectrical measurements

Site map with **geoelectrical surface dipoles** (yellow dots) and **3D seismic survey at the surface** (light blue grid within the yellow quadrangle)
Surface-Downhole Data Acquisition & Pre-Processing

Data Recording
- 16 surface dipoles for current injection (15-20 min at each surface dipole)
- Potential registration at (14+3) dipoles at each well and 15 dipoles at surface
  = 1056 single potential time-series per survey

Including k - geometric factor
\[ k = 4\pi \left( \frac{1}{C_1P_1} - \frac{1}{C_1P_2} - \frac{1}{C_2P_1} + \frac{1}{C_2P_2} \right)^{-1} \]

Filtering and Fourier-Transformation:
calculation of electrical resistance \( R(\Omega) \) from ratios of the amplitudes (spectra)

Pre-Processing & Data quality control
- Assignment of Data and Dipol positions

Calculation of apparent resistivities \( \rho_a \) in \( \Omega m \)
\[ \rho_a = k \cdot R = k \cdot \frac{AV}{I} \]

3D Inversion
- Resistivity changes and anisotropic effects caused by CO₂ migration

Data Readout
- Data files from Texan in own data format

Protocol
- Assignment of Data and Dipol positions
- Conversion in SEGY-Format

Formatting
Surface-Downhole Inversion Results

Resistivity-Ratios:
2nd Repeat vs. 2nd Baseline

Resistivity-Ratios:
3rd Repeat vs. 2nd Baseline

depth slice @ z=-635 m
top of reservoir Ktzi201-Ktzi200

2nd Baseline: 04/2008
2nd Repeat: 11/2008
4,500 t CO₂
Arrival of CO₂ at Ktzi200 (07/2008)

3rd Repeat: 04/2009
13,500 t CO₂
Arrival of CO₂ at Ktzi200 (07/2008)
Arrival of CO₂ at Ktzi202 (03/2009)

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Results and Discussion

Preliminary Inversion Result: using 3D inversion software BERT (Rucker & Gunther, 2006)

Resistivity-Ratios: 3rd Repeat vs. 2nd Baseline

2nd Baseline: 04/2008

3rd Repeat: 04/2009
- 13,500 t CO₂
- Arrival of CO₂ at Ktzi200 (07/2008)
- Arrival of CO₂ at Ktzi202 (03/2009)

[Kießling & Rücker, 2010 (unpublished)]

surface-downhole and surface-surface data; 2nd Baseline: 1025 data points, 2nd Repeat: 1023 data points; calculation of electrical resistance from spectral analysis; 3D Inversion with BERT: calculation: λ = 100 (regularization strength), topography, range 10² to 10⁶ Ωm, error approximation: 1% + 10 μV / 4 A, amount of model cells: 19050 (tetrahedral); plotted depth slice; distribution of resistivity ratios
Results and Discussion

Geoelectrical Surface-Downhole and Crosshole data:

Geoelectrical Surface-Downhole

Geoelectrical Crosshole

Comparison

Ktzi200 Ktzi201

3rd Repeat: 27.-29.04.2009

Depth in m

[Kießling & Rücker, 2010 (unpublished)]

[Rücker, 2010 (unpublished)]

data: any; 29.04.09 (time step 87); 2D inversion with BERT: $\lambda = 100$ (regularization strength), range 0.05 to 3 $\Omega$m, error approximation: 3% + 50 $\mu$V/1 A, amount of model cells: 702 (grid-model); cross section Ktzi200-Ktzi201 with depth; distribution of resistivity ratios

surface-downhole and surface-surface data;
2nd Baseline: 1025 data points, 2nd Repeat: 1023 data points; calculation of electrical resistance from spectral analysis;
3D Inversion with BERT: calculation: $\lambda = 100$ (regularization strength), topography, range $10^2$ to $10^5$ $\Omega$m, error approximation: 1% + 10 $\mu$V/4 A, amount of model cells: 19050 (tetrahedral); plotted depth slice; distribution of resistivity ratios
Sensitivity Considerations

The sensitivity matrix $S_{ij}$ indicates how changes in the model domain element $m_j$ do change the data domain element $f_i$

$$S_{ij}(m) = \frac{\partial f_i(m)}{\partial m_j}$$

$$S = \begin{pmatrix} \frac{\partial f_1}{\partial m_1} & \cdots & \frac{\partial f_1}{\partial m_M} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_N}{\partial m_1} & \cdots & \frac{\partial f_N}{\partial m_M} \end{pmatrix}$$

[Rücker, 2010]
Intended Combination of Seismic and Geoelectric Measurements

Future studies are intended to incorporate structural constraints (e.g. from seismics) and error-weighted inversion schemes

[Bergmann, 2010]
CSEM monitoring of CO₂ injection at Ketzin pilot site
2008-2009 surveys, preliminary results

• Hole to surface CSEM
  – A complementary approach to crosshole tomography
    • Lower resolution but larger zone of detectability
  – Receiver stations in surface do no need electrodes array at the reservoir depth, one point of injection is enough
  – The metallic casing itself may be used to inject electrical current at depth
    ⇒ LEMAM – Long Electrode Mise-a-la-Masse
Two CSEM arrays are used at Ketzin pilot injection

Different current injection but same receiver stations at the surface.

Surveys:
- baseline in 2008 (before start of CO2 injection)
- 1st repeat in 2009 (~18,000 t of CO2)
- 2nd repeat in 2010 → scheduled in 2010
Each array shows a very contrasted response in surface.

Detectability of injected CO2 by surface receivers proven.

The two arrays show clear responses, but current injection at depth (left) shows a better detectability.
On-going:
- Performance assessment of exploiting vectorial nature (left) and frequency behaviour (right) of H & E fields measured in surface, to map resistivity changes at depth and link it to the CO2 saturation in the reservoir

Next field survey in Summer 2010:
- Second field repeat to prove ability to detect slight changes in CO2 saturation (contrast weaker than between survey 09 / baseline 08)
VI. Summary

• VERA system has been successfully installed and is operating since three years

• Resistivity logging and laboratory experiments are available and support geoelectric monitoring with structural and petrophysical information

• Pre-injection resistivity model was built based on site-specific data relating Archie’s law with standard sandstone parameters
  - low-resistivity environment (few Ωm to below 1 Ωm)
  - thin reservoir layer (max. 20 m)
  - small resistivity contrasts $\rightarrow$ max. increase $\approx$300% due to partial CO$_2$ saturation

• Studies incorporating multi-phase fluid flow modelling were performed indicating a significant dependency of apparent resistivity alteration to hydraulic conductivity within the reservoir (due to time-dependent CO$_2$ distribution)

• Inversion results are in good correspondence with current information from other monitoring systems (seismic, gas monitoring, RST and DTS)$\rightarrow$ contribute to the “big picture”, but more detailed investigations have to be conducted
VI. Lessons learned

- Necessity of improved degree of automization as well as a standard workflow for data acquisition, processing and evaluation
  - helps to overcome time-consuming manually data handling and avoids delay in delivering results to site operators / regulators

- Demand for unified models, synchronized parameters and coordinates
  - supports efficient data integration and corresponding joint interpretation
Thanks to all involved persons