Monitoring of CO_2-induced geochemical changes in a shallow aquifer by time domain spectral induced polarization

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1. Introduction

- Geological carbon sequestration is a promising technique for reducing CO_2 release into the atmosphere
- Potential risk: CO_2 or brine leakage into potable aquifers

Monitoring of dissolved CO_2 in shallow aquifers

- No direct CO_2 signal, only geochemical changes induced by the CO_2 can be observed
- Decreasing resistivity due to more dissolved ions, but effect highly site dependent (e.g., Dafflon et al., 2013, ES&T **47**, 314)

Questions addressed here

- Can CO_2-induced geochemical changes be imaged with surface direct current (DC) and time domain induced polarizaion (IP) measurements?
- Is there any IP effect and if so, what causes it and can it be imaged?
- How reliable and stable is IP monitoring?

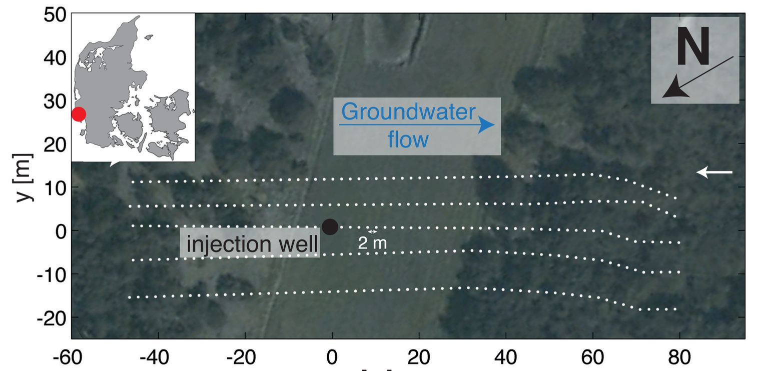
2. CO_2 injection experiment

Field site in western Denmark

- Geology consisting of
  - Aeolian sand (0-5 m depth)
  - Glacial sands (5-10 m depth)
  - Marine sands (below 10 m depth)
- Groundwater table at 2 m depth

CO_2 injection

- 4 injection points at 5 and 10 m depth
- Total of 1600 kg CO_2 injected in 72 days
- Injection started on May 14th 2012, 12 L/min, reduced to 6 L/min after 14 days
- Pilot study showed consistent decrease of resistivity with increasing CO_2 concentrations



Aerial photo of the field site with electrodes marked as white dots

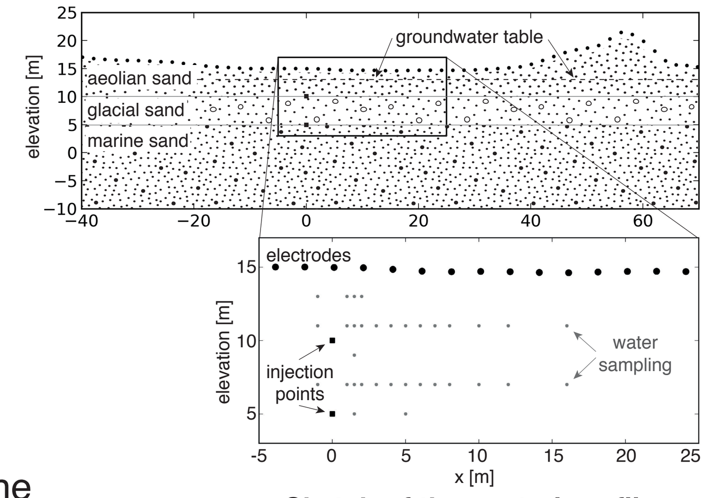
3. DC/IP and geochemical monitoring

DC/IP monitoring

- 64 electrodes at 2 m spacing on profile through injection wells
- Fully automated acquisition
- High-quality measurements before CO_2 injection and continuous acquisition until day 113 (counted from injection start)

Geochemical monitoring

- Frequent monitoring at 33 locations on the profile
- Analysis for electrical conductivity (EC), pH and dissolved element concentrations (Al, Ca, Mn, K, ...)

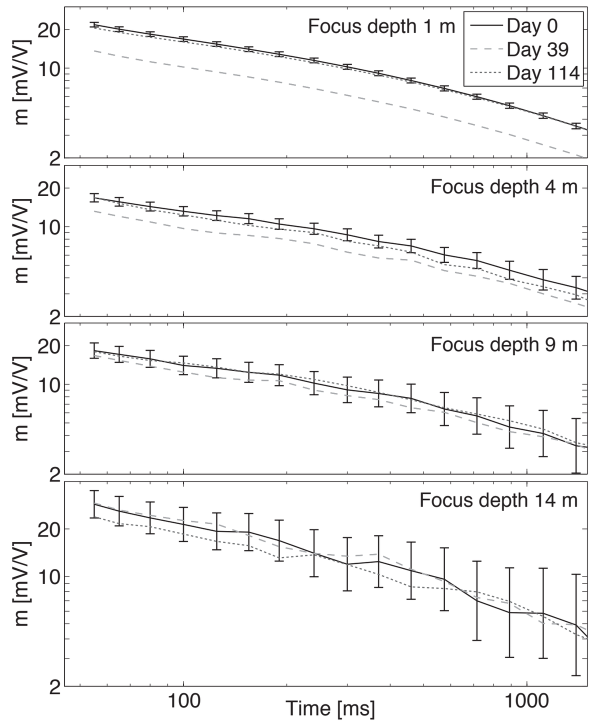


Sketch of the central profile through the injection wells

4. DC/IP data processing

Pre-processing

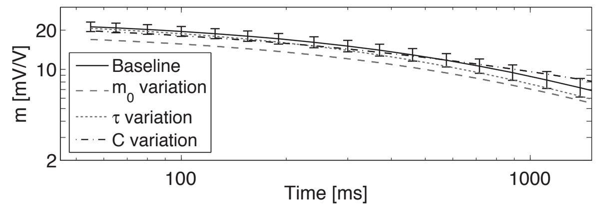
- 886 gradient-type four electrode configurations, 2 s T_{on}, 2 s T_{off} time
- Remove IP decays that were
  - negative
  - above 500 mV/V
  - curve increasing
- Error estimation
  - absolute voltage error of 0.2 mV
  - 4% relative error for DC and IP
  - time-lapse differencing for DC (2% rel. error), but not for IP
- Significant change in IP decay curves in shallow configurations around injection wells



Example IP decays for different depths around the injection wells

Sensitivity of IP decays

- Analyze change of IP decays to 20% variation in m_0, τ and C
- Normalized RMS with 20% variation and typical error estimates for 4 m focus depth configuration
  - m_0 - 2.16
  - τ - 0.73
  - C - 0.75
- Only change in m_0 can be reliably detected



Change of IP decay with 20% variation in Cole-Cole parameters

5. Time domain spectral IP inversion

Full-decay inversion for spectral information

- Simultaneous inversion for resistivity and Cole-Cole parameters using AarhusInv (Fiandaca, G. et al., 2013, GJI **192**, 631)
- Cole-Cole parameters
  - ρ - resistivity
  - m_0 - chargeability
  - τ - relaxation time
  - C - frequency exponent

complex resistivity

$$\zeta(\omega) = \rho\left[1 - m_0\left(1 - \frac{1}{1+(i\omega\tau)^C}\right)\right]$$

frequency - ω

- Full modeling of current waveform and instrument filters
- Spectral information contained in Cole-Cole parameters

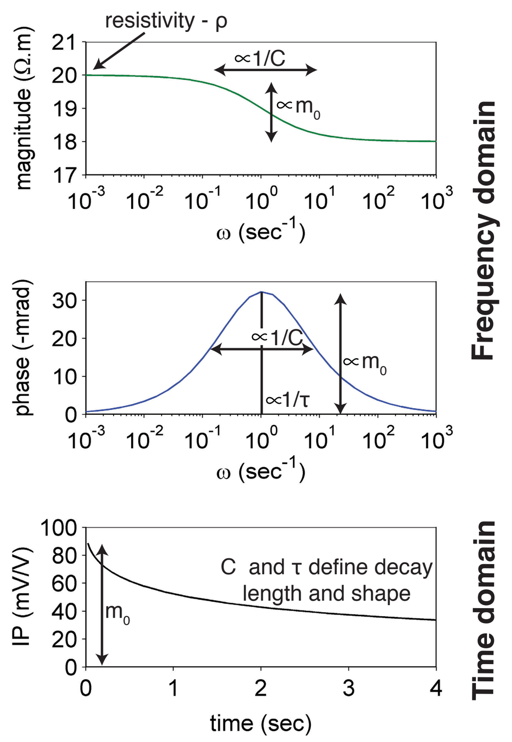
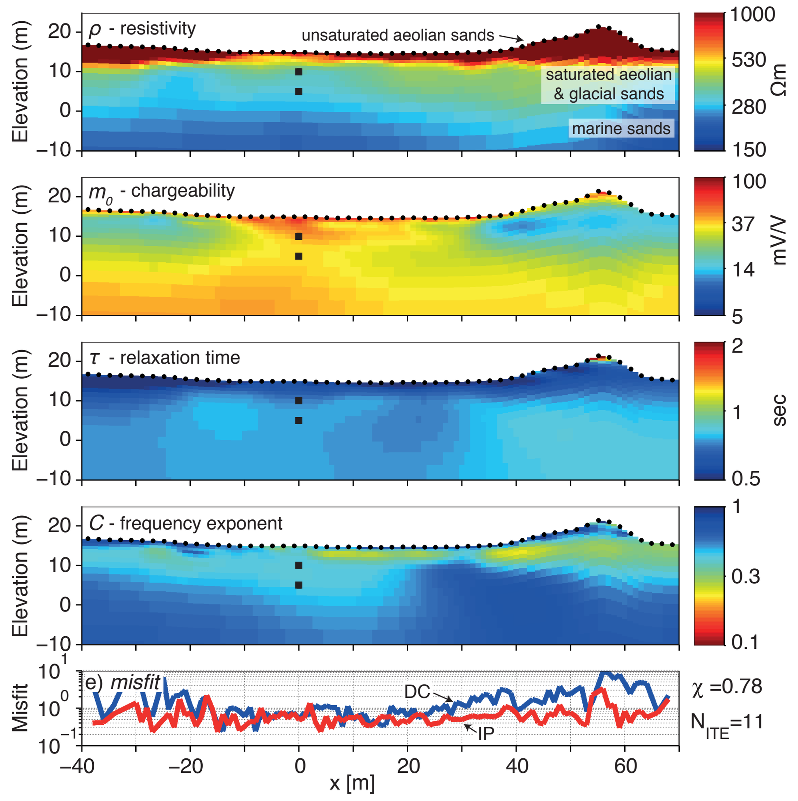


Illustration of the Cole-Cole parameters



Baseline inversion result

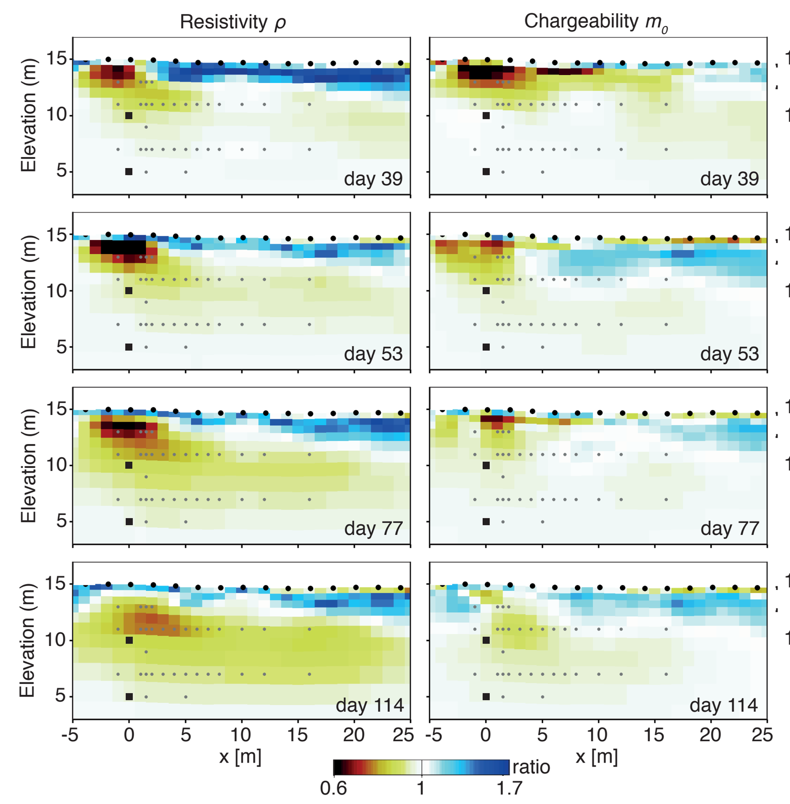
Baseline inversion

- Inversion of pre-injection data
- Sequential inversion
  1. DC only (4 iterations)
  2. combined DC & IP (7 iterations)
- Resistivity section confirms sequence of unsaturated and saturated sands
- Lower chargeability in dune, high m_0 near surface
- τ and C show variation around water table

6. Time-lapse inversions

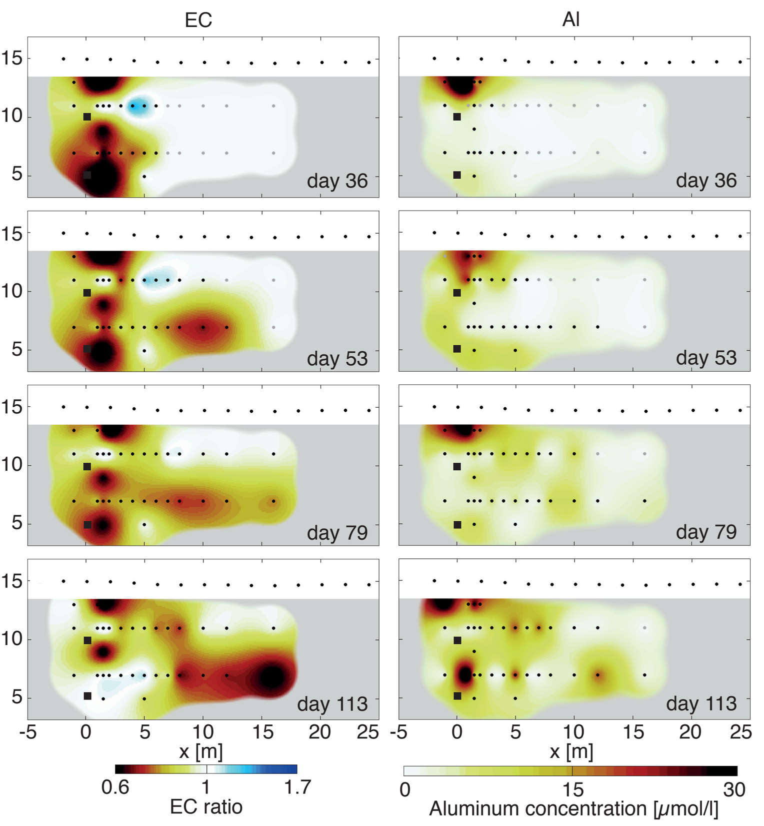
- Invert for differences in Cole-Cole parameters from baseline model
- Distinct CO_2 driven anomalies in ρ, m_0; τ and C variations are below detection limit
- ρ images advective flow of dissolved CO_2; m_0 images increasing persistent acidification, closely related to Al concentration
- IP anomaly moves much slower than resistivity

DC/IP inversion



Time-lapse inversion results (ρ, m_0) for four different days

Geochemical sampling



Interpolated electrical conductivity (EC) and Aluminum (Al) concentrations

7. Conclusions

- High-quality IP monitoring data can be acquired on the field scale over extended periods of time (120 days)
- Surface DC and IP measurements are able to image geochemical changes induced by injected CO_2
- Time-lapse 2D full-decay IP inversions image the CO_2 plume as a decrease in resistivity and a decrease in chargeability
- Two different chemical mechanisms imaged:
  1. advective pulse from carbonic acid reacting with Al-hydroxide minerals forming bicarbonate and Al ions releasing other cations by surface processes (primarily ion exchange) imaged by lower DC-resistivity
  2. pH is lowered by the carbonic acid, changing surfaces directly (by dissolution) and indirectly by altering the surface charge, the combined effect being picked up in the IP signal.
- Good agreement with water chemistry samples from >30 sample locations (see Cahill et al., 2014, WRR **50**, 1735)

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Further information: Contact joseph.doetsch@geo.au.dk and see publication

Auken, E., Doetsch, J., Fiandaca, G., Christiansen, A.V., Gazoty, A., Cahill, A.G., Jakobsen, R., 2014, Imaging subsurface migration of dissolved CO2 in a shallow aquifer using 3-D time-lapse electrical resistivity tomography, J. Appli. Geophys. **101**, 31-41.