Monitoring of geological CO_2 storage with electrical resistivity tomography (ERT): Results from a field experiment near Ketzin/Germany

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Introduction

Geoelectrics has proven to be a valuable monitoring method as part of the required surveillance concept in geological carbon dioxide capture and storage (CCS) projects, since the electrical resistivity of a porous reservoir rock is highly dependent on the presence or absence of CO_2. Experimental (RAMIREZ and Friedmann, 2008) and numerical studies (CHRISTENSEN et al., 2006) demonstrated the promising application of electrical resistivity tomography (ERT) for CO_2 plume detection.

For the Ketzin storage pilot site (Fig. 1), where CO_2 is injected into a deep saline aquifer at roughly 650 m depth (WÜRDEMANN et al., 2010), numerical models predicted a CO_2 saturation of approximately 50% for large parts of the plume. Archie's equation predicts an increase of the resistivity by a factor of approximately 3 for the reservoir sandstone, and laboratory tests on Ketzin reservoir samples support this prediction (KUMMEROW and SPANGENBERG, 2011). Feasibility studies show that tracking the CO_2 plume may be doable with crosshole resistivity surveys under these conditions. The installed permanent vertical electrical resistivity array (VERA) was the first permanent ERT array in a CCS operation world-wide. It was followed by the deepest ERT array (3000 m) at the Cranfield test site in Mississippi, USA (CARRIGAN et al., 2009), and very recently by a planned installation at the typical industrial storage depth of about 1500 m at the Spanish Hontomin site (LEDO et al., 2011). The Ketzin VERA system showed promising results during its run-time since the start of injection in June 2008 until today, and it has mapped the predicted resistivity contrast due to the CO_2 in the rock pores (KIESSLING et al., 2010). Furthermore, the permanent electrodes establish a valuable interface for additional CSEM/MT measurements on a larger spatial scale (GIRARD et al., 2001).

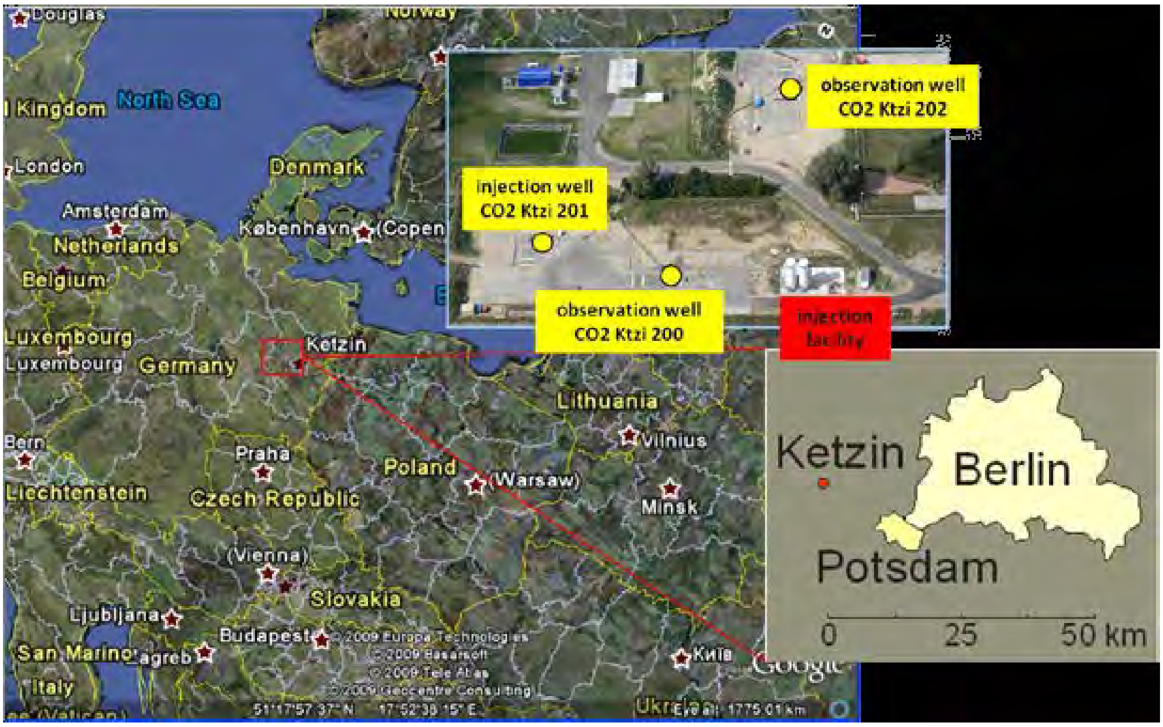


Fig. 1: Location of the Ketzin site in Europe. Inset maps show details of the test site, and its close vicinity to the cities of Berlin and Potsdam.

The Ketzin ERT concept

Ketzin is located in the North East German Basin (NEGB) at about 25 km west of Berlin, and the immediate environment of the CO_2 pilot test site is farmland. The three wells (one injection and two observation wells) arranged in triangular manner were drilled through the Stuttgart Formation, which is situated at about 630-710 m depth. The target storage sandstone reservoir is located at a depth ranging from 630-650 m. The Stuttgart Formation is lithologically heterogeneous, consisting of sandy channel-(string)-facies rocks with good reservoir properties alternating with muddy floodplain-facies rocks of poor reservoir quality (FÖRSTER et al., 2006; NORDEN et al., 2010).

Based on the existing site-specific knowledge we deployed 45 permanent electrodes on the electrically insulated casings of the three Ketzin wells in a depth interval from roughly 590 m to 740 m with spacing of about 10 m (Fig. 2). The electrodes are connected to the current supply and data registration units at the surface through custom-made cables. This deep electrode array allows for the acquisition of electrical resistivity tomography (ERT) data sets at high repetition frequencies and at moderate cost, without interfering with the injection operations.

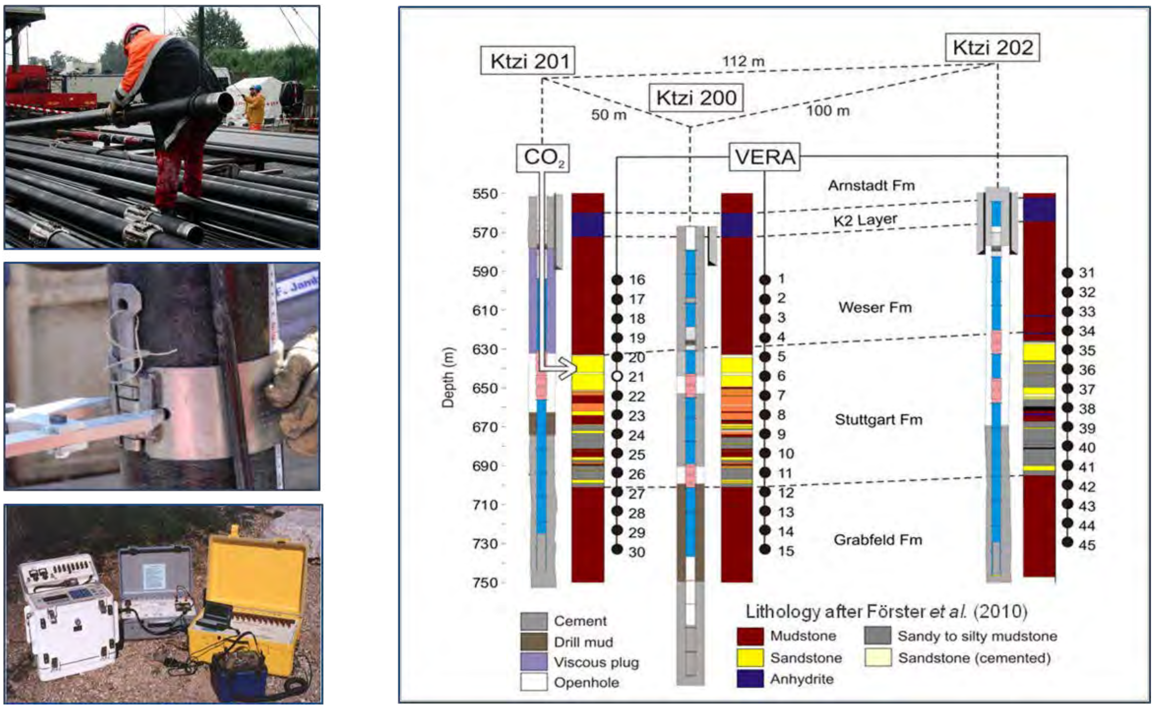


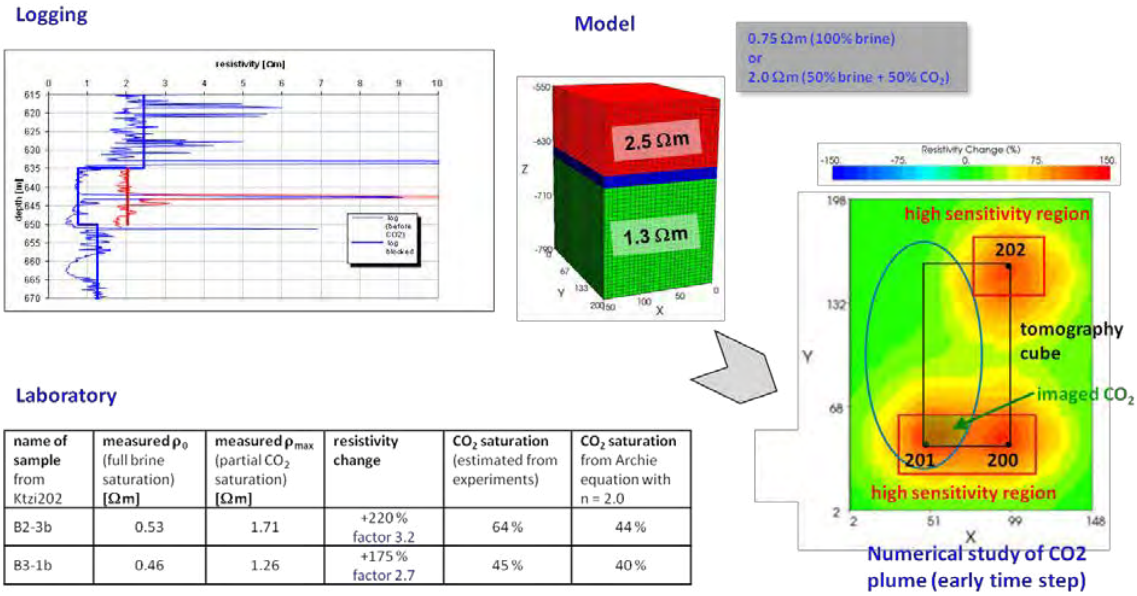
Fig. 2: Relevant components of the Ketzin VERA system: Insulated casing, stainless-steel electrodes, and data acquisition unit from ZONGE Engineering Inc. (left side, from top to bottom).

Well completion scheme, lithology (after FÖRSTER et al., 2010) and electrode positions of the VERA system (black dots) for the three wells at the Ketzin site (right side).

For the Ketzin monitoring concept, the permanent crosshole measurements which are covering the near-wellbore area were combined with surface-downhole surveys at selected time windows during the phase of regular CO_2 injection. These large-scale surveys deploy 16 dipoles (dipole length of 150 m) on two concentric circles at the surface with the radii of 800 and 1500 m, and potential dipoles at the VERA system in all three wells (KIESSLING et al., 2010). Baseline data sets have been measured prior to the CO_2 injection, and monitoring data sets are recorded while CO_2 is being injected. The recorded current and potential raw data are converted to apparent resistivity, and inverted to obtain 3D images of the resistivity distribution in the reservoir. Hence, one can provide information about the saturation state of the reservoir independently from seismic methods. From the technical point of view, the VERA system has to operate under challenging conditions, e.g. the very complex heterogeneity of the reservoir zone, and the potential high possibility of corrosion by high saline formation water and CO_2 in the subsurface environment. The system must have long-term stability, so that it can effectively contribute to the multi-disciplinary monitoring program.

In the frame of a feasibility study the forward modeling based on laboratory and logging results provided a first rough estimate about the distribution of the injected CO_2. The schematic tomography “cube” of the volume imaged by VERA (Fig. 3) shows the CO_2 plume that can be assumed to follow mainly gravity along the structural trend of the anticline, i. e. migrating toward N, N-W. The high-sensitivity zones of the VERA system image this behavior with a radius of about 30 m around each well. A simple 3-layer model has been derived from resistivity log analysis. The thin reservoir target zone was assumed to be saturated with 50% CO_2. Forward modeling based on this simple Archie-model is shown at the bottom of the left side. Here, we find a confirmation of the above sketched performance of the VERA array.

But we should be aware: The preferred flow path depends also on a more complex porosity and permeability distribution, and the CO_2 plume will most likely have a modified shape reflecting the local variations of geology.



name of sample from Ktzi202	measured ρ_0 (full brine saturation) [Ωm]	measured ρ_{max} (partial CO_2 saturation) [Ωm]	resistivity change	CO_2 saturation (estimated from experiments)	CO_2 saturation from Archie equation with n = 2.0
B2-3b	0.53	1.71	+220 % factor 3.2	64 %	44 %
B3-1b	0.46	1.26	+175 % factor 2.7	45 %	40 %

Fig. 3: Numerical study of the CO_2 plume migration imaged by the VERA system (right side), based on a simple 3-layer resistivity model underlined by laboratory data from petrophysical flow-through experiments and by logging results (modified after KIESSLING et al., 2010). The thin target reservoir zone and the relative low resistivity contrast before and after CO_2 injection pose a major challenge to the detectability of the monitoring system.

Data analysis and CO_2 plume detection

Assigned to the four major topics which are: Array design – acquisition – processing – evaluation, we can structure the Ketzin geoelectric concept as modular monitoring system (MMS) with key-modules for realizing an efficient work flow to achieve reliable results from the field data, regarding the CO_2 plume propagation (SCHMIDT-HATTENBERGER et al., 2011).

We have studied the ERT raw data in joint interpretation with the process data from the CO_2 injection operation. Significant temporal variations have been detected between the field data sets of the individual crosshole repeat measurements. This behavior is still being analyzed along the storage process time history, regarding an eventual origin or influence by the injection process.

Due to time constraints arising from the large number of measurements for a manifold of electrode configurations (ABMN schedules), only short signal cycles of 16 s have been recorded. In Fig. 4, we see data examples varying from very good signal quality to spiky and very noisy behavior, or to nearly distorted records. For the preprocessing of the shortened signal time series we had to develop an adapted workflow. This approach provides an adequate powerful tool in comparison to the commonly used selective stacking procedure (STORZ et al., 2000) which is not applicable here.

The preprocessing scheme runs after the following steps: (1) identification of all ABMN combinations from one measurement day, (2) filtering according to data quality control, i.e. upper and lower signal level check of voltage and current as well as their standard deviation, mean values, and error estimation, (3) decision making: useful field data YES or NO, (4) merging by an appropriate average process for identical ABMN combinations, either by simple mean or median filtering, depending on the number of measured values (Fig. 4, left side), (5) curve fit of the data points from merging process, (6) interpolation to achieve continuous data series.

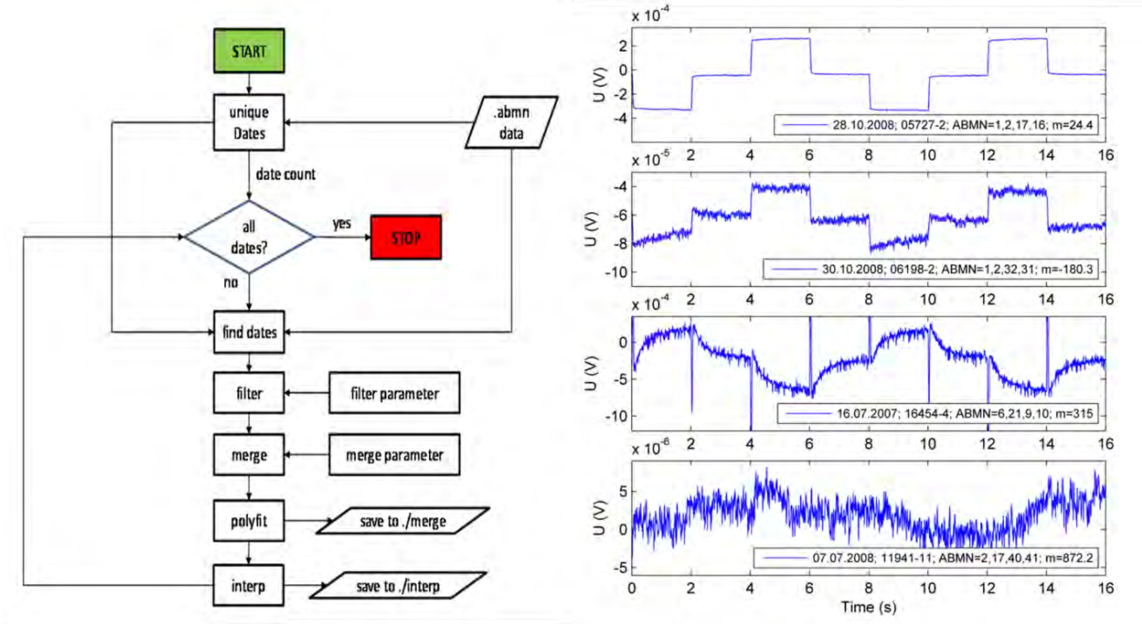


Fig. 4: Prepocessing workflow (left side), applied to all ABMN time series of the measured crosshole electrode configurations, represented by a set of typical signal forms recorded during the field measurements (right side).

To obtain more certainty for the inversion results derived from the processed data, we tried and tested various inversion program codes. Some of them are suitable for quick in-field inversion to get first estimations of results, due to their user-friendly menu-driven workflow. Finally, we remained with the Open Source Code BERT, which stands for "Boundless Electrical Resistivity Tomography" (RÜCKER et al., 2006; GÜNTHER et al., 2006). The script-driven program allows the handling of a large observation space in order to minimize disturbing boundary effects. Furthermore, the program can deal in optimal way with the information-bearing parts of the data sets by a weighted-error procedure inside the inversion operator. The non-regular grid based on tetrahedral elements supports the investigation of areas with several tens of km (surface-downhole measurements) until areas with tens of meters (crosshole measurements), in a smooth transition.

Time-lapse results in 2D and 3D mode were investigated at different phases of injection, in joint evaluation with the current process data of the injection well (Fig. 5). A significant resistivity signature related to the CO_2 migration was detected in the major observation plane between the injection well and the first observation well (Ktzi201-Ktzi200).

Since autumn 2009, an increasing influence of degradation effects at some of the electrode cable take-outs were observed. This process affects a reduction of the 3D effect, and as a result of this some electrodes must be excluded from interpretation, and some of them even from the inversion procedure.

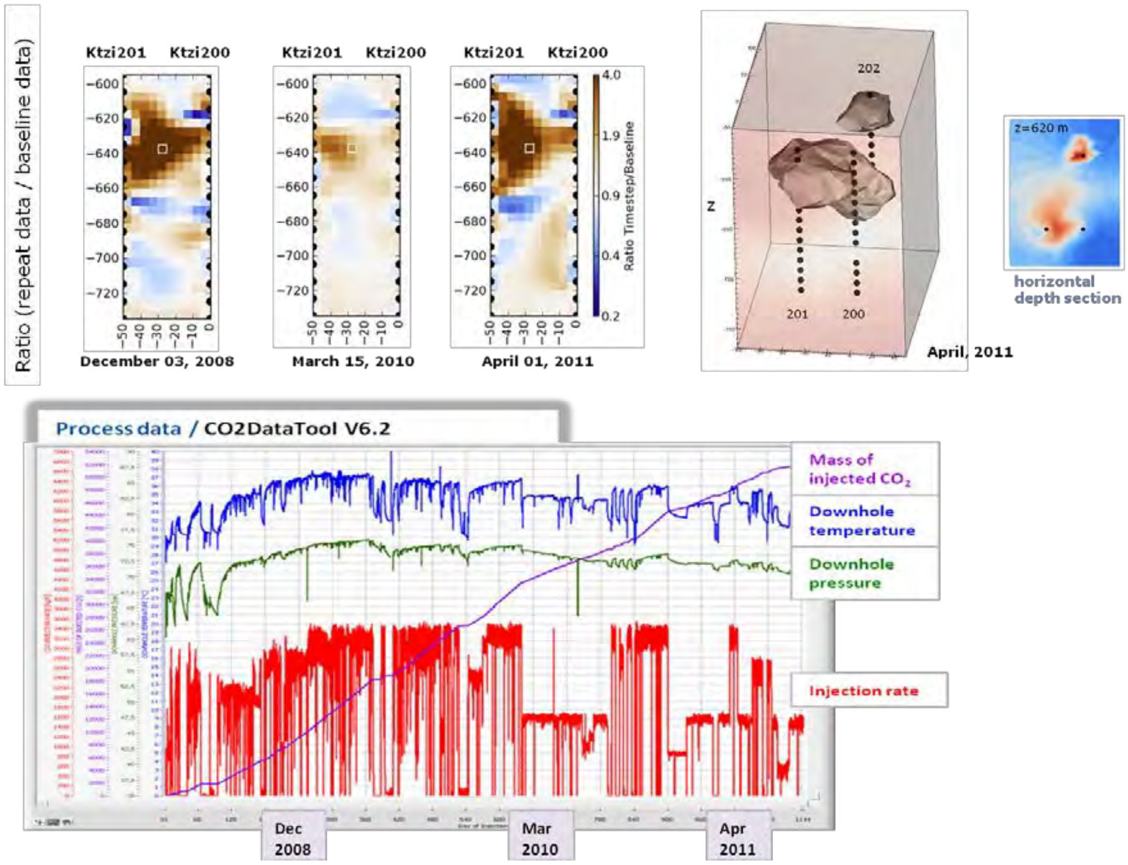


Fig. 5: 2D and 3D time-lapse results (BERT inversion program) assigned to certain phases of CO_2 injection with different flow-rates.

Conclusions

The technology for a permanent ERT downhole installation has been successfully site-proofed. The VERA system has been detected the CO_2 signature in the near-wellbore area, shown in a series of time-lapse inversion results. Due to thoroughly preprocessing work consolidated data sets could be established for the inversion procedure. Due to being a potential method, ERT lacks in imaging of structures at a similar detail as seismic monitoring. Therefore, we address current work on the incorporation of structural seismic information as a priori constraints in the ERT inversion.The general objective of our case study aims to deliver a realistic and reliable specification for the deployed ERT monitoring system, as contribution to the operational reservoir management of the CO_2 storage process.

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