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CO_2 migration monitoring by means of electrical resistivity tomography (ERT) – Review on five years of operation of a permanent ERT system at the Ketzin pilot site

C. Schmidt-Hattenberger[a]*, P. Bergmann[a], T. Labitzke[a], F. Wagner[a]

[a]Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, D-14473 Potsdam, Germany

Abstract

At the Ketzin pilot site, Germany, electrical resistivity tomography (ERT) is a substantial component in a multi-disciplinary monitoring concept established in order to image CO_2 injected in a saline aquifer. Since more than five years, crosshole ERT data sets have repeatedly been collected using a borehole electrode array acting as a permanent reservoir monitoring tool. This contribution summarizes the aspects being essential for a successful deployment and operation of such a downhole installation. It is shown that the presented installation can facilitate stable and reliable data collection at least throughout the investigated five-year period of ongoing CO_2 injection. Based on the experiences being gained so far, it is concluded that a properly calibrated and integrated downhole ERT system allows for mapping of quantitative CO_2 saturation estimates in the subsurface.

Peer-review under responsibility of the Organizing Committee of GHGT-12

Keywords: CO_2 storage; geoelectrical measurements; electrical resistivity tomography; permanent reservoir monitoring

* Corresponding author. Tel.: +49 331 288 1552; fax: +49 311 288 1502.
E-mail address: cornelia.schmidt-hattenberger@gfz-potsdam.de

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1. Introduction

1.1. Ketzin pilot site

Ketzin is the first European research and development project addressing on-shore geological storage of CO_2. The test site includes several infrastructural facilities and is mainly surrounded by farmland (Figure 1a). From the official start of CO_2 injection in June 2008 until the end of the injection phase in August 2013, about 67,000 tons of CO_2 have been injected into an Upper Triassic saline aquifer reservoir, the so-called Stuttgart Formation, at about 630 to 650 m depth. Given this fairly small amount of CO_2, monitoring techniques are demanded to be capable of detecting even small changes in the surveyed parameters. It is to be noted that this refers not only to the presence of the CO_2, but also to its interaction with the brine, rock minerals, and borehole completions. In order to address such tasks, a multi-disciplinary monitoring program was realized at Ketzin using a variety of surface-based monitoring methods as well as downhole monitoring methods (Figure 1b).

The Stuttgart formation originates from fluvial processes and comprises a fairly heterogeneous lithology [1]. The reservoir and the adjacent formations are characterized by rather low electrical resistivities in its pre-injection state. The resistivities in the reservoir sandstones are expected to increase by a factor of 2-3 once being swept by CO_2.

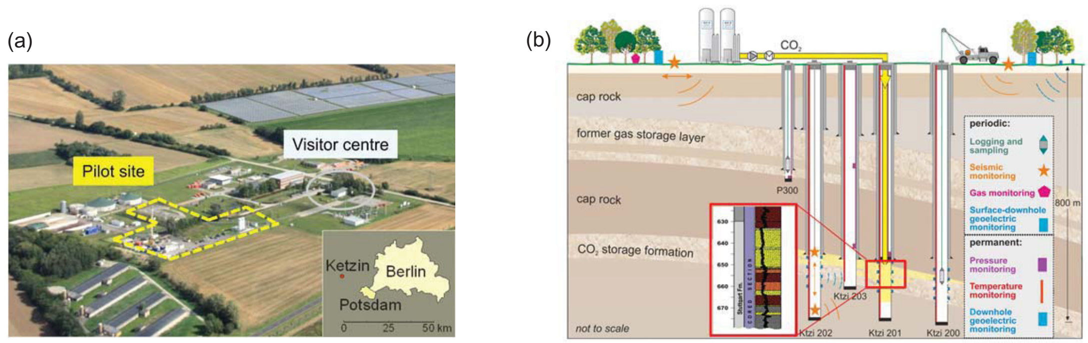

Fig. 1. (a) Aerial view of the Ketzin pilot site and visitor centre being located in rural environment (Photo: Courtesy of GFZ). The inlay shows the distances to the cities Potsdam and Berlin. (b) Schematic plot of the multi-disciplinary monitoring activities realized at Ketzin. The monitoring activities comprise periodic surveys and measurements with permanently deployed instruments. The downhole ERT measurements belong to the latter group. The sandstone reservoir for CO_2 storage as part of the Triassic Stuttgart Formation, is present at depths of about 630 to 650 m (inlay zoom).

1.2. Installation of the permanent ERT monitoring system

The installation of the vertical electrical resistivity array (VERA) was part of the drilling and well completion activities at the Ketzin site in the summer of 2007. Subsequently, it was suspended in stand-by mode for nearly one year until actual monitoring operation commenced with the begin of the CO_2 injection in June 2008. The array consists of a behind-casing deployment of electrodes at three wells of the Ketzin site (Ktzi200, Ktzi201 and Ktzi202). Fifteen electrodes have been deployed per well with a vertical spacing of 10 m, covering the depth range of 590-735 m (Figure 2a). The aspect ratio of vertical array length (150 m) and horizontal wellbore distances (50 m to 112 m) varies between 1, 3.4 and 3. The reservoir exhibits temperatures of up to 37 °C, pressures of up to 75 bar, and highly saline formation brine (240 g/l salinity) [2].

Throughout the injection phase of the Ketzin site, the VERA facilitated extensive performance of repeated crosshole and surface-downhole measurements [3], [4]. Apart from the reservoir monitoring objective, the VERA system has also been used to collect experiences on its technical integrity and lifetime.

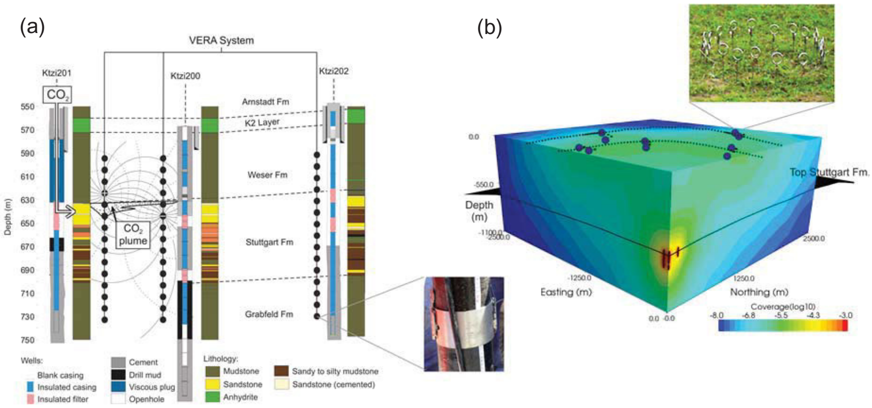

Fig. 2. (a) Schematic plot of the installed electrodes (black dots) in the three Ketzin wells Ktzi200, Ktzi201, and Ktz201. Further, well completions and lithological sequences, modified after [4], are shown. The zoomed photo shows a ring-shaped electrode consisting of stainless steel being clamped on the electrically insulated casing string. (b) Illustration on the combination of VERA electrodes and surface electrodes for periodic surface-downhole ERT surveys. The zoomed photo shows a surface electrode ensemble for current injection (Courtesy of University Leipzig). Colors depict that the coverage, realized in the surface downhole experiments, is focused at the reservoir target.

2. Data acquisition and processing

For the crosshole ERT measurements, we are using mainly the ZONGE GDP32 device. Given that the total number of 45 electrodes theoretically allows for approximately 3.5 million measurements configurations in four-electrode layout, a set of 6590 configurations was selected for frequent repeat measurements. In the following context, we denote these configurations as 3D data. The subset of configurations measured in the major observation plane Ktzi201-Ktzi200 has been denoted as 2D data.
The initial error estimation and quality control routines after [3] have meanwhile been implemented in fully automated manner, being a crucial component for handling of the steadily growing data archive

Rather than performing the four-electrode measurements with their full set of complementary reciprocal configurations included, we used only a subset of reciprocal measurements in order to deduce a representative error model which is subsequently extrapolated to the full set of measured configurations. Reciprocal errors have been derived after [5] as

$$\varepsilon_{n,r} = \frac{R_{n,r}}{\bar{R}_{n,r}} = \frac{2(R_n - R_r)}{(R_n + R_r)}, \qquad (1)$$

with R_n as resistance measurement, R_r as its reciprocal resistance measurement, and $\bar{R}_{n,r}$ as corresponding average of both. Figure 3 shows the crossplot of $\varepsilon_{n,r}$ and the measured resistance R_n for selected times of the injection history. The color-code represents the geometric factor, k, of each individual four-electrode configurations [6]. The geometric factor is considered within the error analysis in order to evaluate whether four-electrode combinations with large electrode spacing are rather prone of reciprocal errors than configurations in which electrodes are closely spaced. Interestingly, Figure 3 points out that not only the geometric factor but also the size of the measured resistances is conditioning the reciprocal errors.

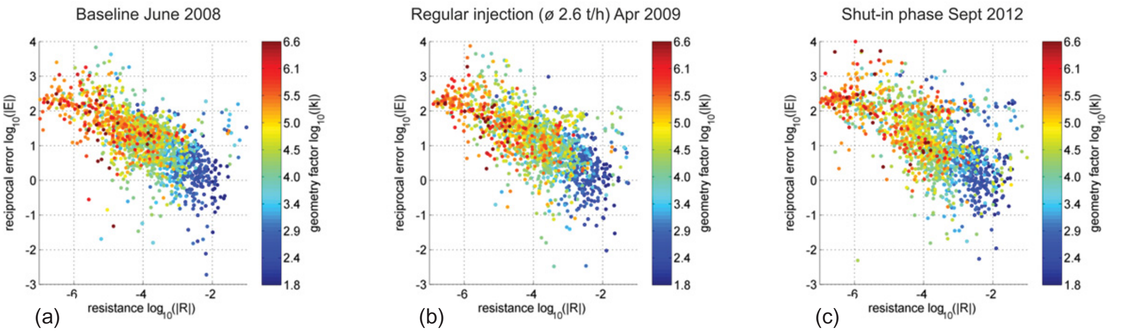

Fig. 3. Reciprocal error evaluation of the 3D field data sets, demonstrated by representative examples along the injection history: (a) baseline measurement; (b) measurement during the phase of high injection rate (~ Ø 2.6 t/h); (c) measurement during the shut-in phase which lasted from May until December 2012. Large reciprocal errors occur dominantly for configurations with large geometric factors and low measured resistances.

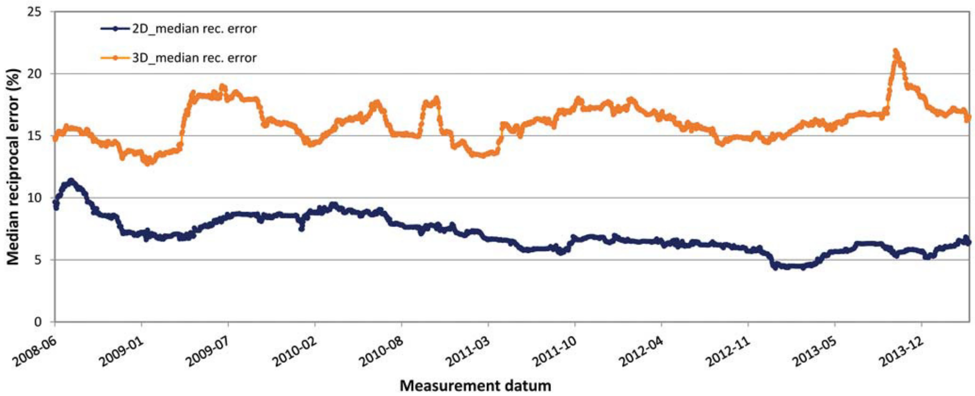

Fig. 4. Median reciprocal error during the five-year storage-operation period for the interpolated 3D data sets and 2D data subsets.

Table 1 gives the median of reciprocal errors for the data sets examples shown in Figure 3. The median is used instead of the mean of the reciprocal errors, since the latter was found to be strongly biased by a relatively small number of outliers. In Figure 4, the median values for all 3D data sets and the corresponding 2D data subsets along the injection history are shown. In the 2D case it is obvious that the median reciprocal error levels have also been influenced by the discontinuities in the injection operations, e.g. at shut-in and re-start phases. Therefore, the CO_2 related resistivity signature is to some extent deteriorated by the variable near-electrode conditions near injection point (electrodes #18 - #21).

Table 1. Reciprocal mean error for selected 2D and 3D data set examples of the crosshole ERT data archive.

Data set / datum	2008-06-21	2009_04_01	2012_09_01
3D	14.8 %	13.8 %	14.4 %
2D	9.6 %	7.1 %	6.2 %

In the case of the 2D data sets, reductions in the injection rate and shut-in periods are observed to have a rather negligible effect on the continuity of error levels. In the case of the 3D data sets, where electrode losses (#39-#45) occurred due to the installation procedure [4], the error levels are generally higher and behave more complex.

3. Long-term field data evaluation

3.1. Raw data

Based on the weekly data acquisition throughout the CO_2 injection period, a continuous data base has established. This data base provided valuable time-lapse information on the electric properties at a scale of several tens of meters around the three Ketzin wells mentioned above. A detailed interpretation of time-lapse resistivity images and technical contact resistance data revealed the some influence arising from variations in the CO_2 injection operation. The contact resistance data, which have been acquired with the same repetition rate as the crosshole ERT measurements, further provided useful information regarding the fidelity and potential degradation of the subsurface electrodes. Throughout the more than five years of operation, we eventually identified about seven electrodes (out of the 45 electrodes in total), being inacceptable for measurement due to reasons such as damaged or degraded cable break-outs.

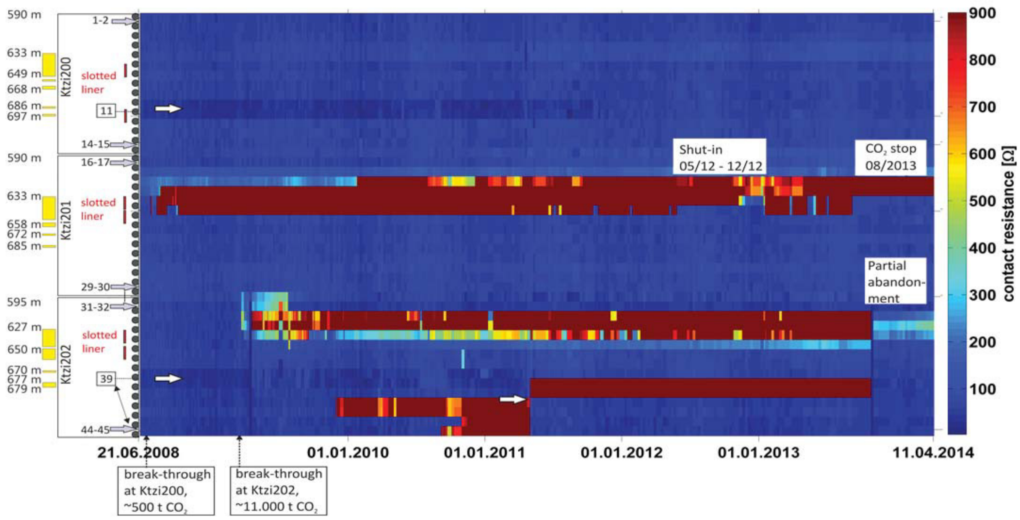

Figure 5: Update of the compact overview plot of contact resistances versus the injection history according [7], starting in June 2008 and ending in April 2014. In autumn 2013, the partial abandonment of Ktzi202 has caused as a side effect the sealing of the free annular space by overflowing cement suspension and subsequently better coupling of the electrodes along this section. The white arrows symbolize parts of the ERT arrays with gradually electrode degradation (#11, #39-#45).

The key findings from this long-term quality control procedure is underlined by Figure 5: (1) Electrodes #11 and #39 show degradation indicated by stable and low contact resistance values (<50 Ohm). (2) Brine and CO_2 intrusion via the cable break-outs occurred also at electrodes #40-#45. (3) At Ktzi201, a dry-out effect around the electrode position #21, due to up-rising of CO_2 within the uncemented annulus of the well, can be observed. (4) Similar behavior at Ktzi202 during March 18th 2009 in connection with the impending CO_2 break-through at this well. (4) No indication for CO_2 in the annular space of Ktzi200, indicating sufficient cement job quality in the annular space.

3.2 Tomographic data

The inverted resistivity models reveal that a rapid increase in electrical resistivity occurred in the reservoir within the first weeks of CO_2 injection. Subsequent periods were found to yield rather stationary resistivity distributions. In several periods, where injection has been suspended, the resistivity signature was noticed to decrease in amplitude. This behavior is assumed to result mainly from the repeal of the contact surface of CO_2/brine and subsequent inflow of brine into the near-wellbore area. This interpretation is in good consistency with the results from repeated Pulsed-Neutron-Gamma (PNG) loggings and a displacement saturation model used in their interpretation [8].

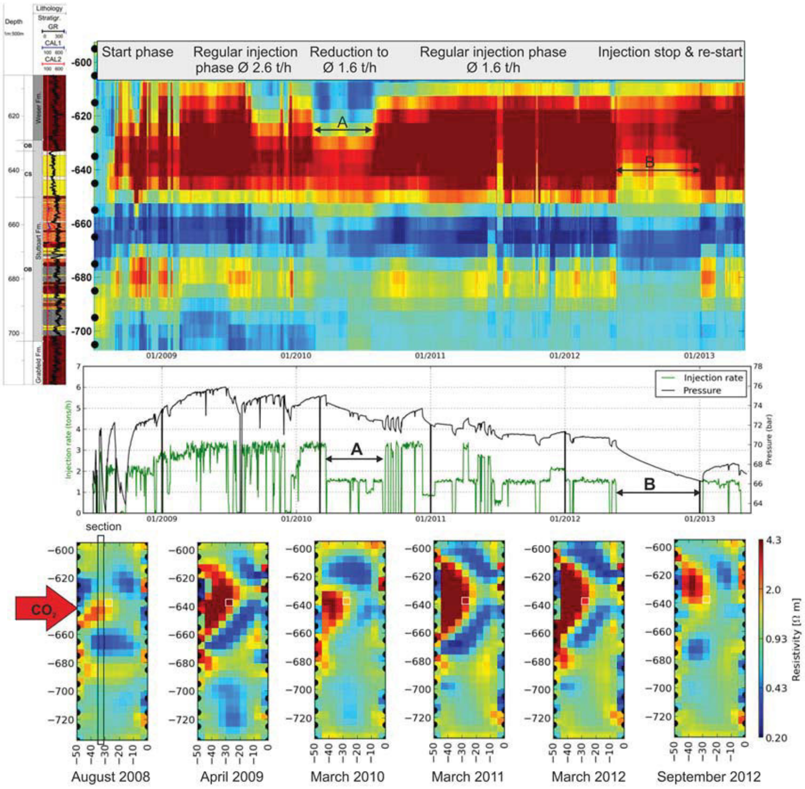

Fig. 6. In the upper panel, resistivities of a cross-section (vertical profile through the major plane Ktzi20 -Ktzi200) is depicted on the same time-scale as the injection data below. On the left-hand side, the lithological profile of the well Ktzi201 shows the major sandstone compartments of the reservoir in yellow. The center panel shows reservoir pressure (black curve) and the injection rate (green curve) over time. 'A' denotes a phase of reduced injection rate (from max. 3.2 t/h down to 1.6 t/h), whereas 'B' denotes a phase of injection shut-in enduring from May 2012 until December 2012. The bottom panel shows a sequence of resistivity models for selected stages of the injection history (the black mark indicates the location of the cross-section observed in the upper panel).

4. Saturation evaluation

For an estimation of CO_2 saturations from the time-lapse resistivity data, we used an inverse petrophysical relation that has been calibrated with laboratory experiments performed on core samples of the reservoir sandstone [9] (Figure 7a). Assuming the applicability of Archie's second law, the so-called resistivity index RI, which is the ratio of the baseline resistivity ρ_0 and the repeat resistivity ρ, can be rearranged in order to infer the CO_2 saturation, S_{CO2}, from relative resistivity changes

$$S_{CO2} = 1 - RI^{-\left(\frac{1}{n}\right)} = 1 - \left(\frac{\rho_0}{\rho}\right)^{1/n} , \qquad (2)$$

where n is the saturation exponent that was determined by [9] to be near 1.62. The application of this quantification approach is outlined in Figure 7 and resulted in maximum inferred CO_2 saturation of up to 60-70% around the CO_2 injector. The right hand side of Figure 7 shows further that these CO_2 saturations can for instance be interpreted in the light of the temporally rather sparsely sampled PNG loggings. Thereby, ERT is offering an opportunity to serve reservoir engineering requirements in a quantitative manner.

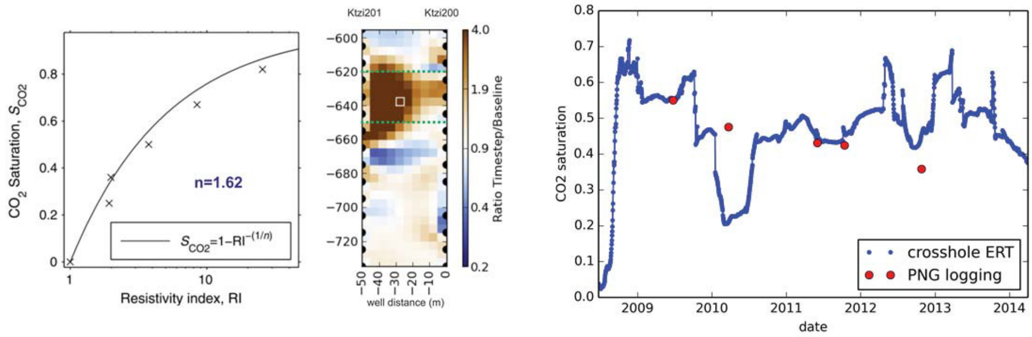

Figure 7: Left side: Petrophysical relation of Ketzin sandstone samples derived in lab experiments [9]. Middle: Typical 2D resistivity distribution, where the target reservoir sandstone zone is designated by dashed lines. For this region, the resistivity index relation has been applied. Right side: Sequence of CO_2 saturations, independently derived from crosshole ERT (blue) and Pulsed-Neutron-Gamma (PNG) logging (red). CO_2 saturations from logging have been computed from the thickness-weighted average over the CO_2 saturations that have been reported by [8] for the wells Ktzi200 and Ktzi201.

5. Discussion and Outlook

We see multiple benefits in the application of a permanent ERT downhole array for monitoring the CO_2 storage operations. First, inverted time-lapse resistivities allow for CO_2 saturation quantification when being integrated with operational data, petrophysical data, and well log data. Secondly, a permanent installation can be used for frequent largely unsupervised crosshole ERT measurements as well as periodic surface-downhole surveys (large-scale DC geoelectrics or controlled-source EM). Thirdly, beyond an imaging of the dynamic initial stages of a CO_2 plume development, the ERT array can also be used to monitor the rather stationary stages during progressed injection operations. Fourth, contact resistances between electrodes and well completion/cement provide significant information about a potential presence and migration of CO_2 in the well annulus.

Within a forthcoming controlled CO_2 back-production experiment and brine injection experiment, the presented ERT downhole array will also be evaluated with regard to its monitoring capabilities in the post-injection phase of our storage site.

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