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Electrical resistivity tomography (ERT) for monitoring of CO_2 migration - from tool development to reservoir surveillance at the Ketzin pilot site

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Abstract

Since more than four years of operation, the Ketzin pilot site is successfully demonstrating a multi-disciplinary monitoring concept for detecting and tracking the CO_2 distribution in the subsurface. In this research frame, the electrical resistivity tomography (ERT) is part of the geophysical measurement program and contributes to the observation of the pore fluid changes due to the CO_2/brine displacement process in the reservoir zone. Our work demonstrates the feasibility of a permanently installed geoelectrical array and its potential for providing frequently acquired time-lapse results as well as for supporting periodical surface-downhole surveys. Based on standardized technical components and equipped with a sequence of suitable data evaluation tools, this permanent reservoir monitoring system aims to support subsurface management solutions.

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

1. Introduction

At the Ketzin pilot site, Germany, the electrical resistivity tomography (ERT) is part of a multi-disciplinary monitoring concept to detect and image the spatial extent of the CO_2 plume in a saline aquifer [1]. Since more than four years a vertical electrical resistivity array (VERA) has been operating for geoelectrical monitoring in permanent mode under the brine-CO_2 prevailing conditions of the Ketzin reservoir. This tubing-conveyed installation was the first of its kind for ERT monitoring of a real CO_2 storage site. The array is located at a depth-range of 590-740 m on Ryt Wrap® insulated casing sections, and the total number of 45 stainless steel ring-shaped electrodes has been arranged as 15 electrodes of 10 m spacing per each of the three Ketzin wells [2]. The Ketzin ERT array was followed by the worldwide deepest ERT application for CO_2 monitoring at the test site of Cranfield Mississippi (USA) in about 3000 m depth [3]. Here, a total number of 21 electrodes was deployed in two wells. In the near future, a newly scheduled ERT application is expected in the frame of the Compostilla CCS project at the Hontomin CO_2 test site [4].

Besides of continuous crosshole ERT measurements, the VERA system is also used for surface-downhole ERT (SD-ERT) measurements that take place on a larger scale. These SD-ERT measurements are performed on a periodical basis during significant phases of the regular CO_2 injection, and their acquisition geometry is indicated in Figure 1.

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They comprise 16 surface dipoles, each with a length of 150 m, which are distributed over two concentric circles with a radius of r_1 = 800 m, r_2 = 1500 m, respectively [5].

The complex geological conditions at the Ketzin site represent challenging circumstances for any ERT monitoring concept. The sandstones of the reservoir (Stuttgart Formation) have a complex heterogeneous lithology and consist of sandy channel-(string)-facies with good reservoir properties, alternating with muddy flood-plain-facies of poor reservoir quality [6]. The reservoir and adjacent formations constitute a low-resistivity environment with an indication for CO_2 induced resistivity alterations by a factor of 2-3, which was confirmed by well logging and laboratory flow-through experiments on core samples [2].
Correspondingly, low-to-medium resistivity contrasts could be found in the time-lapse ERT data. These conditions constitute difficult constraints for a geoelectrical monitoring system, which have been addressed by a modular workflow that combines an appropriate technical design, stringent data quality checks, acquisition-adapted data preprocessing, an optimized inversion technique, and an integrated interpretation with other monitoring data.

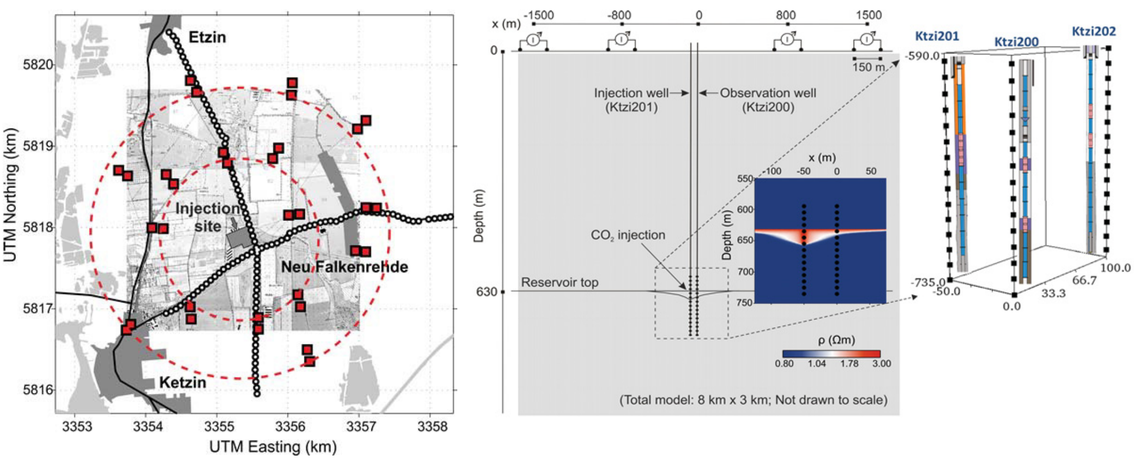


Fig. 1 Left hand: Area of the Ketzin test site, indicated by a white star. Pairs of red boxes mark the positions of the 16 non-permanent surface dipoles, each with a length of 150 m, as used for the periodical surface-downhole ERT (SD-ERT) surveys. Right hand: Schematic of the boreholes and the permanent VERA electrodes (black dots in dashed box). The rightmost illustration shows that the completions of the three Ketzin wells are different among each other.

2. Workflow for establishing a geoelectric concept for subsurface CO_2 monitoring

2.1 Design of the permanent electrode array as the centerpiece of the Ketzin ERT concept

Present experience from Ketzin recommends starting with the design of a VERA-like installation at least one year prior to drilling operations (Figure 2). In the early stage of this design a baseline reservoir characterization (similar to that referenced by [6]) can assist in a preliminary array layout with principle design parameters such as the position of the array, its total length, and the number of electrodes per well. For instance, it may be reasonable to design the array in centered manner with respect to the target reservoir, i.e. it starts in the bottom of the cap rock layer above the storage horizon and captures with some electrodes the immediate substratum below the storage horizon. For the Ketzin VERA system, the phase of the basic design was accompanied by a feasibility and performance assessment using a synthetic modeling study which was based on results from laboratory experiments on core samples. From these experiments the factor of change of resistivity to be expected before (baseline) and after CO_2 injection (repeat) was of greatest importance.

Based on this feasibility study the specification, selection and purchase of the necessary components for the Ketzin array were performed. The major technical components of the array system are the electrodes, the customized multi-

conductor cables, and the insulated casing segments for the depth range of the ERT array. For Ketzin, these components were ordered to be ready in place before the start of drilling the wells (Figure 2).
The tubing-conveyed installation procedure of the VERA system was thoroughly planned to be part within the regular drilling work of the three wells Ktzi200, Ktzi201 and Ktzi202 covering the period June to August 2007. Until the start of CO_2 injection in mid of 2008, the ERT array operated in the reservoir for about one year under highly-saline brine conditions (240 g/l). Crosshole ERT inversions from the early injection phase imaged that the CO_2 plume development took rapidly place in the near-wellbore area and approached after a couple of month towards a steady-state stage [7]. Beyond the region where the crosshole ERT measurements allow for imaging, the VERA system proved to be substantial in order to carry out the periodical large-scale SD-ERT surveys as well as a controlled-source electromagnetic (CSEM) measurement on a more regional scale [8]. The phase of long-term studies and data integration is still ongoing and will provide a summary about the lifetime of the components of the downhole array and its versatility as permanent monitoring system.

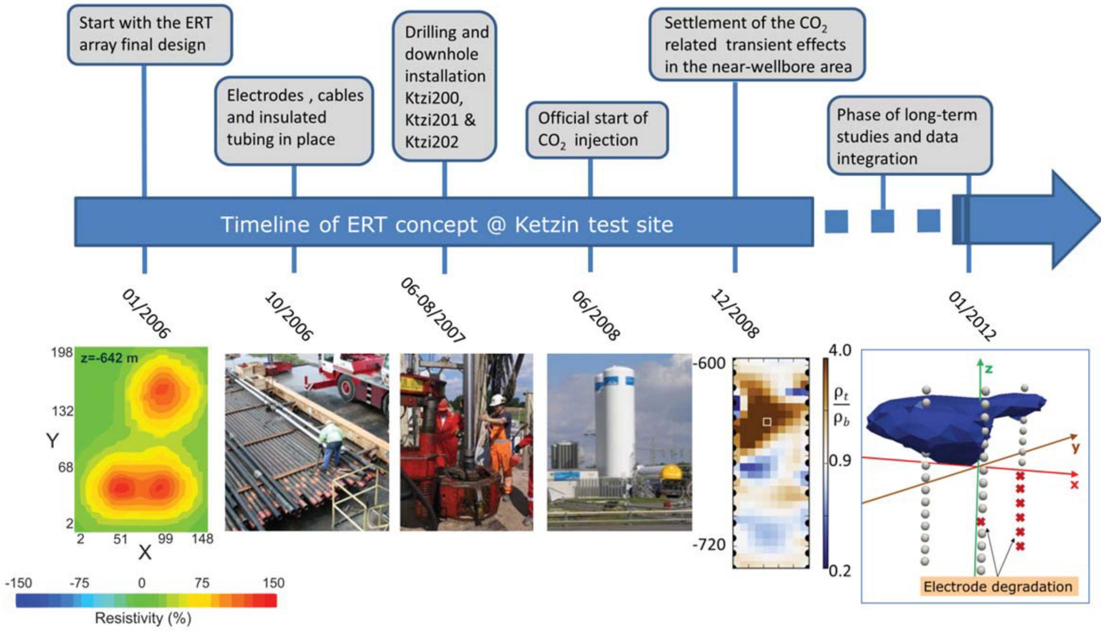


Fig. 2 Overview on the different stages of the development of the Ketzin geoelectrical concept (Photos: S. Mielitz, F. Möller).

2.2 Synthetic geoelectrical modeling to investigate the imaging characteristics

Although started in the design phase, geoelectrical modeling followed the entire data processing phase by means of iterative updates. Therein, we used for example a synthetic input model that incorporates the major geologic features of the site and simplified CO_2 distributions as the radially symmetric plume depicted in Figure 3a.
The main objective of these synthetic studies was to compare the synthetic and real data in order to evaluate the plausibility of the detected signatures in the field data. These modeling studies were performed for both the crosshole ERT acquisitions and the SD-ERT acquisitions. In consistence all modelings showed that the significant time-lapse signals occur for those downhole electrodes that are situated directly in or near the reservoir (Figure 3b). This is in agreement with our observations from the field data (Figure 3c) and underlines the importance for proper quality control routines.
By means of sensitivity calculations, these modeling studies also allowed for a description of the imaging characteristics with respect to the acquisition geometry. For example, in case of the acquisition geometry of the SD-ERT, the resistivity pattern of the field data (Figure 3 c) is dominated by the typical dipole pattern with positive and negative sensitivity cones. Here, the cumulative sensitivity has been used as an image appraisal tool to subdivide the model space in segments with different degrees of reliability [9].

Such sensitivity studies assist the data interpretation and play an important role for the optimization of acquisition geometries in the design phase prior to the field experiment. Furthermore, they can deliver indications on the capabilities to derive quantitative CO_2 saturation estimates.

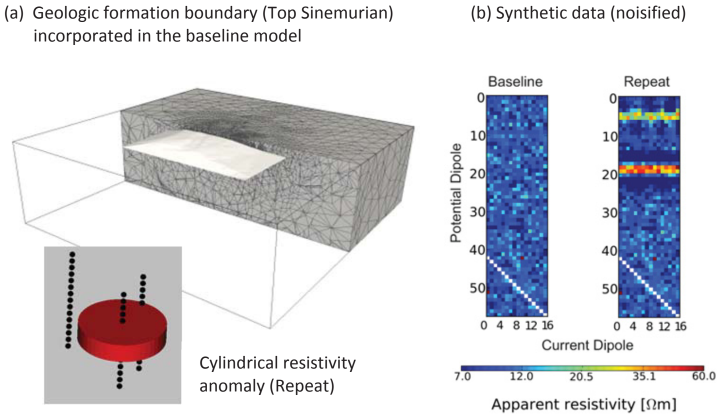


Fig. 3 (a) Synthetic geoelectrical modeling to investigate imaging characteristics and plausibility of field data; (b) The pseudosections show that only the electrodes in and near the reservoir are showing a time-lapse signal due to the migrating CO_2 (here: electrodes #4-#6 of Ktzi200 and electrodes #19-#21 of Ktzi201); (c) Real data results from a crosshole ERT inversion and SD-ERT inversion, which are found to be in reasonable agreement.

2.3 Development of practical processing and evaluation tools for the ERT data

Throughout the CO_2 injection at the Ketzin site a comprehensive ERT data base was acquired. This data base covers weekly-measured crosshole ERT data, which image the near-wellbore area at a scale of several tens of meters [2], and the periodical SD-ERT data, which cover an extended lateral observation area [5].

At the Ketzin site we further monitored the state of the VERA downhole electrodes by means of resistance checks. These resistance checks used adjacent pairs of electrodes for simultaneous current injection and voltage acquisition and provided information about of the temporal condition of the individual electrodes. A match of these resistance data (Figure 4) with the process data from the CO_2 injection operation and the well completions were found to be critical prerequisites for understanding spurious effects in the time-lapse ERT data.

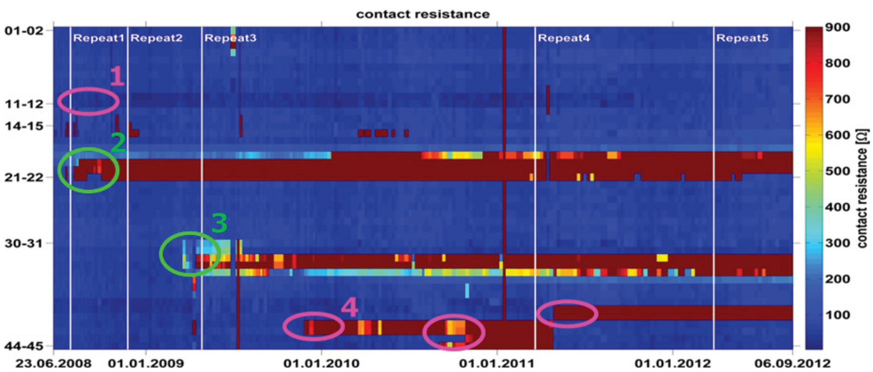


Fig. 4 Investigation of the contact resistances vs. time history as indicator of the individual electrode vitality. Case (1): Indication of cable issue for electrode #11 of Ktzi200, case (2): Dry-fall of electrode #21 of Ktzi201 due to the intensive CO_2 contact at the injection point, case (3): CO_2 contact of electrodes #31-#35 due to the uncemented annular space of Ktzi202, case (4): Progressive degradation issue of the electrodes #39-#45 of Ktzi202. The perpendicular white lines indicate the dates of the SD-ERT repeats.

For instance, we identified the dry-fall of electrode #21 (case 2 in Figure 4) at the injection point. For this reason, we discarded this electrode from current transmission. A staged cementation job was conducted in the well Ktzi200 in order to prevent the migration of CO_2 in the annular space of this well. However, a clear indication of CO_2 in the uncemented annular space could be pointed out in the well Ktzi202 already end of March, 2009, which is corresponding with the CO_2 break-through time at this well. Substantial indications for electrode degradations were detected since November 2009 in the well Ktzi202 (case 4 in Figure 4).

The Ketzin crosshole ERT measurements comprise a total number of about 6590 ABMN combinations, which are shown in their temporal development in Figure 5. The number of individual combinations split up into subsets of different electrode configurations (dipole-dipole, bipole-bipole, and user-defined options). Due to operational reasons, not all of them were retained throughout the present day. In order to foster the choice of electrode configurations, a script-controlled procedure was developed, which consists of the following modules: selection of the most reliable ABMN combinations, application of an adapted preprocessing scheme to each of them (see Figure 5, right hand), evaluation of error range and establishing as final input data for the inversion [7].

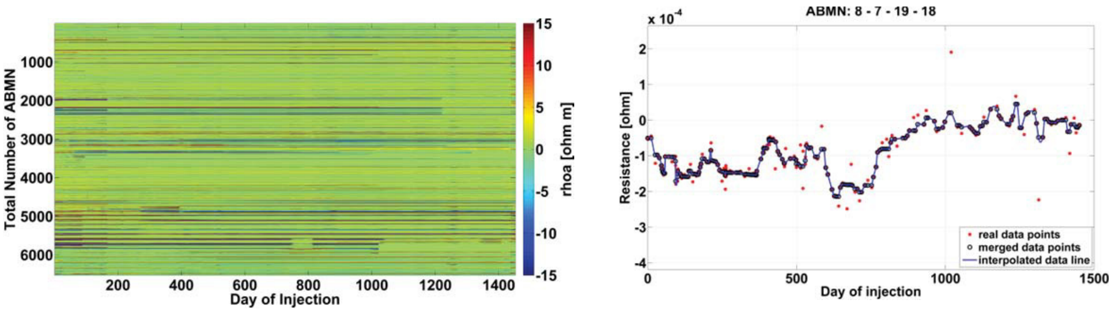


Fig. 5 Left hand: Automated archiving of the total number of 6590 deployed ABMN configurations in the crosshole ERT mode (apparent resistivity ρa), plotted as time history. They are selected regarding stability and continuity for subsequent preprocessing. Right hand: Arbitrary example selected from the number of ABMN readings which represents a consistent resistance trend for the injection time.

3.3 Tomographic inversion of the crosshole data and surface-downhole data

In order to obtain more certainty with regard to our subsurface models, we compared several inversion codes, from which we opted for the open-source code BERT (Boundless Electrical Resistivity Tomography) [10]. This code uses a triple-grid inversion technique employing unstructured tetrahedral meshes. Figure 6 illustrates the finite-element discretization used for the Ketzin case together with a cross-section that shows the electrical potential during a forward modelling. The use of such a non-regular grid enabled us to incorporate the different scales of both acquisition types, the crosshole ERT (some tens of meters) and the surface-downhole ERT (some kilometers).

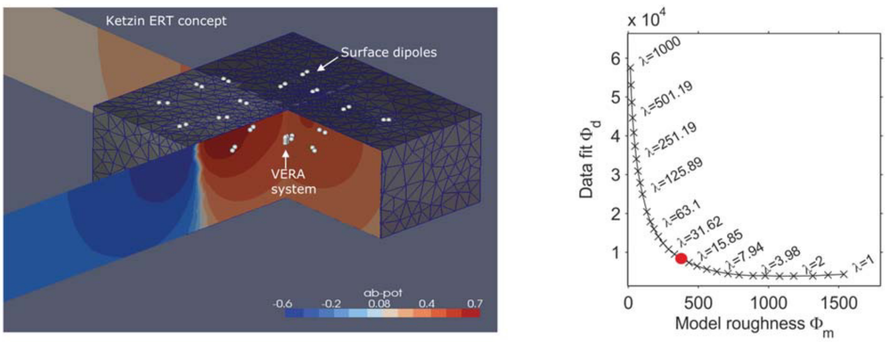
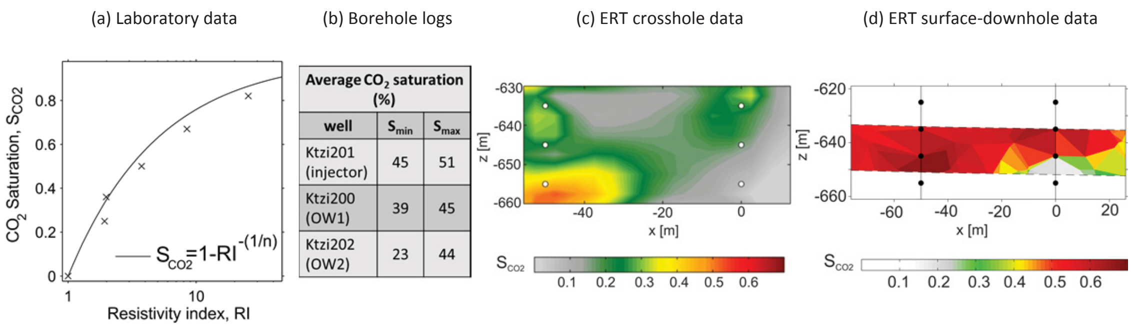


Fig. 6 Left hand: Visualization of the tomographic cube (side length 5 km, height 2 km) for the Ketzin case by means of unstructured tetrahedral elements. Right hand: The plot compares data misfit and model misfit as a function of spatial regularization [5].

As indicated by the lateral extent of the cross-section in Figure 6, the forward modeling domain was enlarged in order to minimize disturbing boundary effects. An optimization of the spatial regularization was performed according to the discrepancy principle. This was done with a particular aim to compromise both the data misfit and the model misfit to a reasonable degree (see Figure 6, right hand). This procedure was carried out for the surface-downhole data as well as for the crosshole data separately in order to provide temporally consistent inversion results.

3.4 Petrophysical conversion from resistivity distributions to CO_2 saturation distributions

Investigations of inverted resistivities focused on the two major observation planes Ktzi200-Ktzi201 and Ktz200-Ktzi202. Due to a significant degradation of the VERA electrodes being present in the lower part of the Ktzi202 well, the latter observation plane made imaging of CO_2 induced resistivity changes rather difficult. However, where stable inversion results indicated a sufficient degree of reliability, CO_2 saturation estimates were drawn from imaged resistivity changes (Figure 7c and 7d). Therefore, a petrophysical relation between CO_2 saturation and relative resistivity change (resistivity index) was derived from laboratory experiments on core samples of the Ketzin reservoir sandstones (Figure 7a). This established spatially and temporally variable CO_2 saturation estimates, which are jointly interpreted together with the CO_2 injection history and results from repeated Pulsed-Neutron-Gamma (PNG) loggings (Figure 7b). In a further assessment, we identified potential improvement of this workflow by means of (i) consideration of the spatio-temporal sensitivity patterns established by the individual ERT measurements, and (ii) application of adapted petrophysical relations which better reflect the heterogeneous character of the Ketzin reservoir.



Average CO_2 saturation (%)		
well	S_{min}	S_{max}
Ktzi201 (injector)	45	51
Ktzi200 (OW1)	39	45
Ktzi202 (OW2)	23	44

Fig. 7 Comparison of saturation results from different measurement methods: (a) laboratory data of Ketzin reservoir sandstone samples [11]; (b) borehole data of the Pulsed-Neutron-Gamma logs [12]; (c) saturation calculation for the crosshole ERT data, and (d) for the surface-downhole ERT data [5].

3. Integrated assessment of the ERT monitoring results

Exploration and reservoir monitoring projects usually comprise seismic surveying, which offers multiple potential for a combination with corresponding ERT measurements. At the Ketzin site, a combination of the surface-downhole ERT measurements with 4D seismic data is performed by means of a structurally constrained inversion approach. This approach is based on the minimum-assumption that if a change in petrophysical characteristics (e.g. rock type, porosity, pore-fill) poses a change in elastic properties, it is likely to do so for electric resistivity, and vice versa. For this purpose, lithostructural constraints are interpreted from seismic reflection data and implemented in the geoelectric inversion by means of a local regularization technique (Figure 8). Consequently, seismics and geoelectrics are arranged in a sequential workflow which is based on a structural similarity for their relevant petrophysical parameters [9]. Prior to an application to the Ketzin datasets, i.e. the repeated 3D seismic surveys and repeated surface-downhole ERT surveys, this approach was tested by means of a synthetic data example. In consistency, both the synthetic and the real data example demonstrated that the constrained inversion allows for an enhanced resistivity imaging along the cap rock-reservoir boundary than a conventional ERT inversion (compare Figure 8 and Figure 3c) [9].
This local regularization technique can also be utilized to account for the borehole environment [13], which proved to be of great relevance for the implementation of the challenging borehole completions of the Ketzin wells into the finite-element discretization and ERT inversion (Figure 9).

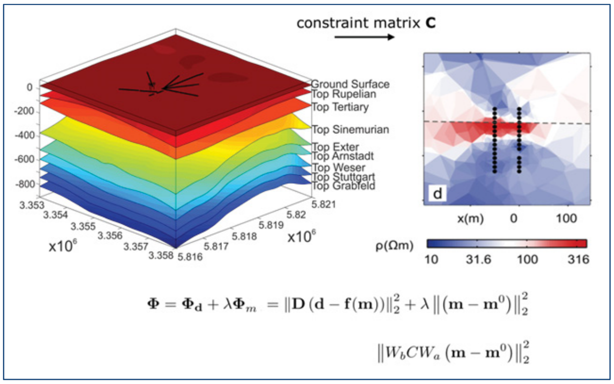


Fig. 8 Optimized imaging of the CO_2 signature in the reservoir zone: (a) Implementation of structural information [14] based on 3D seismic results as *a priori* constraint into the inversion of the surface-downhole geoelectric data [9].

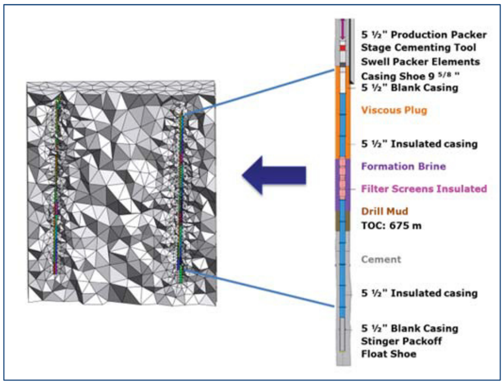


Fig. 9 Implementation of the well completion scheme into the inversion of the crosshole geoelectric field data.

4. Versatile applications of a permanently installed ERT system

In the context of CO_2 storage monitoring, it was realized that associated secondary effects also demand for monitoring. Such an effect is possible brine migration into freshwater aquifers being driven by displacement. This might especially be important for storage processes on an industrial scale, where the volume pressure increase can be substantially larger than the CO_2 distribution itself [15]. In such a case ERT arrays can also contribute to the detection of freshwater salinization. Potential pathways for an upward migration of brine include permeable fault-zones, poorly cemented annuli of existing wellbores with pathways along their annuli, and defects within impermeable cap rock layers (Figure 10) [16]. Such potential pathways must be taken into particular consideration when establishing a monitoring concept for brine displacement. Therefore, modeling studies can be integrated with laboratory measurements in sandbox experiments (Figure 11) in order to evaluate electrode arrangements at the surface in connection with shallow observation wells and deep injection or observation wells [16].

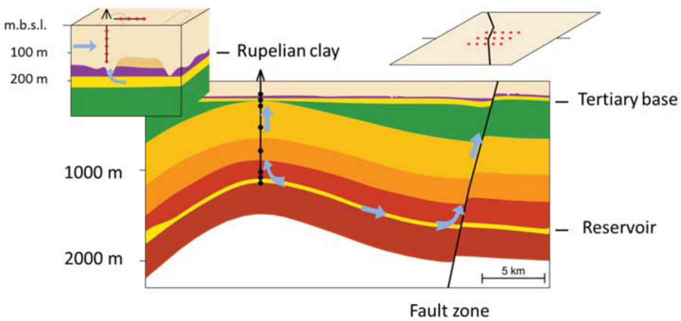


Fig. 10 Schematic of a geoelectrical monitoring concept for combined surface-downhole measurements being optimized for salinization detection at potential brine migration pathways [16]. Optimized electrode array designs, e.g. that penetrating the Rupelian clay barrier (indicated in purple), can provide monitoring beyond the particular CO_2 migration.

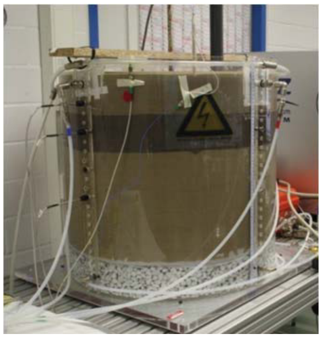


Fig. 11 Sandbox facility for studying salinization scenarios. The diameter of the cylinder is about 0.6 m. The fluid injection into the tank was realized by a peristaltic pump. A miniaturized electrode layout consisting of horizontal and vertical electrode strings has been developed [16].

5. Conclusions

The Ketzin ERT concept has been evaluated regarding reliability and longevity based on more than four years of CO_2 injection. An extensive ERT data base was established which allows for exchange and cross-evaluation with similar field experiments at other CO_2 storage sites. From the key findings of the Ketzin pilot project we conclude that ERT measurements can be valuable within multi-method and multi-scale CO_2 monitoring programs. The frequent data collection from permanent downhole arrays in combination with automated data processing tools are a first necessary step towards remote underground monitoring in real-time mode. Additional periodically surface-downhole surveys provide a suitable supplement to other geophysical large-scale measurements such as seismic surveys and allow for joint data evaluations. Despite its site specific technical layout, the permanent array represents a cost-efficient and environmentally sound solution. This is also because most of the used technical components can be customized by standard suppliers. In conclusion, permanent (subsurface) ERT array installations can support site operators regarding their demands for long-term surveillance and efficient reservoir management well beyond the bare CO_2 migration monitoring (e.g. brine displacement detection).

Acknowledgements

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