A modular geoelectrical monitoring system as part of the surveillance concept in CO₂ storage projects

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Abstract

The major task of a safety surveillance concept is to support the closed loop of reservoir management, i.e. to guarantee an iterative interaction between reservoir monitoring and numerical simulation. The presented research is based on the experience gained on the permanent geoelectrical monitoring at the Ketzin CO₂ pilot storage site continuously operating since 2007. We have structured this experience in a modular monitoring workflow which offers well prepared links to actual process data, petrophysical data, and reservoir simulation. First results have been reached in major topics such as site-specific customization of technical tools, data acquisition and processing, and data evaluation. Structuring this approach in a modular manner allows the geoelectric monitoring at the Ketzin site to be efficiently scaled up and adapted to the fit-for-purpose requirements of future CCS demonstrations.

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1. Introduction

CCS projects demand for detection and quantification of CO₂ stored in the subsurface. Therefore, the development of "Measurement Monitoring Verification (MMV) techniques" plays an important role in the time frame of achieving the commercial use of CO₂ storage [1]. Geoelectrics has proven to be a valuable monitoring method, since the electrical resistivity of a porous reservoir rock is highly dependent on the presence or absence of CO₂. Because of their ease of use in field applications, geoelectrical measurements provide valuable and cost-effective contribution to the required surveillance concept of CO₂ storage sites. Current state-of-the-art instrumentations allow for geoelectrical measurements from...
surface-to-surface, crosshole or combinations of both. These measurements are inverted to image the resistivity distribution within the subsurface as well as CO₂ induced time-lapse effects [2, 3]. Modern inversion methodologies incorporate a-priori information and structural constraints, which improve the certainty of results and the subsequently following interpretation [4]. Repeated observation of the resistivity distribution within the target reservoir and neighbouring formations can constitute a key component in monitoring and quantitative assessment of injected CO₂. We have tackled this task by using permanent installed electrode arrays, time-lapse acquisition and data inversion, and joint interpretation gathering a variety of monitoring data. The established monitoring system presents itself as modular workflow which divides into the following main items (Fig. 1): Preparation – Acquisition – Processing – Evaluation. Within these items, some modules have been identified as key features which seem to be vital for the realization of a reliable monitoring system.

Fig. 1. The Ketzin geoelectric concept customized as modular monitoring system for integrated CO₂ storage surveillance.

2. Structure and capability of the Ketzin geoelectric system

2.1 Preparation: Design and feasibility study

Feasibility studies, carried out in the framework of the Ketzin site, have shown that optimized time-lapse data acquisition can be achieved by permanent electrode installations. In consequence a permanent geoelectric system, the so-called Vertical Electrical Resistivity Array (VERA), has been developed and installed in the three Ketzin wells. Further improvement of the measurement scheme was gained by use of additional non-permanent dipoles deployed at the surface. These dipoles increase the imaged volume...
beyond the near wellbore region by surface-downhole measurements in combination with the VERA system. The technique of electrical resistivity tomography (ERT) with downhole installations has been successfully demonstrated for CO₂ storage monitoring [2, 3]. In this article we focus on the VERA system as central element not only for the geoelectric measurements, but also for controlled-source magnetotelluric and controlled-source electromagnetic investigations carried out at the Ketzin site, e.g. [5].

Fig. 2a shows the three Ketzin wells with its individual well completions and lithologic sequences. The VERA setup consists of 15 electrodes per well (indicated by black dots) distributed in the depth range from 590 m to 735 m. Because the Ketzin storage reservoir has a very heterogeneous lithology, the electrode spacing was chosen to compromise between vertical resolution and investigation depth. Fig. 2b shows the VERA setup to have highest sensitivities near the wellbores. Assuming favourable circumstances regarding reservoir heterogeneity and corresponding plume migration, one can expect also sufficient coverage for the region between the Ketzin wells. Synthetic modelling confirms that 50 % CO₂ saturation can be imaged for a homogeneous sandstone layer with a thickness of a few meters.

2.1 Acquisition: Raw data related to relevant process parameters and first data quality check

An important engineering work for the persistent VERA operation was the development of the program CO₂ Data Tool. The program links the geoelectric data to a variety of CO₂ process parameters such as well-head pressure and temperature, bottom-hole pressure and temperature, injection rate and regime (shut-in, re-start, regular operation), and injected CO₂ mass data (Fig. 3a). These process parameters are of significant relevance to the ERT crosshole data, and can deliver important information used for the interpretation of the repeated resistivity measurements.

We have studied the process data in order to understand the temporal variations in the VERA raw field data, and to identify their origin. This procedure helped us to distinguish whether data alterations were caused by the actual CO₂ injection or by noise-generated fluctuations, and gave indication for processes which have reasonable influence on the field data quality.
The ERT system was among the first instruments of the Ketzin monitoring concept which could detect the CO\textsubscript{2} plume signature. In this context, very valuable information were derived from the so-called "resistance checks", carried out at the beginning of each crosshole survey. Low-level electric currents are injected through adjacent electrodes while simultaneously measuring the voltage in order to assess the contact resistances. Resistance checks were conducted with a daily frequency in the injection start phase (from July to August 2008) and a weekly frequency later. Readings of the resistance checks are shown in Fig. 3b.

As the electrode spacing is equidistant along the array, one would expect similar contact resistances along each well. The variation in well completion and geology, however, poses some variation in contact resistances which is mainly imaged in the baseline measurements. For the repeated surveys, temporal variations in contact resistances were identified which reflect physical effects related to the CO\textsubscript{2} injection (e.g. start/stop of injection, break-through at observation wells, rising of CO\textsubscript{2} in the uncemented wellbore annulus). In addition, degradation effects become visible as, for instance, cable breakout-failures which can cause short circuits. Therefore, the resistance checks are an indicator for the state of the individual electrodes, and improve the understanding on CO\textsubscript{2}-related effects in the geoelectrical raw data.

### 2.3 Processing: Conditioning of field data by optimized pre-processing routines

Because the Ketzin site constitutes an environment with a high level of anthropogenic noise, robust infield pre-processing routines are demanded. The development of the system module ERT Analyzer operates at the interface between acquisition and processing with the following steps: data transfer and conversion in standard formats, pre-processing and quality control, and data archiving and mining. In contrast to the surface-downhole data, where the pre-processing routine is based on the established algorithm of "selective stacking" of the multiple time-series [7], the crosshole measurements provide only two-cycle time-series per electrode combination [8]. This was realized to allow for the acquisition of a large number of electrode combinations (> 3000) in an acceptable time. Thus, an appropriate pre-processing scheme was demanded in order to separate the significant CO\textsubscript{2} caused variations from erratic fluctuations.
The fully automated pre-processing scheme starts with the collection of the entire ABMN electrode combinations each day (Fig. 4). The module "filter" checks the readings regarding error level, upper and lower bounds of voltage and current values, standard deviation, and mean value. Strongly noise affected data are then eliminated. The module "merge" performs either an averaging by the arithmetic mean (in case of only two readings) or by median (in case of multiple readings). The module "polyfit" investigates the voltage values over time and deduces a smoothed curve. The module "interp" performs an interpolation of the smoothed curve to provide voltage data for arbitrary points of time (Fig. 5).

Fig. 4. (a) Pre-processing part (ERT Analyzer) of the modular workflow which has been applied to the VERA crosshole data; (b) Error quantification based on voltage levels with respect to the signal-to-noise ratio and polarization-related asymptotes.

Fig. 5. Example for a time history of electric voltages, currents and resistances for the CO$_2$ injection period from June 2008 until August 2011. Red markers show original data, and blue markers the original data after the pre-processing procedure. The electrode configuration under investigation (ABMN = 3-2-18-17) is shown to the left.
The representative example of Fig. 5 shows that the pre-processing has a smoothing effect on the voltage and resistance signals without distorting the underlying trend. In consequence, this pre-processing helped to establish consolidated datasets as input for the resistivity inversion.

2.4 Evaluation: Resistivity inversion and geophysical interpretation

We have found it useful to test several inversion programs and codes in order to get a better certainty for the processing of our field datasets. Commercial codes had been tested and found to be well suited for quick in-field inversions due to their comfortable menu-guided workflow. Their inversion capabilities are rather limited. For this reason, we tested as an alternative the open-source code BERT - Boundless Electrical Resistivity Tomography [9, 10] which offers several useful features such as

- efficient treatment of the information-bearing parts of the datasets by an error-weighted inversion procedure;
- handling of inversion volumes comprising cell parametrization ranging from several kilometers (surface-downhole) to several meters (crosshole) by irregular tetrahedral finite-element meshes.

Initially, the crosshole data have been investigated between the boreholes as 2D observation planes in order to find optimal inversion settings. The plane between the wells Ktzi201 and Ktzi200 shows a notable increase of resistivity near the CO₂ injector (Fig. 6). From the measurements conducted in middle of August 2008, the increase of resistivity is observed as a funnel-like patch and may be an indicator for the gravity driven upward migration of the CO₂. From August 2008, the measurements show some fluctuations which relate to optimization tests of the CO₂ injection. Since December 2008, the increased resistivities seem to have reached a steady-state situation. Injection rates were significantly reduced in the subsequent phase March to August 2010, which results in a remarkable weakening of this feature. The data pre-processing contributes clearly to the stability of the time-lapse inversion results shown in Fig. 6.

![Fig. 6.](image)

Upper image: 2D time-lapse inversions of ERT crosshole data presented as ratio of repeat resistivities and baseline resistivities.

Lower image: Inverted resistivity observed in a model cell [5m x 5m] over time. The cell is positioned as shown in the lower right inlay at a depth of about 640 m near the centre of the storage reservoir.
In comparison with the performed 2D calculations, the complete 3D resistivity inversions provide consistent results in the investigation plane Ktzi200-Ktzi201 (Fig. 7). For the whole time history of the injection process the observed 3D time-lapse effect correlates with the information from the resistance check data (Fig. 3 (b)). Therefore, at the second observation well Ktzi202 a noticeable change of resistivity was detected primarily since the CO₂ arrival in end of March 2009. Later on, the effect of degraded electrodes becomes an increasing influence on the resistivity distribution of this wellbore investigation area. Depending on the degree of perturbation one has to decide to exclude these critical electrodes from the signal interpretation, or in some cases even from the inversion procedure.

Fig. 7. Left: Volume with the resistivity ratio larger than 2.6, as result of the 3D inversion of field data from April 2011. Centered sections: Resistivity ratios mapped for constant depths in the storage reservoir. Right: Investigation plane Ktzi200-Ktzi201 viewed from the South. Vertical electrode spacing is 10 m, and the lateral distance between the wells is 50 m for Ktzi200-Ktzi201, and 100 m for Ktzi200-Ktzi202, respectively.

3. Conclusions

In this contribution we described geoelectric monitoring of CO₂ storage by means of a modular workflow. The workflow gathers the experience we made in the integrated monitoring of the Ketzin site using the permanently installed VERA system, and covers the planning, installation, and actual operation. Decomposition into separate modules allows for flexible distribution of the various technical and scientific subtasks. Furthermore, it allows for an efficient interaction with the overall site operation, as e.g. links to external databases are provided which keep the process parameters. On the other hand results of the resistivity monitoring can easily linked back to contribute to CO₂ tracking and reservoir management. A central part of the modular system is its capability to operate and provide imaging of resistivity changes continuously throughout the operation duration of the site.

Practical geoelectric monitoring is faced with several challenges. External noise and degradation of permanently deployed elements requires thorough pre-processing and quality control routines. Changes in the injection can have a dynamic impact on the reservoir conditions. Therefore, it has been found
important to realize a real-time link to the injection parameters in order to discriminate the CO₂ related resistivity changes. Starting from rather practicable 2D inversions we stepped forward to full 4D inversions which allowed imaging of a significant resistivity increase near the injector. Since this resistivity increase is interpreted to be caused by the injection and migration of the CO₂ its dynamics were explained in good agreement with the process parameters.

The modularization of the geoelectric monitoring further improves cooperation with other investigations, such as large-scale surface-based geoelectric and electromagnetic surveys. Moreover, it is suited to transfer the Ketzin technology and experiences to the demonstration-scale CCS projects to come.

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