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Monitoring the complete life-cycle of a CO_2 storage reservoir – Demonstration of applicability of geoelectrical imaging

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Abstract

In this paper, the applicability of deep downhole geoelectrical monitoring for detecting CO_2 related signatures is evaluated after a nearly ten year period of CO_2 storage at the Ketzin pilot site. Deep downhole electrode arrays have been studied as part of a multi-physical monitoring concept at four CO_2 pilot test sites worldwide so far. For these sites, it was considered important to implement the geoelectrical method into the measurement program of tracking the CO_2 plume. Analyzing the example of the Ketzin site, it can be seen that during all phases of the CO_2 storage reservoir development the resistivity measurements and their corresponding tomographic interpretation contribute in a beneficial manner to the measurement, monitoring and verification (MMV) protocol. The most important impact of a permanent electrode array is its potential as tool for estimating reservoir saturations.

Keywords: Geoeletrical imaging; permanent downhole electrode array; CO_2 storage monitoring

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1. Objectives

Based on the recent IPCC Special Report on Carbon Dioxide Capture and Storage [1], significant developments in legal and regulatory aspects have been made to ensure guidelines for geological storage assessments [2]. An appropriate monitoring program is a key requirement for any CO_2 storage site, and has to address the following main objectives:

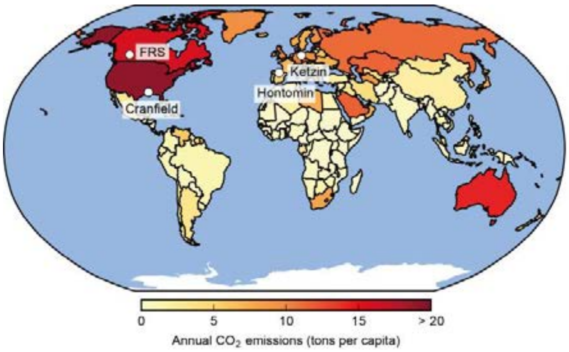
- Support of safe and efficient storage operations (operational monitoring)
- Quantitative imaging of CO_2 plume development (migration monitoring)
- Control of brine displacement as a consequence of injection-related pressure increase (safety monitoring)

To solve these tasks, geophysical and geochemical surveillance systems are required, which allow both continuous and periodic measurements. Reliable and robust sensor techniques are a necessary prerequisite for long-term data acquisition throughout the full life-cycle of storage operation. Efficient methodological approaches are needed to process data sets recorded from multiple monitoring systems and to integrate and evaluate the results within a joint data interpretation. Multi-parameter monitoring and constrained or coupled inversion of field data form the basis for reducing uncertainties in imaging the CO_2 plume distribution and estimating CO_2 saturations. Here, the geoelectrical method has earned a respectable place within the CO_2 monitoring framework.

2. Method

The application of geoelectrical measurements, also denoted as electrical resistivity tomography (ERT), for CO_2 storage monitoring was first introduced at the Ketzin [3] and Cranfield test sites [4], followed by the Hontomín site [5] and, very recently, the Field Research Station [6] (Figure 1). The usage of the geoelectrical method is motivated by the significant resistivity contrast between conductive brine and electrically insulating CO_2. Depending on the site and the wellbore characteristics, different types of casing pipes, electrodes and cables are required. For example, at the Ketzin site, a stainless steel metallic casing covered with insulating textile material carries the ring-shaped stainless-steel electrodes together with a customized multi-conductor cable [3]. At the Cranfield site, stainless-steel electrode collars are mounted with their epoxy-based centralizers on glassfiber casing pipes. A customized cable-splitter provides the transition from the individual electrode cables to the multi-conductor borehole cable [4]. An alternative option for mounting permanent electrodes along a casing is given by bow-spring centralizers [7].

A single well equipped with electrodes allows in-well measurements, and therefore, can provide useful information about the near-wellbore area. Together with an appropriate surface acquisition geometry, 3D tomographic imaging is also feasible. Two adjacent wellbores allow crosshole measurements for studying CO_2 arrival time and signature thickness in between the wells. Only the Ketzin pilot site offers the unique scenario of three electrode-equipped wells facilitating crosshole measurements in three dimensions.



Test Site/Country	No. of electrodes	Depth (m)	No. of wells
Cranfield/USA	21	~ 3,200	2
Hontomín/Spain	34	~ 1,500	2
Ketzin/Germany	45	~ 650	3
Field Research Station, Alberta/Canada	16	~ 300	1

Fig. 1. Left side: Deep ERT array installations involved in CO_2 research projects. The map is colored by annual CO_2 emissions in metric tons per capita averaged between 1960 and 2015 [21]. Right side: Key parameters of the particular ERT arrays (modified after [18]).

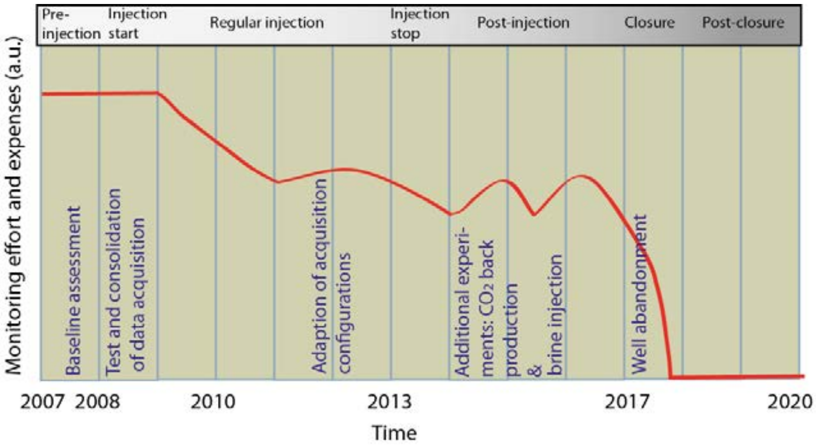


Fig. 2. Schematic illustration of monitoring effort and expenses, estimated and summarized for the geoelectric surveys of the Ketzin injection history (based on Figure 3.1 in [8]).

In general, the monitoring program of a test site extends over a number of distinct operational phases [8]. In Figure 2, the effort for the geoelectric surveys at the Ketzin site is schematically displayed. The ERT monitoring has contributed to all of the above mentioned monitoring aspects (operational/migration/safety) and comprises crosshole and large-scale surface-downhole measurements. The crosshole surveys are based on a total number of 45 permanent electrodes, located in the three wells Ktzi200, Ktzi201, and Ktzi202. In the initial phases, measurements have been conducted first on a daily and later on a weekly basis, providing images of the subsurface region between the boreholes. Surface-downhole ERT measurements enlarge the imaged region and have been performed once a year on average [9]. Test and selection of measurement protocols, daily measurements in the starting phase of the injection (characterized by adjusting the rates and observing the pressure evolution) as well as establishing of an automated data processing scheme [10] required enhanced initial effort, as reflected by Figure 2.

Since the start of the CO_2 injection at the Ketzin site in June 2008, the geoelectrical system has been continuously operated, collecting a comprehensive 8-year monitoring data set up to the present day. A well proven measurement program has kept the effort and cost at a moderate level, as seen in Figure 2 for the regular injection phase. Merely the improvement and technical adaption of surface-downhole acquisition geometries led to some additional surveys and consecutive data evaluation. After the stop of the CO_2 injection in August 2013, the post-injection phase started. In this phase, the observation well Ktzi202 was completely abandoned by cutting the technical casing above 460 m including all cable strings, and cementing the wellbore. Therefore, the electrodes of this well are no longer available, and the crosshole measurements have been reduced to 2D investigations of the major observation plane Ktzi200-Ktzi201. Afterwards, two special experiments were conducted: the CO_2 back production in October 2014 [11], and the brine injection from October 2015 till January 2016 [12]. Here again, due to daily recording and testing of additional measurement schedules, a slightly increased monitoring effort has been noted. In 2017, the closure phase will begin and all remaining wells will be abandoned. After this step, no further downhole monitoring is possible.

3. Results

Time-lapse analysis of the crosshole ERT data displays the temporal succession of the imaged resistivity distributions for the 3D tomographic cube around the three boreholes and for representative 2D sections. In addition, the permanent downhole electrodes were used as receivers in various acquisition geometries of surface-downhole geoelectric surveys [9]. Surface-downhole measurements can extend the imaging volume for monitoring the CO_2 plume and brine interaction in the near-wellbore area. Based on the results of synthetic models regarding sensitivity patterns and consequential coverage of the target storage zone, it is possible to determine the sensitivity of the acquisition geometries to preferential CO_2 migration in certain directions and investigate the detection limit of CO_2 [13].

The following phases of the CO_2 injection and post-injection operation were successfully monitored:

(1) During the initial phase of CO_2 injection, ERT measurements display the rapid evolution of a CO_2-related resistivity signature and its transient behavior. The arrival of CO_2 at the monitoring wells can be observed by the contact resistances in the target reservoir zone (Figure 3). At Ktzi200, the contact resistances of electrodes directly located in this zone show only very small variations due to the sufficient and good cement bonding of the electrodes in the annular space. At Ktzi202, the electrodes close to the upper filter region, which connects the casing with the sandstone channel, display the contact with CO_2 almost instantaneously due to the open annular space. In addition to the increase in CO_2 saturation, this signature is driven by the increasing reservoir pressure. A view of the different tomographic planes of the Ketzin triangular well arrangement is given in Figure 4.

(2) Various injection regimes (i.e. variable injection rates, shut-in and re-start periods) have led to a transition from a steady-state CO_2/brine contact towards a decreasing CO_2 plume thickness. This is further conditioned by the brine backflush, corresponding solubility trapping and halite precipitation [14].

(3) The post-injection phase shows the buoyancy-driven behavior of the plume and its spreading with significantly reduced vertical thickness.

(4) From controlled CO_2 release and brine injection experiments, the cone-shaped CO_2/brine front has been investigated in order to study the capability of such withdrawal/injection measures for potential CO_2 plume management (Figure 5).

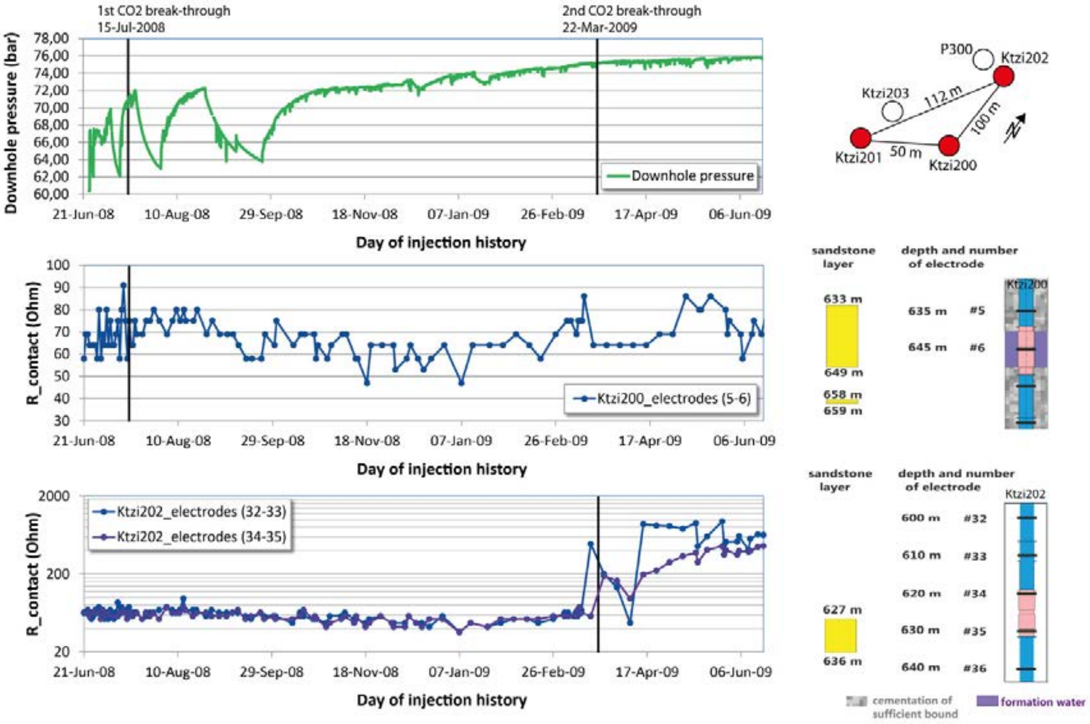


Fig. 3. Initial phase of CO_2 injection: Detection of CO_2 arrival at the monitoring wells. The upper panel shows the downhole pressure evolution (left side) and a schematic of the triangular arrangement of the wells Ktzi200, Ktzi201 and Ktzi202, carrying the permanent electrodes (right side). The middle panel displays the contact resistances in the target reservoir zone at Ktzi200 (left side) and its corresponding well completion (right side). The lower panel displays the contact resistances in the target reservoir zone at Ktzi202 (left side) and its corresponding well completion (right side).

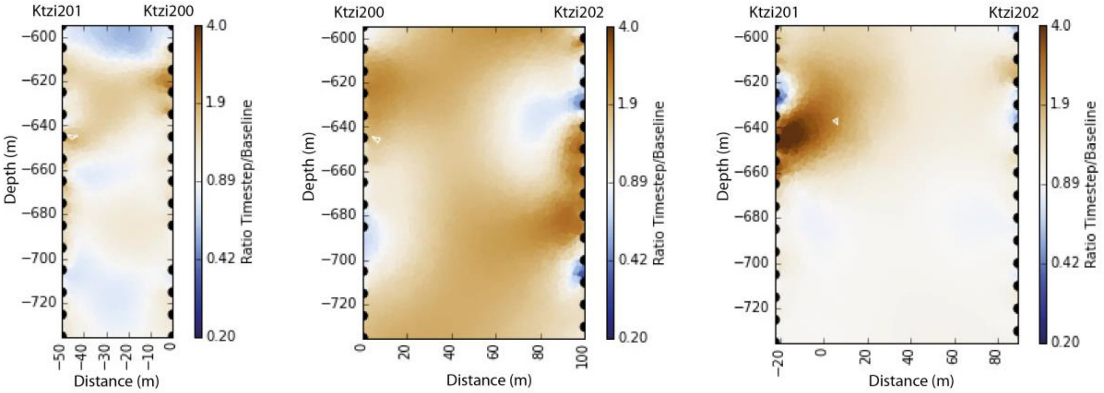


Fig. 4. Initial phase of CO_2 detection: Examples of the tomographic results for the individual observation planes: Ktzi200-Ktzi201 (d=50 m), time step of September 2008 (left side); Ktzi200-Ktzi202 (d=100 m), time step of April 2009 (middle); Ktzi201-Ktzi202 (d=112m); time step of November 2008 (right side).

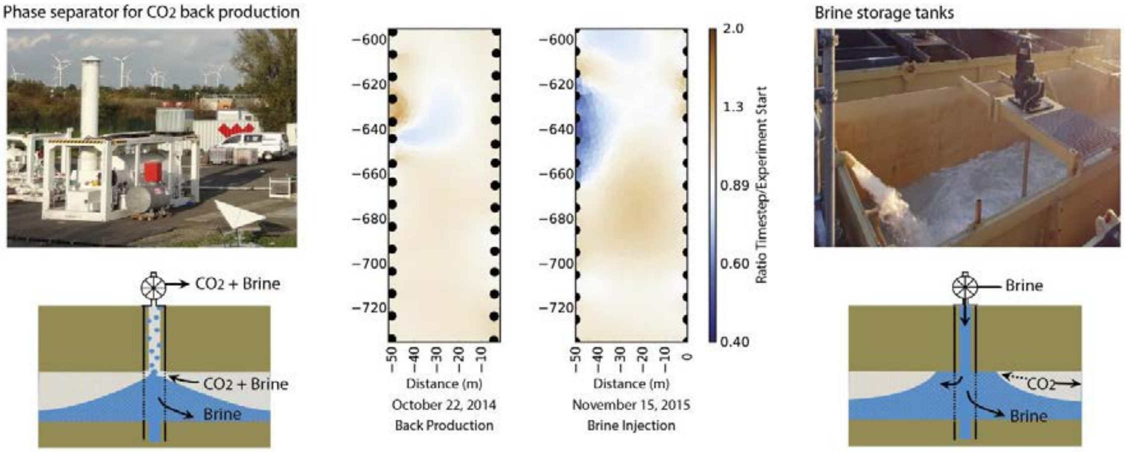


Fig. 5. CO_2 plume control (pressure management and flow diversion): Resistivity maps (middle) display the spatio-temporal evolution of the CO_2-brine contact in the near-wellbore area, as e.g., for a controlled CO_2 release (left side) and a brine injection experiment (right side).

During all operational phases, the partial CO_2 saturation can be directly derived from the apparent resistivity ratio. The interconnection between fluid saturation and geoelectrical properties has been taken into account by a petrophysical relation based on true core-sample investigations [11, 18]. The continuous ERT time-lapse data and its corresponding thickness-averaged saturation estimates provide useful information about the storage horizon and form a very good complementary method in comparison to the very locally imaging pulsed neutron gamma logs [10].

4. Advanced developments

The use of borehole electrodes for medium to deep storage projects produces a number of challenges for the subsequent data evaluation. The data acquisition might be influenced by the finite extent of the electrodes, unintended borehole deviation and complex borehole completion conditions [16]. For example, resistivity contrasts between the borehole filling fluid and the rock formation could be a source of systematic data error that can produce artifacts in the inversion images. By introducing explicit discretization of the true borehole completion into an unstructured finite-element mesh, smoothness-constrained inversions can behave discontinuously across the boundaries characterized by the different borehole completion materials. It has been shown by synthetic examples that the uncemented parts (as occurring in the Ketzin case) can evoke strong imaging artifacts under brine prevailing conditions [16].

4.1 Optimization of electrode arrays

Various methodological approaches have been studied to achieve further improvements of the geoelectrical imaging under long-term CO_2 storage conditions. The depth of the wells, the distances between them in case of a crosshole regime and the thickness of the target storage zone form certain constraints for optimal downhole electrode locations. Driven by the monitoring responsibility of site operators and the substantial expenses associated with permanent downhole installations, optimized experimental design gains particular importance. Based on an iterative appraisal of the formal model resolution matrix, a method has been developed to estimate optimum electrode locations along the borehole trajectories with the objective to maximize the imaging performance in the target horizon [17]. A first test of this method for the Ketzin reservoir has shown an enhanced resolution of the imaged CO_2 signature for synthetic design improvements. If the array design had deployed more densely spaced electrodes in the target zone of the reservoir, a smaller CO_2 signature would have become better detectable (Figure 5).

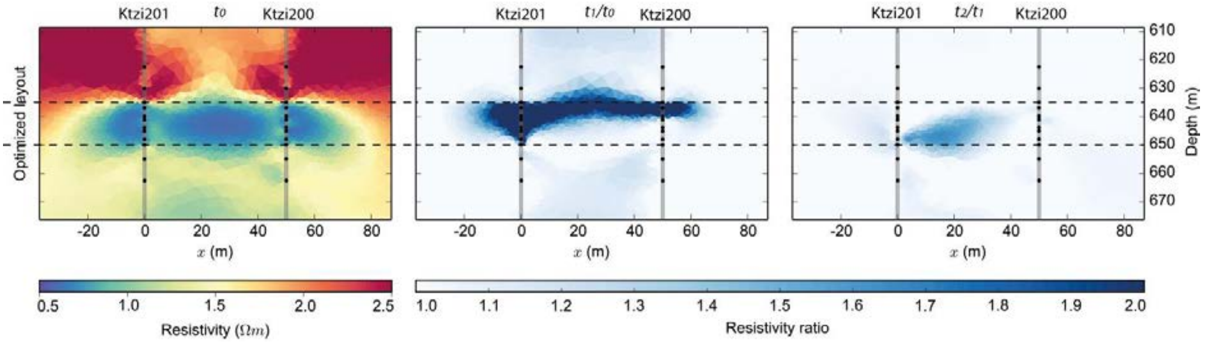


Fig. 5. Left side: Ketzin baseline resistivity model (t_0), for an optimized array with a non-equidistant number of electrodes (black dots) in the target reservoir zone (dashed lines). Middle: Resistivity increase at time t_1 in comparison to the respective previous time step, representing the major part of the typical CO_2 signature. Right side: Time step t_2 represents a split of the CO_2 plume along the cemented sandstone intercalation [24]. This scenario is used to investigate the sensitivity to small-scale CO_2 changes within the reservoir (modified after [18]).

The optimization algorithm has also been applied to a deep CO_2 storage reservoir in the Williston Basin, Canada. For the so-called Aquistore test site [19], possible types of electrode arrays for different plume migration scenarios were modelled within the frame of a synthetic study (Figure 6). Here, CO_2 migration in different layers is expected to occur, with various thicknesses of the CO_2 signatures [20]. At this site, no permanent crosshole ERT array has been installed yet due to technical and economical reasons. Our feasibility study has shown that after the assessment of geological site information and first constitutive modelling of the reservoir behaviour, operators might find a compromise between several optimized scenarios and a cost compatible solution with sufficient number of electrodes [22]. The simplest way is almost the equidistant array installation in all three layers (caprock – reservoir – substratum), which provides a quite reasonable spatial resolution of the CO_2 signature.

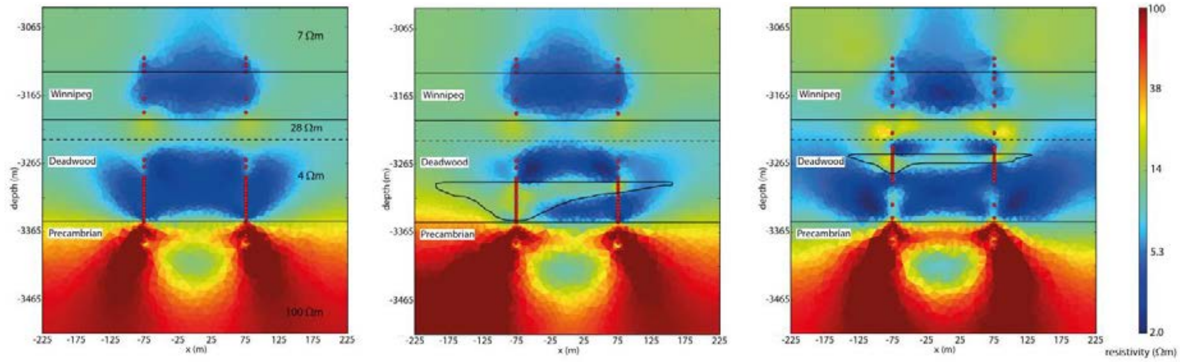


Fig. 6. Baseline situation and resistivity model of the Aquistore site, with the Deadwood formation as target reservoir zone (left side). The injected CO_2 is assumed to migrate at different depth levels. Two scenarios have been investigated in the optimization scheme: Large CO_2 plume in the lower part of the Deadwood Fm. (middle); small CO_2 plume in the upper part of the Deadwood Fm. (right side); the simulated plumes are indicated by black lines. The distribution of the deployed 48 electrodes (total in both wells; distance of the wells: 150 m) depends on the scenario under investigation [22].

4.2 Coupled hydrogeophysical inversion

A very promising development is the recently studied hydrogeophysical inversion which allows a quantitative evaluation of the CO_2 distribution [18]. Based on the permeability distribution of the geological model, a hydraulic simulation and a CO_2 migration simulation can be established. With the CO_2 saturation as input data and an empirical petrophysical relation between saturation and electrical resistance, a resistivity field is generated. A geoelectrical forward simulation is carried out to produce the measurement and observation pattern of the electrodes (Figure 7).The hydrogeophysical simulations will be benchmarked against electrical field observations.
The advantage compared to traditional electrical inversion is, that other physical underground processes as e.g. hydraulic pressure, gas pressure, gas-arrival time are simulated based on a consistent geological permeability and porosity. A high number of model parameters such as spatially distributed geoelectrical saturation exponents, permeability and porosity can be calibrated by coupling with an inverse modelling routine [23].

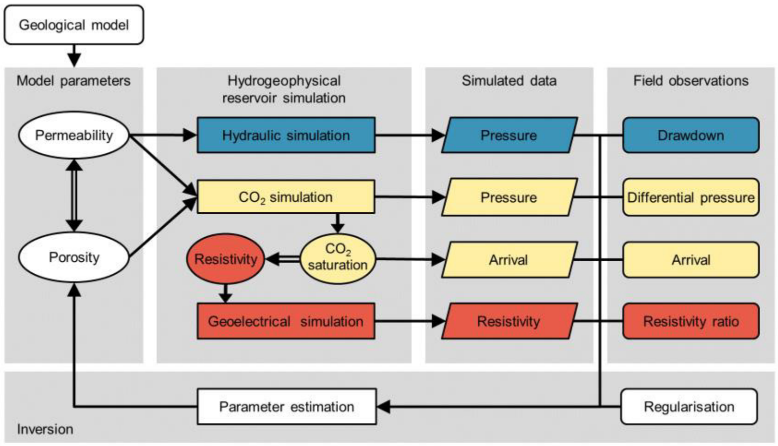


Fig. 7. Flowchart of the hydrogeophysical inversion framework. Blue color indicates the hydraulic branch, yellow color the CO_2 branch and red color the geoelectric branch. Ellipses indicate population of the reservoir model, rhombs indicate model generated time series, round cornered boxes indicate constraining data, rectangles represent numerical simulators. Double line arrows indicate petrophysical relations [23].

Conclusions

A geoelectrical monitoring concept, based on permanent borehole electrodes, offers promising imaging characteristics in the near well-bore area. As shown for the Ketzin case, the ERT downhole array is capable of detecting small amounts of CO_2 right from the beginning of the CO_2 injection and provides continuous data for CO_2 quantification. Additional methodological developments, as e.g. array optimization have shown the possibility of tailored site-specific solutions. The major forthcoming challenge comprises the transfer of this monitoring technique towards further test sites and greater depths.

Acknowledgements

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