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Probabilistic electrical resistivity tomography of a CO_2 sequestration analog

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A B S T R A C T

Electrical resistivity tomography (ERT) is a well-established method for geophysical characterization and has shown potential for monitoring geologic CO_2 sequestration, due to its sensitivity to electrical resistivity contrasts generated by liquid/gas saturation variability. In contrast to deterministic inversion approaches, probabilistic inversion provides the full posterior probability density function of the saturation field and accounts for the uncertainties inherent in the petrophysical parameters relating the resistivity to saturation. In this study, the data are from benchtop ERT experiments conducted during gas injection into a quasi-2D brine-saturated sand chamber with a packing that mimics a simple anticlinal geological reservoir. The saturation fields are estimated by Markov chain Monte Carlo inversion of the measured data and compared to independent saturation measurements from light transmission through the chamber. Different model parameterizations are evaluated in terms of the recovered saturation and petrophysical parameter values. The saturation field is parameterized (1) in Cartesian coordinates, (2) by means of its discrete cosine transform coefficients, and (3) by fixed saturation values in structural elements whose shape and location is assumed known or represented by an arbitrary Gaussian Bell structure. Results show that the estimated saturation fields are in overall agreement with saturations measured by light transmission, but differ strongly in terms of parameter estimates, parameter uncertainties and computational intensity. Discretization in the frequency domain (as in the discrete cosine transform parameterization) provides more accurate models at a lower computational cost compared to spatially discretized (Cartesian) models. *A priori* knowledge about the expected geologic structures allows for non-discretized model descriptions with markedly reduced degrees of freedom. Constraining the solutions to the known injected gas volume improved estimates of saturation and parameter values of the petrophysical relationship.

1. Introduction

Geophysical monitoring of subsurface processes is a requirement for the effective management of hydrocarbon and geothermal resources, and to assess the integrity of storage units for sequestrated CO_2 or nuclear waste (e.g., Bhuyian et al., 2012; Chadwick et al., 2005; Li, 2003; Orange et al., 2009; San Andres and Pedersen, 1993). Adequate monitoring tools provide time-lapse data that allow changes in subsurface properties to be detected and analyzed. Recovering the subsurface properties involves geophysical inversion, that is, the inference of a set of model parameters **m** from a set of data **d**. In this study, the focus is on geophysical monitoring of geologic CO_2 sequestration, where electrical resistivity tomography (ERT) has shown great potential (al Hagrey, 2011; al Hagrey et al., 2013; Bergmann et al., 2012; Carrigan et al., 2013; Christensen et al., 2006; Doetsch et al., 2013; Nakatsuka et al., 2010). The benefits of ERT arise from the sensitivity of electrical resistivity upon liquid/gas saturation and from well-established and cost-efficient techniques for sensor installations at the surface and within boreholes (Ramirez et al., 2003; Slater et al., 2000).

Inverse problems can be tackled deterministically (e.g., Menke, 1989) or probabilistically (e.g., Tarantola, 2005). We herein use a probabilistic approach, namely Markov chain Monte Carlo (MCMC) sampling of the posterior probability density function (pdf) (Mosegaard and Tarantola, 1995; Sambridge and Mosegaard, 2002). Obtaining a full marginal pdf for each model parameter is especially beneficial when the interest is not solely on the estimated parameter value itself but also on its uncertainty. If, for example, the objective is to locate possible leakage of injected CO_2, one single model as obtained by deterministic inversion is not enough to assess the risk that leakage takes place.

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Geophysical inversion results are dependent on the entire modeling process, including the formulation and accuracy of the forward problem, the data quality and processing, and the formulation and parameterization of the inverse problem. Adequate analysis of these possible sources of error and bias is an active field of research (e.g., Hansen et al., 2014; Kalscheuer and Pedersen, 2007; Ory and Pratt, 1995; Scales and Tenorio, 2001; Trampert and Snieder, 1996). A better understanding of these error sources will improve the resulting inverse models or at least help to better characterize model resolution and uncertainty. In this study, we probabilistically invert ERT data to recover the spatial saturation field in 2D. While the forward formulation and the data remain unchanged, the inversions are repeated for different parameterizations of the spatial water saturation distribution. This allows us to highlight benefits and limitations of different model parameterizations in terms of the estimates of the saturation field and petrophysical parameters, as well as their computational requirements and dependence on additional information.

This research builds on the work by Breen et al. (2012). They recorded time-lapse ERT data for a brine-saturated sand chamber during injection of air, a reasonable surrogate for supercritical CO_2. The sand was arranged to mimic a geologic formation targeted for CO_2 storage in the form of an anticlinal trap, the sand chamber can thus be seen as a reservoir analog. They inverted for resistivity models using standard smoothness-constrained deterministic inversion before translating them into saturation models assuming a known petrophysical relation. The resulting 2D saturation models were compared to high-resolution saturation images obtained with a CCD (charge-coupled device) camera. These ERT data are here inverted within a probabilistic framework and the obtained models are compared to the inversion results and the CCD images by Breen et al. (2012).

The ERT data were acquired in a laboratory environment, which constitutes a compromise between data from real field experiments and data from entirely numerical studies. Unlike synthetic data, the available lab data allow investigating measurement-related issues and possible model bias, since synthetic data are usually contaminated with zero-mean random noise only. At the same time, the laboratory environment provides full control and knowledge of the underlying 'geology' and the resulting saturation field which enables a detailed quality assessment of the inverse models. Examples of recent bench-scale analogs of ERT monitoring experiments include the work of Wagner et al. (2012) and Pollock and Cirpka (2012).

2. Methods

2.1. The forward problem

The principle of ERT surveys is the sequential injection of electrical currents between many pairs of electrodes distributed on the surface or within boreholes. Simultaneously, resulting potential differences away from the injection pairs are measured across other electrode pairs in the array. These voltages are a function of the local electrical resistivity distribution (unknown), the source current magnitude (known), and the electrode geometries (known). The forward problem in ERT thus consists of calculating the electrical potential differences for all pairs of measurement and current injection electrodes for a given resistivity model, where the electrodes are considered as point-electrodes. This involves solving Poisson's equation for the electrical potential, here performed on a finite difference grid (Binley and Kemna, 2005).

The two experimental relations of Archie (1942) provide a petrophysical link between the bulk resistivity field $\boldsymbol{\rho}$ and the spatial distribution of fluid saturation $\mathbf{S}_w$ for partially saturated porous media:

$$\boldsymbol{\rho} = \rho_w \varphi^{-m} \mathbf{S}_w^{-n}, \qquad (1)$$

where ρ_w is the resistivity of the pore fluid (here, water), φ is the porosity, m and n are the cementation and saturation exponents, respectively. The dimensions of $\boldsymbol{\rho}$ and $\mathbf{S}_w$ are given by $N_x \times N_z$, with N_x and N_z being the grid dimensions. Eq. (1) is valid when φ, m and n are constant throughout the domain and when surface conductivity is ignored (Waxman and Smits, 2003). Replacing φ^{-m} by the formation factor F yields

$$\boldsymbol{\rho} = \rho_w F \mathbf{S}_w^{-n}. \qquad (2)$$

The product $\rho_w F$ is the bulk resistivity at full saturation, often referred to as ρ_b. The basic assumption behind this relationship is that all resistivity changes are related to changes in saturation. This means that at full saturation $\boldsymbol{\rho} = \rho_b \mathbf{1}_{N_x \times N_z}$, where $\mathbf{1}$ is a matrix filled with ones. Simultaneous estimation of ρ_b and n allows inverting for $\mathbf{S}_w$ directly. The model vector is then

$$\mathbf{m} = \{\mathbf{S}_w, \rho_b, n\} \qquad (3)$$

of dimension $N_x \times N_z + 2$ and the forward problem is

$$\mathbf{d} = g(\mathbf{m}) + \boldsymbol{\varepsilon}, \qquad (4)$$

where $g(\mathbf{m})$ is the forward response of $\mathbf{m}$ and $\boldsymbol{\varepsilon}$ is an error term summarizing all measurement and modeling errors.

2.2. Experimental setup

A full description of the experiment and the measurement system is given by Breen et al. (2012). We only summarize the main elements of the experimental setup here (see also Fig. 1).

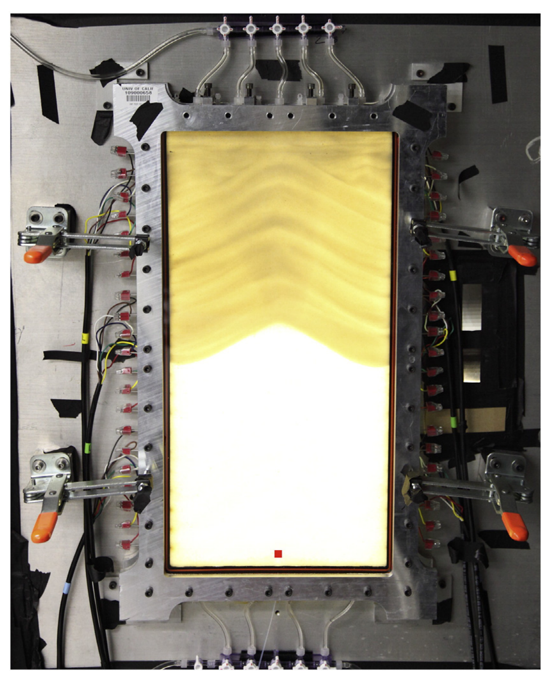

Fig. 1. The fully assembled chamber containing saturated quartz sand, reproduced from Breen et al. (2012). The red square near the bottom of the chamber indicates the gas injection point. Electrode connections can be seen on the left and right sides, and inlet/outlet tubing on top and bottom. The anticlinal transition from the coarser sand on bottom to the finer sand on top was designed to imitate a caprock barrier, while finer layering throughout the chamber imitated natural micro layering in sedimentary formations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)