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Monitoring freshwater salinization in analog transport models by time-lapse electrical resistivity tomography

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A B S T R A C T

Deep saline aquifers are target formations both for the geological storage of carbon dioxide as well as for geothermal applications. High pressure gradients, resulting from fluid or gas injection processes, provide a potential driving force for the displacement of native formation waters, implicating a potential salinization of shallow freshwater resources. Geoelectrical monitoring techniques are sensitive to compositional changes of groundwater resources, and hence capable to detect salinization processes at an early stage. In this context, numerical simulations and analog modeling can provide a valuable contribution by identifying probable salinization scenarios, and thereby guiding an optimum sensor network layout within the scope of an early warning system. In this study, coupled numerical flow and transport simulations of a laterally uniform salinization scenario were carried out and used to support a subsequent realization in a laboratory sandbox model. During the experiment, electrical resistivity tomography (ERT) was applied in a practical surface–borehole setup in order to determine the spatio-temporal variations of electrical properties influenced by saltwater intrusion. Inversion results of different electrode configurations were evaluated and compared to numerical simulations. With regard to surface–borehole measurements, good results were obtained using crossed bipoles, while regular bipole measurements were more susceptible to noise. Within the scope of a single-hole tomography, the underlying resistivity distribution was best reproduced using the Wenner configuration, which was substantiated by synthetic modeling.

1. Introduction

Geological storage of CO_2 has received considerable attention as a technology to support the transition to low-carbon energy systems, while being consistent with continued fossil fuel use. On a global scale, deep saline aquifers offer the highest storage capacity for CO_2 (IPCC, 2005) and are also target formations for geothermal applications. Synergetic utilization of geothermal energy and CO_2 storage is part of ongoing research (e.g. Pruess and Spycher, 2010; Randolph and Saar, 2011) and may be a sustainable concept to combine renewable and transitional energy technologies.

Several hydrogeological aspects have to be considered, when deep saline aquifers are engineered for storage and production activities. General water challenges of carbon capture and storage operations (e.g. water demand for the capture process) as well as potential impacts on shallow freshwater resources have been reviewed recently by Newmark et al. (2010) and Lemieux (2011). One key concern is the potential upward migration of native formation fluids through hydraulic conduits driven by induced pressure gradients. Upon intrusion into shallow aquifers, brine can lead to significant freshwater salinization and potentially limit the use of freshwater resources for domestic, agricultural and industrial applications.

High resolution monitoring concepts are sorely needed to identify preferential flow pathways of saline water and thereby allowing countermeasures to be taken in time prior to large-scale groundwater deterioration. Geoelectrical monitoring techniques are particularly suited to detect freshwater salinization, as electrical properties of the medium are directly sensitive to compositional changes in the pore-filling fluid. As part of an integrated monitoring concept, the electrical resistivity tomography (ERT) can provide useful information on the near-surface region and the vicinity of (electrodes-equipped) boreholes. A number of case studies have demonstrated the value of ERT to detect freshwater salinization (e.g. Bauer et al., 2006; de Franco et al., 2009; Maurer et al., 2009; Nguyen et al., 2009), whereby most of the work is related to seawater intrusion in coastal areas. Although important principles can be derived from these studies, the application to CO_2 storage related salinization is not straightforward and requires further (site-specific) research, as salinities, flow rates and spatial extent of the salinization scenario may differ considerably.

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Since geoelectrical field data from prospective storage sites is usually scarce, numerical simulations and analog laboratory experiments play an important role during the planning phase of reliable monitoring systems in advance to their field-scale implementation. ERT has been successfully applied in analog transport modeling studies to image and characterize the movement of conductive saline tracers through unconfined sediments (Slater et al., 2000, 2002) and undisturbed soils (Binley et al., 1996; Koestel et al., 2008; Olsen et al., 1999). In this study, we experimentally simulate pressure-driven upward migration of a synthetic brine through an initially freshwater-saturated porous medium in a laboratory sandbox model. In doing so, we evaluate the monitoring performance of frequently used electrode configurations carrying out a miniaturized ERT survey in a practical surface–borehole setup. The workflow includes numerical flow and transport simulations of the selected salinization scenario, which serve as the basis for a synthetic ERT study and are additionally used to support the experimental procedure and to validate the monitoring results.

2. Experimental and numerical transport modeling

2.1. Experimental design and procedure

A schematic cross-section of the experimental setup is shown in Fig. 1. The cylindrical sandbox consists of acrylic glass and has a height of 640 mm and an inner diameter of 634 mm. Thus, it comprises a volume of approximately 200 l, which corresponds to about 300 kg of dry sand (assuming a density of 1,600 kg/m^3). A total of 100 mounting-holes at the walls allow flexible drainage and sensor placement. For this experiment, connections for recharge and discharge were drilled at four opposite positions close to the bottom and the top of the tank, respectively (Fig. 1). Saltwater injection into the tank was realized by employing a peristaltic pump connected to a suction pipe. The cylinder was positioned on a customized laboratory desk, which incorporates a load cell facilitating in-situ porosity determinations.

In this study, laterally uniform brine migration through a homogeneous medium is investigated. A gravel filter layer was incorporated at the bottom of the model to allow for a widespread and non-localized upward migration of the injected saline solution. After filling the gravel to a height of 9 cm and addition of water, an in-situ porosity of 32% was determined and adopted in the numerical model (Table 1). With the aim of preventing the considerably smaller sand grains to slip into the large pore volume of the underlying gravel, a textile filter was positioned in between both layers. Prior to sand emplacement, a vertical electrode array was positioned and fixed in the center of the sandbox. Sand filling was performed incrementally, meaning that a certain amount of water was added to the tank and sand was emplaced subsequently. During this procedure, the amount of inserted sand grains was chosen carefully in order to avoid air entrapment. Very fine sequences developed, which were reduced by mixing the sand during sedimentation. Controlled percussions at the sides of the sandbox led to near-wall consolidation counteracting wall effects. No further efforts were made towards compaction of the medium.

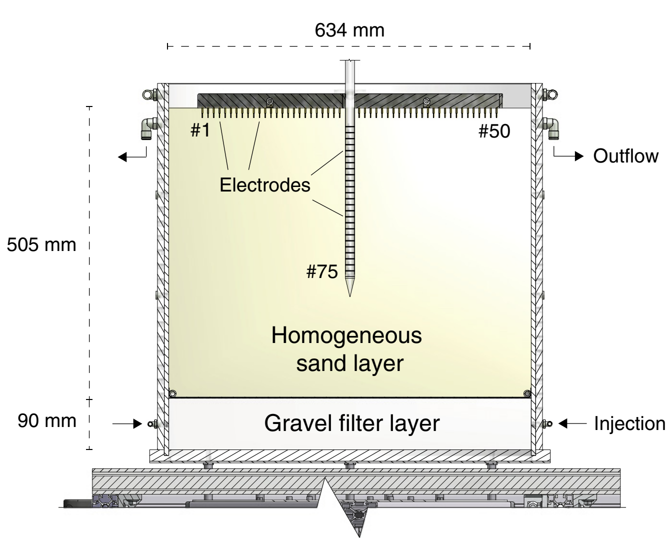

Fig. 1. Cross-sectional view of the laboratory sandbox model showing the electrode layout of the two-dimensional image plane.

As a consequence of the wet packing method, the medium was prepared to be fully saturated with freshwater at the beginning of the experiment. Subsequently, a highly saline solution with a NaCl concentration of 200 g/l solution, as to be expected in deep saline aquifers relevant for geological CO_2 storage (Michael et al., 2010), was injected via four opposite inlets vertically centered with respect to the gravel layer. The injection rate of 10 ml/min was kept constant over a period of six days providing a steady pressure gradient for the upward movement of the denser saltwater. A fiber optic refractive index sensor (FISO Technologies, Québec, Canada) placed at the outflow of the sandbox provided salinity measurements of the effluent every ten minutes. Thereby, salt arrival at the top of the sandbox was captured to validate the prediction from numerical flow and transport simulation.

2.2. Material characterization

The homogeneous medium was prepared with a well-sorted Fontainebleau sand, which is frequently used in laboratory sandbox studies (e.g. Allègre et al., 2010; Bordes et al., 2006). To adequately parameterize the numerical flow and transport model, hydraulic properties of the material were determined in advance. A constant-head permeameter yielded a permeability of 23 Darcy. This value is in good agreement with calculations on the basis of empirical formulas (Fair and Hatch, 1933; Harleman and Melhorn, 1963), reflecting good sorting of the sand. Bulk porosities were determined gravimetrically in containers of different volumes and in the sandbox setup applied. Porosity calculations are based on the total volume, the sand mass and the amount of water added to ensure full saturation. Laboratory measurements revealed a porosity of 37% for the medium sand opposed to 44% obtained in the sandbox model. This large value may reflect the loose packing of the material immediately after emplacement. Similar contrasts were observed in the experiments of Slater et al. (2002). For numerical simulations, a bulk porosity of 40% was assumed.

2.3. Numerical model setup

Numerical flow and transport simulations of the selected saltwater migration scenario on the laboratory scale were performed using *TOUGH2* (Pruess, 1991; Pruess et al., 1999). *TOUGH2* is a general-purpose fluid and heat flow simulator applied for multi-dimensional, multi-component and multi-phase flow and transport processes in porous and fractured media. In this study, the *ECO2N* module (Pruess, 2005) was employed, which compromises the thermodynamics and thermophysical properties for mixtures of water, NaCl and CO_2. Although influences of temperature and CO_2 were not considered in the simulations, the module provides all relevant equations of state for the calculation of isothermal salt transport at room temperature.

The conceptual model consists of a cylindrical boundary according to the sandbox dimensions. Cells outside of the boundary act as an impermeable boundary condition (*Neumann* type). Discharge is realized by a top layer with an increased permeability and an infinite volume, which has its base at the vertical position of the upper drains of the sandbox. The large volume of the top boundary condition cells ensures that flow into the top layer has a negligible effect on pressure.