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Analysis of alternative push–pull-test-designs for determining in situ residual trapping of carbon dioxide

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ABSTRACT

Carbon dioxide storage in deep saline aquifers is a promising technique to reduce direct emissions of greenhouse gas to the atmosphere. To ensure safe storage the in situ trapping mechanisms, residual trapping being one of them, need to be characterized. This study aims to compare three alternative single-well carbon dioxide push–pull test sequences for their ability to quantify residual gas trapping. The three tests are based on the proposed test sequence by Zhang et al. (2011) for estimating residual gas saturation. A new alternative way to create residual gas conditions in situ incorporating withdrawal and a novel indicator-tracer approach has been investigated. Further the value of additional pressure measurements from a nearby passive observation well was evaluated. The iTOUGH2 simulator with the EOS7C module was used for sensitivity analysis and parameter estimation. Results show that the indicator-tracer approach could be used to create residual conditions without increasing estimation uncertainty of S_{gr}. Additional pressure measurements from a passive observation well would reduce the uncertainty in the S_{gr} estimate. The findings of the study can be used to develop field experiments for site characterization.

1. Introduction

Geological carbon dioxide storage in deep saline aquifers is a promising technique to reduce direct emissions of greenhouse gas from large point sources to the atmosphere. Trapping of carbon dioxide in the formation occurs through structural and stratigraphic, hydrodynamic, residual, solubility and mineral trapping (IPCC, 2005). To ensure that the carbon dioxide is safely stored, the trapping mechanisms in the subsurface need to be characterized and quantified. Residual trapping has been identified as an important trapping mechanism (Kumar et al., 2005) and the relatively short time scale at which it occurs makes it feasible to assess during site characterization. The residual trapping capacity and thereby also the suitability of a formation to store carbon dioxide is site specific and dependent on several formation properties. Maximum residual gas trapping in general depends on the imbibition procedure, prevailing thermodynamic conditions and properties of the ambient rock, e.g. porosity and permeability (Holtz, 2002). This urges the development of field tests that will be able to estimate in situ formation properties during site characterization, providing a means for estimating residual trapping.

Single-well injection-withdrawal tests, so called push–pull tests, are intermediate-scale methods for characterizing properties of and processes occurring in the subsurface. Benefits of these tests, such as lower costs and smaller required injection/extraction volumes of fluid as compared to two- or multiple-well tests have been noted by several authors (Istok et al., 2002; Zhang et al., 2011).

Historically single-well push–pull tests have been developed and used for assessing in situ non-aqueous phase liquid saturation (Istok et al., 2002; Tomich et al., 1973); microbial metabolic activities (Istok et al., 1997) and characterizing solute retardation due to sorption (e.g. Schroth et al., 2001). Tomich et al. (1973) utilized in situ reactive tracers with different retardation properties to obtain tracer break through curves (BTCs) with the difference in arrival times dependent on the residual oil saturation. Estimation of the residual oil saturation was then done through comparison with numerical simulations. Istok et al. (2002) used a nonreactive partitioning tracer test approach with a combination of multiple partitioning tracers and conservative tracers. To detect NAPL in situ the test exploited the NAPL-saturation dependent

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retardation of the partitioning tracers, compared to the conservative tracers, seen as an increased apparent dispersion in the tracer BTC.

Carbon Capture and Storage (CCS)-related single-well push–pull tests include those to characterize geochemical processes and residual trapping (Assayag et al., 2009; Matter et al., 2007; Myers et al., 2012; Zhang et al., 2011). Reactions occurring between carbon dioxide, water and rock are of importance for geochemical trapping. In studies by Assayag et al. (2009) and Matter et al. (2007) water saturated with carbon dioxide was injected into a basaltic rock formation at shallow depth. Measurements of electrical conductivity, temperature, pH and chemical analysis of water samples were taken from which dissolution rates were determined. Zhang et al. (2011) presented a single-well push–pull test design utilizing thermal, hydraulic and partitioning tracer methods for determining the residual carbon dioxide saturation. It was shown through inverse modeling on synthetic data that the uncertainty of the estimated parameters decreased when different types of tests (thermal, hydraulic and tracer) were combined. Myers et al. (2012) suggested a single-well tracer test to quantify residual carbon dioxide saturation utilizing reactive partitioning tracers, which would produce in situ, new tracer components with different partitioning properties. After the tracers had been given time to react, formation fluid was withdrawn and BTCs recorded. Residual saturation was then inferred from modeling.

The preceding summary shows that only a limited number of design studies involving single-well push–pull tests has been carried out so far for CCS-related site characterization. This motivates the study presented in this paper of alternative test designs that could yield additional valuable information on in situ properties.

The modeling in this study aims to evaluate alternative single-well carbon dioxide push–pull tests for their ability to quantify residual trapping. The three sequences under study are based on the proposed experimental sequence by Zhang et al. (2011) for estimating residual gas saturation. An alternative way to create residual gas conditions in situ incorporating withdrawal and a novel indicator-tracer approach has been investigated. In addition, the value of added information in terms of pressure measurements from a nearby passive observation well was evaluated. Comparison of the alternative push–pull-test-designs for determining in situ trapping of carbon dioxide was carried out through numerical simulations with iTOUGH2 (Finsterle, 2007) and the EOS7C module (Oldenburg et al., 2004). A systematic sensitivity analysis was conducted to explore the relative importance of different measurement data sets for the alternative test sequences. An inverse modeling approach using synthetic data was then adopted to identify how accurate parameter estimates could be obtained. The uncertainties in the parameter estimations were used to discriminate between the abilities of the alternative test sequences to determine the residual gas saturation of the formation. Note that in this study, supercritical carbon dioxide is referred to as gas. Results from this study will be used to develop a test design suitable to be part of the field experiment conducted at the Heletz site, Israel, within the EU FP7 MUSTANG project (Niemi et al., 2012).

2. Methodological approach

2.1. Alternative test sequences

The alternative test sequences presented and numerically evaluated in this study take as starting point the test design with hydraulic, thermal and tracer tests proposed by Zhang et al. (2011) for estimating residual gas saturation, S_{gr}, in situ. Their test sequence consisted of three stages where tests were performed at different gas saturation conditions. First, prior to carbon dioxide injection, a reference test with thermal, hydraulic and tracer measurements was carried out. Second, carbon dioxide was injected, a thermal test was performed, followed by injection of water saturated with carbon dioxide thereby pushing the free carbon dioxide-phase further into the formation and leaving carbon dioxide at residual saturation in a zone around the well. Carbon dioxide-saturated water was used to prevent dissolution of residual trapped carbon dioxide during the creation of the residual zone. Third, thermal, hydraulic and tracer measurements were performed at residual gas saturation. Zhang et al. (2011) demonstrated through inverse modeling on synthetic data that combining several types of measurements (thermal, hydraulic, and tracer) has the advantage over only using one type of measurement, in that the uncertainty of the estimated parameters is reduced.

In the present study two types of tracers are used; dissolved gas tracer and indicator tracer. Dissolved gas tracers (Kr and Xe) are partitioning tracers which distribute between the gaseous and aqueous phase, leading to a difference in BTC for tracer tests carried out at fully water saturated conditions and at residual gas conditions, and this ability is exploited when estimating S_{gr}. The second type of tracer, the indicator tracer, should preferably be non-reactive, stay in the aqueous phase, i.e. not partition to the gaseous phase and not precipitate. A simple salt such as bromide (Br^-) may be a potential candidate, as used in this study. This type of tracer is used as an indicator of when residual gas conditions have been reached in the formation when creating a residual gas zone through withdrawal. This tracer type is throughout this study referred to as indicator tracer, while the word tracer is used to refer to dissolved gas tracers. Dissolved gas tracers are used in test sequences 1–3, presented later in this section. An indicator tracer is used in test sequences 2 and 3.

The first alternative test sequence (see Fig. 1) patterns after that of Zhang et al. (2011), with the values of the injection rates adapted to the conditions at the Heletz site. During this test sequence residual gas conditions are established through carbon dioxide injection, followed by injection of carbon dioxide-saturated water. In Fig. 1 the arrows below indicate the sampling intervals for temperature, pressure and dissolved gas tracer concentration data sets used in the sensitivity analysis and for parameter estimation. The acronyms represent datasets of temperature (T), pressure (P) and dissolved gas tracer concentration (C) measurements in the injection well and pressure measurements in the passive observation well (PO), and numbers refer to the chronological order of the datasets.

The second alternative test sequence (see Fig. 2, explanation of acronyms same as for Fig. 1) aims to create residual gas conditions through a different procedure: withdrawal of formation fluid for a given duration. As it is not obvious when residual conditions are obtained during fluid withdrawal, a specific approach — the use of an indicator tracer — is introduced, the BTC of which allows one to determine the point in time when the residual conditions are established. During the stage of establishing the residual zone an indicator tracer is first co-injected (1 h pulse) with water before the carbon dioxide is injected. The amount of indicator-tracer should be chosen such that a high enough BTC concentration to be detected by the measuring device is received. No carbon dioxide-saturated water injection follows the carbon dioxide injection as in the first alternative test sequence; instead, fluid is withdrawn while indicator-tracer concentration in the aqueous phase is monitored. The establishment of residual gas conditions around the well coincides with the online-measured concentration of the indicator tracer approaching zero (the concept is displayed in more detail in connection with the presentation of the third test sequence).

The third alternative test sequence (see Fig. 3, explanation of acronyms same as for Fig. 1, with addition of data set TX corresponding to temperature measurements taken during multiple stages of the test, i.e. the carbon dioxide injection, soaking,