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Pre-Operational Considerations In A Poro-Elastic Site Assessment For The Svelvik Field Lab

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Summary

A re-establishment of the Svelvik Field Laboratory for active CO2 migration monitoring is accompanied with numerical pre-injection site investigations using a poro-elastic description of the glacio-fluvial and marine deposits. The aim is to discriminate pressure and saturation effects of CO2 injection and provide an optimized layout for a multi-physical monitoring campaign. Near surface and appraisal well grain size analysis and appraisal well logging data are used to constrain the elastic properties of a forward model. Results of the previous monitoring campaign and simulation for the planned injection are used to design the layout of the individual monitoring technologies optimized for a range of plume migration scenarios. The monitoring campaign and observation well locations are designed such that the CO2 plume will be captured by cross-well data. The simulated gas saturations and pressures are used to obtain elastic parameters describing the acoustic response. Using worst to best case scenarios being based of rock physical parameters provide resulting sensitivities to particular conformance criteria.

Introduction

Any monitoring campaign to assess the safe and reliable long term storage of CO_2 requires pre-operational site assessment. On a field scale these considerations are generally experience driven and rely on the results obtained from similar studies. Targeting a deeper aquifer in the current upgrade of the field laboratory, pre-injection measurements and simulations are required to define and design the monitoring systems to be able to discriminate pressure and saturation related effects. Different monitoring systems can be used to measure or infer these effects. In this study the potential of acoustic systems to quantitatively assess their suitability for pressure-saturation discrimination in a poro-elastic description of the subsurface is analysed. Pre-injection simulations identify where and how acoustic systems can be complemented with pressure and geoelectric measurements. The design and layout of these systems is most commonly governed by experiences obtained from previous campaigns. This is certainly a shortcoming in the setup of a monitoring campaign. Methods such as value of information (VOI) could potentially be used to circumvent the experience driven need of designing monitoring layouts in general. Here the composition, layout and design could be considered the objective to minimize the operational consideration of a pre-injection site assessment anticipating a particular CO_2 migration footprint.

Field site description

Bakk et al (2010) have performed a site assessment of the Svelvik field laboratory prior to a CO_2 migration and leakage experiment in 2011. The field located on a peninsula approximately 50 km SW of Oslo, Norway is classified as a glaciofluvial-glaciomarine terminal deposit and is characterized by highly variable grain deposits with pebble and cobble beds in the overburden (Barrio et al., 2014). Results of the acquisition campaign in 2011 (Denchik et al., 2014 and Jones et al., 2014) and investigations made prior to the re-establishment of the site in early 2019 are incorporated in the rock physics description of the site and subsequent numerical simulations of an expected CO_2 plume migration. Because in soft poorly consolidated sediments we do expect significant compaction as a result of increasing pressure in the following synthetic study we include the pore pressure effects while we are injecting into a very shallow aquifer at approximately 60m depth. Pore Pressure increase will then be a function of burial depth, hydrostatic and injection pressure only.

Theoretical background

Generally the porous media for CO_2 injection can be described as a combination of a frame of rock matrix with porosity which accommodates fluids or gas. The density can therefore be described by a dry matrix and fluid density filling the pore space. The dry rock frame is described as soft sand with the Hertz-Mindlin model and is a mixture of two or more components. Computing the upper and lower Hashin-Shtrikman bounds it is possible to obtain a mixed solid frame using a solid mixing parameter (Mavko et al., 2009 and Avseth et al., 2010). Based on the field site specific data we assume a solid mixture of quartz and clay. The spatial distribution of the fluids is described conventionally using Gassmann's formulation, and the two cases of a perfectly uniform and a perfectly patchy fluid mixture consisting of a CO_2 gas and water fluid phase considered (Domenico, 1977). Mavko and Jizba (1991) investigated acoustic dispersion effects as a function of effective pressure leading to an effective moduli description of the subsurface. This scaling of the velocity pressure dependence is adjusted based on additional information from pressure monitoring, pumping tests and further site specific information. Figure 1 shows the rock physics template of the quartz-shale frame and the corresponding response to increasing saturations and porosities. The actual acoustic impedance changes as we are injecting CO_2 into the formation is visualized in Figure 1b and 1c.

First preliminary simulations reveal that the saturation effect is several orders of magnitude larger than the pressure response. This will make pressure-saturation discrimination very difficult using only acoustic monitoring as the overall pressure related changes are limited due to the small overpressure that can be achieved at the shallow site. For this reason a pressure monitoring string is applied to explicitly determine pressure and for pressure tomography. The mapping of the CO_2 saturations is further supported by surface and downhole electric resistivity measurements in a similar concept as applied at the Ketzin pilot site (Schmidt-Hattenberger et al., 2013).

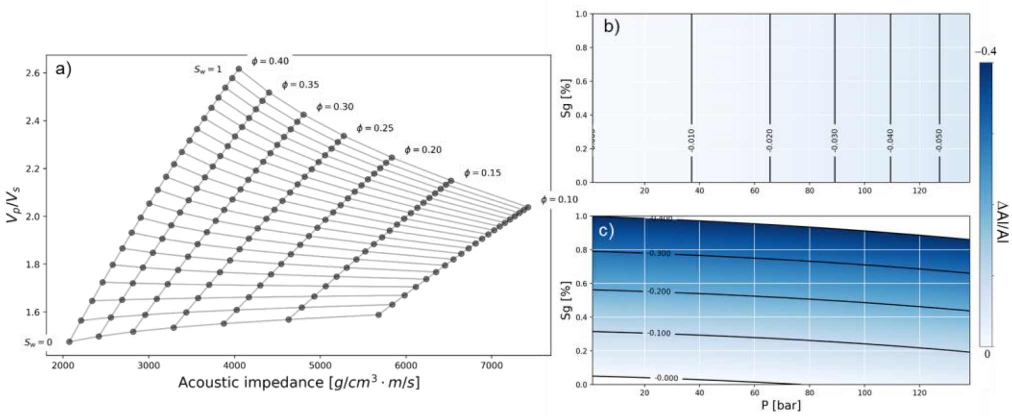

Figure 1 *Rock physics template (a) of a quartz shale mixture in the Hertz-Mindlin soft sand description. Change of acoustic impedance separated into pressure (b) and combined pressure-saturation (c) response.*

Workflow

No matter which monitoring system is used in the discrimination of pressure and saturation effects all have one common denominator. They are subject to the environmental conditions and have a limited resolution power. The response we observe from simulating the CO_2 migration, is a function of a multitude of parameters defining the subsurface. The underlying parameters defining the rock physics model that are used to derive a response in the frame of a solid-fluid mixture are not unique. Given the above described considerations in the development of a poro-elastic description of the subsurface we investigate shortcomings of the electric, pressure and acoustic monitoring system.

Schematically shown in Figure 2 is the description of the subsurface as a result of the available data, the underlying model parametrization allowing a first pass simulation of the CO_2 injection and plume migration. Aiming for a high coverage to track the plumes' front advancement, the monitoring system consists of electric resistivity, pressure and acoustic data to be jointly interpreted. Variation in the model parameters and limitations in resolution of the acquisition technologies can be used to estimate and optimize the monitoring layout given a spread in the response. This approach requires a common subsurface description and forward modeling approach and can be considered as an experience driven survey design.

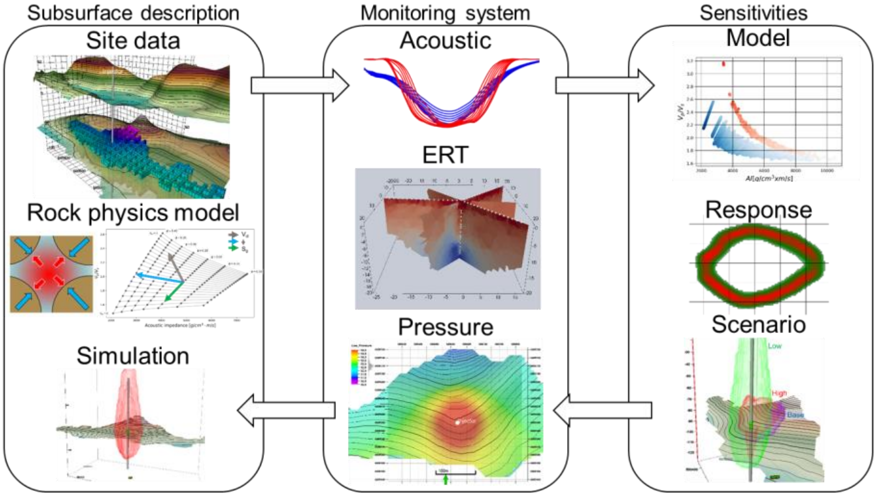

Figure 2 *Schematic description of the individual monitoring systems in relation to the subsurface description and the sensitivity analysis to optimize their layout and design.*

<u>Acoustic monitoring</u>

We generated synthetic seismic shot gathers using an explicit second order differencing method described by Alford et al. (1974) to analyze the offset dependent amplitude variation of a synthetic plume without any leakage into the overburden. The overburden consisted of a two-layered medium which was assumed to be perfectly sealing. The plume is both growing spatially and with increasing pore pressure and gas saturation affecting Vp/Vs and density. Sources were positioned every 25 m and a receiver line with a group spacing of one meter defined. After an initial setup and finite difference modeling we sorted, NMO corrected and stacked the data. With these common offset or angle dependent stacks we automatically picked the amplitudes at the cap rock aquifer interface and compared these with gas free conditions. The scans were performed in an angle range of approximately 5°.

Electrical resistivity monitoring

Due to their sensitivity with regard to pore fluid changes (water/gas) in the subsurface, geoelectrical methods have been proven as suitable technique to detect and track CO2 migration in shallow aquifers (Auken et al., 2015; Yang et al., 2016). For the planned shallow monitoring wells at the Svelvik CO_2 Field Lab, surface profiles of various acquisition geometries will be able to image a sufficient depth of investigation. For example, one relevant target zone is the freshwater-seawater transition, where a CO_2 intrusion might occur during the envisaged migration experiment. A former surface-downhole survey has clearly indicated this transition zone at ~12 m depth (Figure 3).

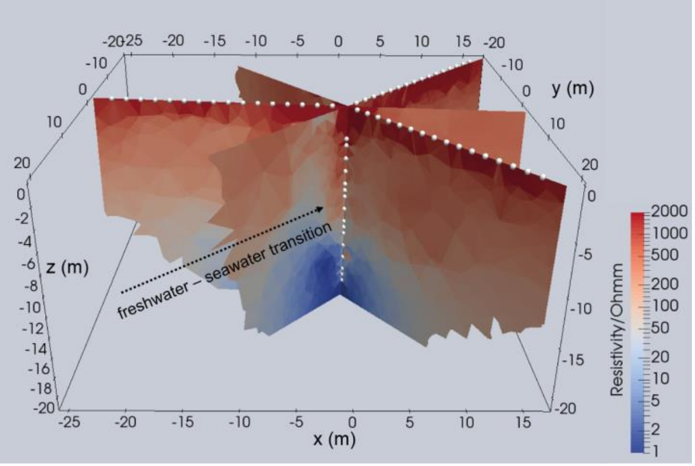

Figure 3 *Resistivity distribution imaged by a surface-downhole survey at Svelvik CO_2 Field Lab (Strom et al., 2017), recorded in an area adjacent to the location of the new experiment.*

Another zone of interest is the reservoir zone at ~ 60 m depth, where the planned CO_2 injection will take place. To image the CO_2 migration in that zone, four monitoring wells with permanent electrode arrays are suggested. Such a typical cross-well arrangement guarantees a reasonable coverage of the CO_2 signature in the subsurface and could provide information about preferential pathways.

Pressure monitoring

The pressure monitoring system is aimed for a high spatial and temporal resolution. The observation wells are equipped with spatially distributed pressure sensors. They are installed at the main aquifers between low permeable layers to obtain a description of the main hydrogeologic features. The sensors are installed on the outside of a smart casing wherefore the pressure can be continuously monitored during all experiments and the pressure monitoring can be complemented with wireline in-hole measurements. Further, pressure tomography can be carried out with pre-injection pumping tests to determine permeability and also after CO_2 injection to determine CO_2 saturation distribution. To discriminate, with high precision the pressure response, the limitations in the acoustic system had to be evaluated. Hu et al. (2015) use time lapse pressure tomography inversion to characterize CO_2 plume development in deep aquifers. The saturation effects dominate the response in the acoustic system and a more detailed pressure tomography is used to understand the subsurface response to pressure build-up in more detail.

Conclusions

As part of the re-establishment of the Svelvik CO_2 field laboratory in Norway a pre-injection site assessment based on a poro-elastic description of the subsurface was performed. A 3D geological model is generated based on legacy data and recent monitoring campaigns. These data are also used to conceptually develop and to constrain a rock physical model for the matrix and pores filled with arbitrary water/CO_2 mixtures. Simulations show only a weak resolution power to determine pressure effects with acoustic methods. Therefore a pressure monitoring network is proposed to determine pressure directly. The present results provide a benchmark to further CO_2 characterisation with pressure tomography and geoelectric resistivity tomography. The individual monitoring systems have been identified out of a need to discriminate pressure and saturation related effects. Non-uniqueness in the subsurface parameters as well as the limited resolving power of the monitoring equipment have a significant and measurable impact on these effects and their response. Optimization of the layout therefore has to account for these uncertainties and limitations of the acquisition systems. As perspective, interfaces should be defined, where the latter methods are required to complement acoustic tomography.

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