Geophysical and Hydro-Mechanical Coupled Monitoring for Efficient Control of CO2 Storage

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Summary

Geological reservoirs can be structurally complex and respond to CO2 injection both geochemically and geomechanically during Carbon Capture and Storage (CCS) practices. This paper presents an experimental rig designed to simultaneously monitoring geophysical and hydromechanical properties of rock samples under reservoir conditions in the laboratory. The rig combines ultrasonic waves and electrical resistivity measurements with permeability and strains. It aims to provide data for joint inversion of seismic and electric field data, but also to couple seismic and hydromechanical models to improve CO_2 storage monitoring and prediction. Accordingly, the well-documented Sleipner site in the North Sea is being experimentally analysed as an example of a saline aquifer, and preliminary results regarding CO_2 flooding of brine-saturated sandstone are presented here.

Introduction

Atmospheric concentrations of carbon dioxide (CO_2) have increased dramatically since the end of the nineteenth century, chiefly owing to increased burning of fossil fuels by humans, but also to steel works, cement factories and chemical plants. According to experts, the only realistic leading mitigation strategy is Carbon Capture and Storage (CCS). CCS technologies involve the sequestration of CO_2 into deep geological formations found in the Earth's continental crust, including sub-seafloor geological formations, which have been specially selected for such massive-scale storage. While the concept is a promising one, uncertainties and risks remain a matter of concern, especially with regard to public acceptance related to induced overpressure from CO_2 injection, such as seismicity (earthquakes and landslides). Geological reservoirs are commonly complex both structurally and stratigraphically, and can respond to CO_2 injection both geochemically and geomechanically. CO_2 is a reactive fluid whether in a liquid, gas or supercritical state, that when injected into deep geological formations may trigger various physical phenomena as a result of pressure and temperature gradients, and chemical disequilibria. These phenomena are commonly grouped under the term Thermo-Hydro-Mechano-Chemical coupled processes (THMCs). The need to accurately model THMCs using 3D earth models of storage sites constrained by field and laboratory data has been specified in European Directive 2009/31/EC. Data required for such models include host rock pore volume, CO_2 –rock geochemical reactions, geomechanical behaviour of the seal (cap rock) and reservoir formations, and fluid flow dynamics. To address THMCs phenomena, we have designed an unique multidisciplinary plan which combines experimental procedures on rock samples exposed to CO_2 injection under realistic environmental and geological conditions with state-of-the-art data analysis and interpretation. The experimental procedure is based on coupling geophysical and hydro-mechanical monitoring, controlling real P-T reservoir conditions (P-T) and fluid composition. In this contribution, we present the experimental rig and methodology applied in our tests, and show some results of an ongoing flooding test through a sample from the Utsira sand formation at the Sleipner site.

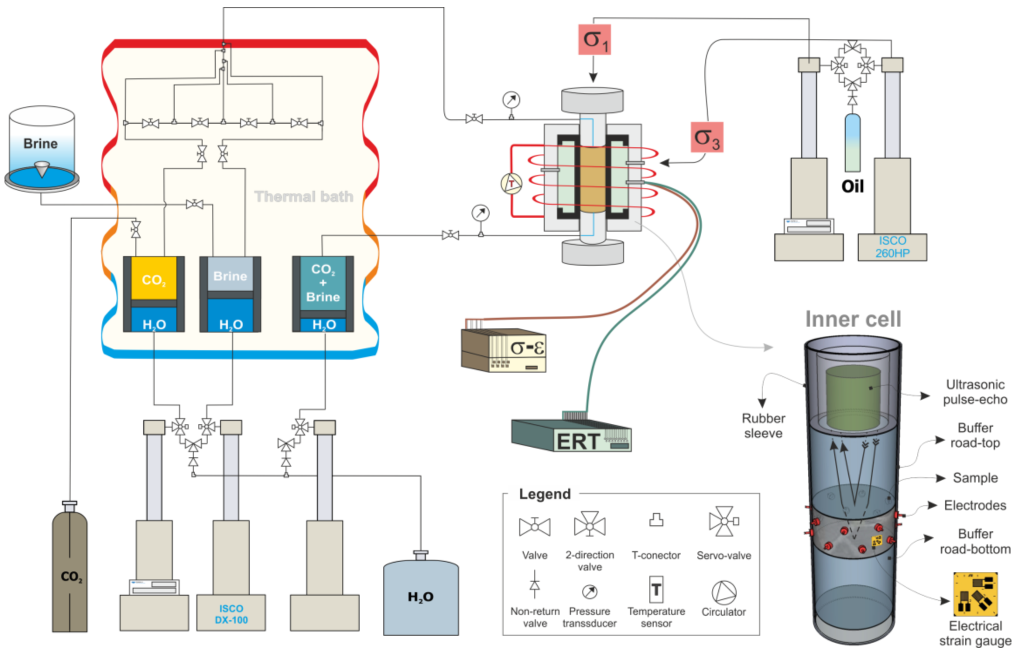

Figure 1. Experimental rig.

Experimental rig

Figure 1 shows a schematic diagram of our experimental rig, partially upgraded from the one presented by Falcon-Suarez et al. (2014). The rig is designed around a triaxial cell that allows rock samples to eb subjected to axial and lateral confining pressures (up to 69 MPa) using manual pressure controllers. Inside the triaxial cell, the rubber sleeve that isolates the core plug from the confining fluid (ideally mineral oil) is equipped with 16 electrodes for electrical resistivity tomography measurements (ERT), (North et al, 2013); strain gauges (350 Ohm) are also added on the sleeve-wall to measure axial and lateral strains during tests. Both signals are extracted via feedthrough connectors. The sample is in contact with the ultrasonic pulse-echo instrumentation – for measuring the ultrasonic velocity to a precision of ± 0.3% and the ultrasonic attenuation to a precision of ± 0.1 dB/cm (Best et al, 2007). The core plug is isolated from the rest of the rig and the ultrasonic transducer by two acrylic buffer roads. These buffer rods have well defined acoustic impedance and low loss, providing a delay path to enable the identification of top/base sample reflections for calculating velocity and attenuation. The buffer rods present pathways (in- and out-let ports) to conduct pore fluid through the sample. Up- and downstream, two piezo-resistivity pressure transducers (0 - 70 MPa Keller-Druck pressure transmitter) continuously monitor the pore pressure.

Pore fluids are transferred using high pressure pumping controllers (ISCO-EX100D) via fluid transfer vessels. The aim of these vessels is twofold: firstly, preventing potential damage to the controller due to the high corrosiveness of brine and CO_2; and secondly, heating the fluids up to target conditions by direct immersion into a thermal bath (up to 100 ˚C circulator). As a result, three vessels are connected to three pumping cylinders: two for transfer brine and CO_2 to the sample; the third to act as backpressure for controlling the pore pressure downstream of the sample. The brine and CO_2 hosting-cylinders are connected to a hydraulic circuit that spreads both fluids between 1 - 5 conduits, in such a way that the relative flow between them can be varied at 20% intervals. This has been specially designed to address relative permeability measurements.

Material and methods

As a part of a long-term experiment regarding a combined geophysical and hydro-mechanical study of the Sleipner site, we have prepared several samples from the Utsira sand formation, using trimmings from the Well 15/9-A-23 (1085 m to 1086 m). One of them was selected to conduct a sea water brine flooding test at reservoir conditions, attempting to simulate the original conditions of the reservoir before starting the CCS activities. The sample consists of 5 cm diameter, 2 cm length compacted fine-medium grain size, brine-satuarted sandstone, mineralogically composed of 75% quartz, 14% feldpar and minor content of albite, aragonite, mica and calcite (Chadwick et al, 2004), while the porosity was estimated to be 35 - 37%. The sample was firstly saturated in low-conductivity brine and frozen to facilitate the emplacement in the triaxial cell. Once inside the cell, it was hydrostatically confined at 16.4 MPa to replicate a nominal depth of 900 m in the reservoir; the pore pressure (Pp) was set at 7 MPa, and temperature kept at 33 ˚C. After 4 days of compaction and settlement, the temperature was set at 35 ˚C and the sample was subjected to an unload/loading sequence of effective pressure (P_{eff}), i.e., varying the pore pressure (P_p) in 1 MPa steps from 7 to 12 MPa (using sea water), while keeping confining pressure (hydrostatic conditions, i.e., $\sigma_{1=2=3}$) constant. For each step, permeability, electrical resistivity, ultrasonic wave velocity and attenuation, and strains, were measured.

Results and discussion

Figure 2 shows the preliminary results of the flooding test through the Utsira Formation sample. The graph combines geophysical (P-wave velocity and attenuation, and ERT) and hydro-mechanical (strains and permeability) information. The ultrasonic P-wave velocity (V_p) varies with P_{eff} while the attenuation (Q_p^{-1}) does the contrary.The S-wave signal was very weak, related to the low consolidation of sample grain contacts; therefore, S-wave information is unavailable in this study. The electrical resistivity decreases as a result of the flooding with sea water brine which replaces the original low-salinity brine used for saturating the sample. This process can be deduced from the 3D tomography presented for the start, mid-point and end of the test.

Strains measured by the strain gauges are consistent with P_{eff}. The deformation of the sample reaches a maximum in the beginning of the experiment, as well as the effective pressure. At each step, P_{eff} decreases and the sample tends to recover its original condition. However, the axial strain shows that the behaviour of the sample is far from elastic and permanent deformation can be observed under loading. The permeability is also influenced by P_{eff} variations, i.e., the higher the compression induced in the sample, the lower the permeability. Permeability varies from 1 - 4 Darcy, which is consistent with the data reported by Chadwick et al (2004).

The integration of the geophysical and the hydro-mechanical data aids interpretation of the phenomena occurring during flooding tests. In this particular case, only brine was used as pore fluid, but this is a valuable first step of the characterization. Hereafter, the same procedure is adopted and repeated, but the fluid composition will be varied by mixing CO_2 and brine in known proportions. However, the test also highlighted some gaps regarding the instrumentation and procedures that will be addressed. Accordingly, improved equipment and techniques will be implemented in the rig to accurately determined strains, and the failure of S-wave signals requires further investigation for possible solutions.

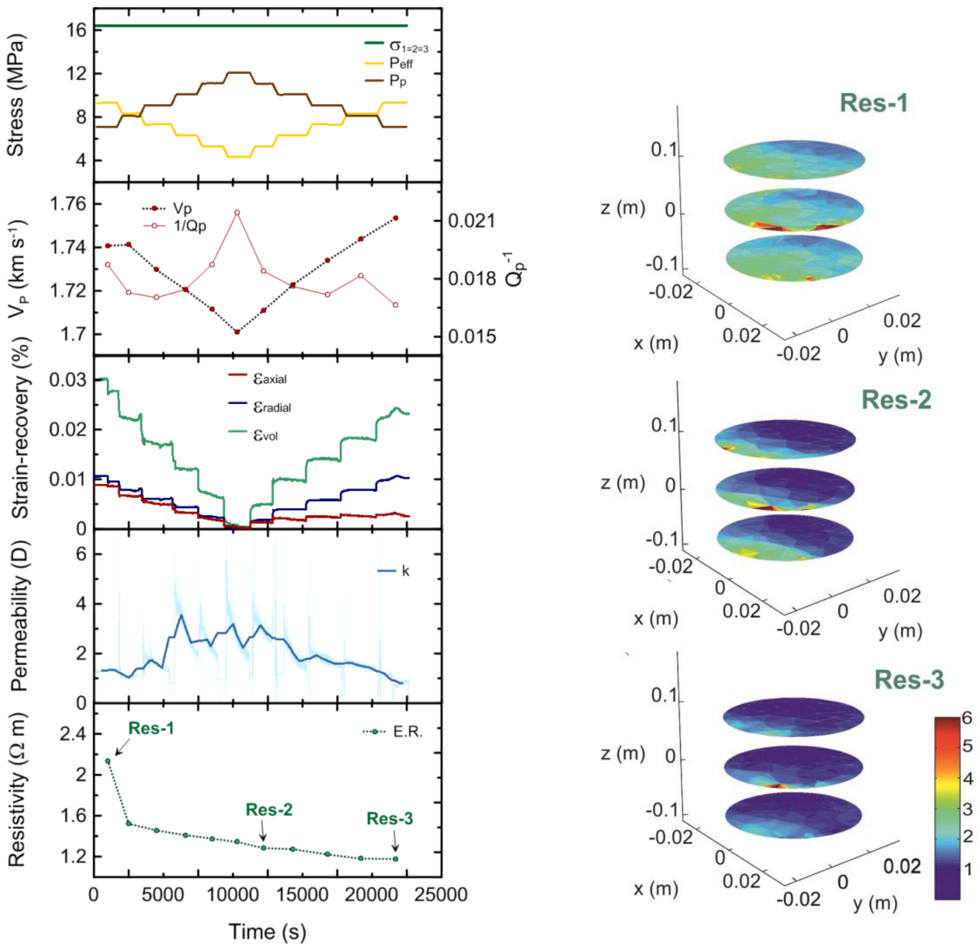

Figure 2. Left, geophysical monitoring and hydro-mechanical evolution of Utisira sand during the brine flooding test. Right, 3D-ERT of the sample in three test steps (Res-1, Res-2 and Res-3).

Acknowledgements

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