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Investigation of Geomechanical and Rock Physics Aspects Related to Underground Storage and Monitoring of CO_2

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ABSTRACT
This paper presents an overview of activities related to identifying and quantifying leakage risks as well as monitoring methods as applied to large scale, long term underground sequestration of CO_2. Here, the focus is on geo mechanical and rock physics related issues that are identified as major show stoppers for successful operations as well as potential monitoring methods in addition to surface seismic techniques. Laboratory experiments are made to investigate possible fracturing mechanisms around injection wells and stress change effects on sonic velocities in sealing overburden cap-rock associated with injection in an underlying reservoir. Numerical simulations investigate both the near-well region and large reservoir-scale, looking for relevant scenarios where stress changes can trigger fracturing, in particular, the sealing cap-rock.

INTRODUCTION

Mitigating climate change implies reducing dramatically the amounts of greenhouse gases in the Earth's atmosphere. In particular, many research projects target reducing the amount of CO_2, by targeting efficiency improvements leading to reduced CO_2 emissions and by attempting to capture the gas (e.g. from coal-fired power plants) before it is released to the atmosphere. An inevitable corollary to CO_2 capture is its disposal and hence, the research efforts are to be put in to identify suitable storage sites. In particular, the idea to enable large scale underground sequestration is gaining momentum, either in aquifers or depleted oil and gas reservoirs.

In order to successfully store CO_2 underground, it is imperative to be able to identify all risks that could lead to leakage and loss of containment. In addition, if a leak occurs, monitoring methods must be elaborated to provide early warning and enable efficient intervention. Reliable monitoring methods should also provide the means to quantify and locate stored CO_2 volumes. Two areas are identified as most problematic for storage, namely injection wells that contain sealing caprock. Loss of injectivity and failure of well barriers together with fracturing in the overburden are the most serious factors for loss of reservoir containment.

4D MONITORING TECHNIQUES AND CHALLENGES

Various monitoring techniques are envisaged to be used in the long term surveillance of a CO_2 injection storage site, such as repeated seismic surveys and frequent common source electro-magnetic (CSEM) surveys. The Combination of these two techniques will improve imaging resolution as will added sonic monitoring.

In order to improve 4D monitoring, fundamental understanding of the impact of fluid injection on the sonic velocity is required (e.g due to stress changes occurring in the reservoir and the overburden during injection of CO_2). These variations add to velocity changes caused by fluid substitution. The acoustic signature of both reservoir and overburden, at different locations, must be interpretable in terms of stress state, in particular in the overburden. This can help in determining whether the overburden strength is being exceeded and leakage becoming imminent. Both seismic frequency and sonic log interpretation for repeat surveys rely on knowledge of the elastic properties of the rock layers above, inside, below and around the storage reservoir. These will change with stress change and fluid saturation. It is thus expected that both the cap-rock and reservoir stress states will change with increase in the reservoir pore fluid pressure, itself accompanying CO_2 injection campaigns. Due to the limited extent and shape of the reservoir, these stress changes are complex and location-dependent.

The purpose of acoustic monitoring under injection of CO_2 in a reservoir is thus to map the acoustic signature of both reservoir and overburden rocks. The velocities measured must be interpreted in terms of corresponding stress state. Once the stress map is obtained, local values can be compared to the formation strength. If there is excess stress, a fracture may start developing from this location. This is particularly important for the overburden rock, right above the reservoir, since opening a fracture there implies loss of sealing of the reservoir with potential upwards migration of the stored CO_2 towards overlying aquifers and their contamination, let alone a worst case scenario with the CO_2 migrating all the way to surface.

Laboratory experiments have been performed with soft synthetic sandstone cemented under stress. Passive listening to sandstone rock plugs was achieved by using the

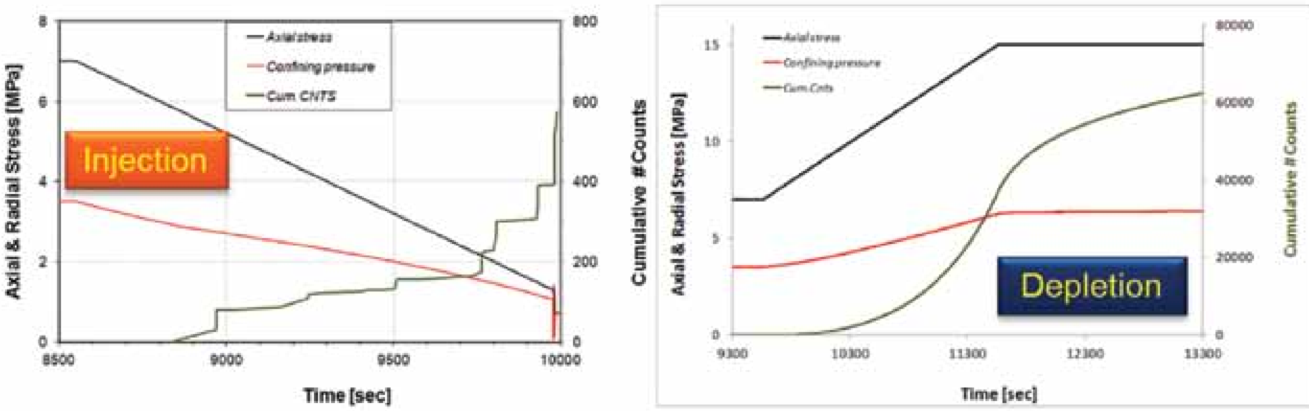

Figure 1. Acoustic emission counts for stress paths simulating injection of a pore fluid (left) and depletion associated with pore pressure decrease (right).

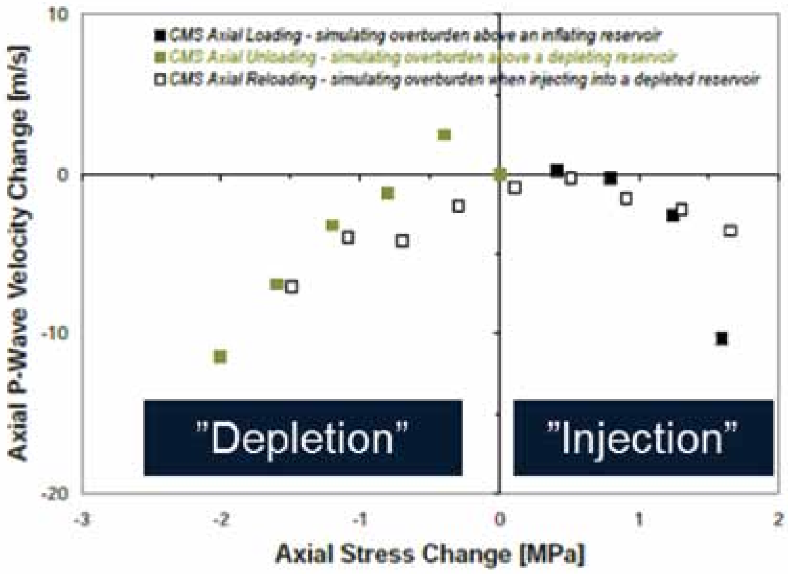

Figure 2. Experiments on compacted brine-saturated clay specimens to simulate low permeability cap-rock formations: transmitted sound velocity measurements for initial stress state and stress changes representative of those occurring in-situ during depletion of or injection into an underlying reservoir.

acoustic emission (AE) technique to monitor the stress state in an analogue to a reservoir rock as pore pressure changes (Gettemy and Holcomb, 2006). This technique captures the sonic bursts accompanying micro-fracturing events in the rock. Hysteresis behaviour was observed, where depletion-related compaction or even shear failure produced more AE events than injection-induced extension of the rock matrix (Fig.1). This is expected, since bulk rock behaviour during unloading is largely elastic and hence does not generate significant amount of AE. However, one will be able to pick up micro seismic events associated with fracturing or fault displacements induced by the injection process (Zoback, 2011), but most likely not their precursors.

The data demonstrate that non-elastic, grain-scale processes contribute to large acoustic emission (AE) activity during depletion-induced compaction and to significantly less but pronounced AE activity associated with injection-induced extension. Grain scale deformation mechanisms contribute to our understanding of rock failure processes at this scale. Experiments with transducer arrays to locate the fracturing events in space and waveform analysis to address focal mechanisms will be helpful in further studies along this line. Although failure mechanisms are largely scale invariant, the findings from this type of laboratory experiments cannot be directly transferred to complex field situations; laboratory data are useful for generating constitutive models for prediction of fracture initiation and growth under the right field conditions.Wave velocities

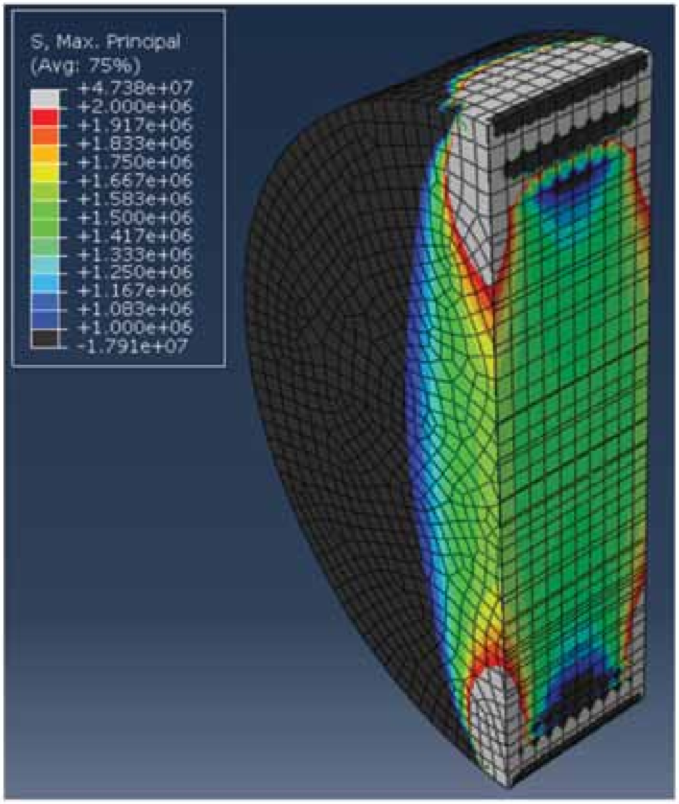

Figure 3. Tensile principal stress distribution in a steady-state simulation of a disk specimen placed between fixed pistons and heated from 0°C to 80°C.

in the synthetic sandstone are strongly stress dependent, in particular, implying a strong seismic velocity decrease during simulated injection (Holt and Stenebråten, 2013). Other experiments have been conducted on compacted brine-saturated clay specimens. These experiments simulated an initial stress state and stress changes representative of those occurring in-situ during depletion of or injection into an underlying reservoir. The results (Fig. 2) show that under injection conditions, the slow-down in sonic velocities serves as a signal when the cap rock is on the verge of failure, thus giving an early warning for a potential leakage.

THERMAL STRESS RISK ASSESSMENT

Injecting cold CO_2 into a warmer reservoir may create thermal contrasts all along the well trajectory (Krogh et al., 2012); in the worst case, the thermal stresses may induce tensile fracturing of the overburden in the immediate vicinity of the well, creating a leakage path. Another danger is the delamination or interface fracturing of the different layers around the injection well (metal casing, cement sheath and surrounding formation).

Numerical simulations confirmed that radial tensile fractures can be expected in the near-well area in shale layers adjacent to sandstone layers if the cooling is sufficient, typically by more than 50°C, for given, typical, rock properties (Hettema et al., 1992). The simulations indicate that tensile hoop stresses are likely to develop in the shale layers and be sufficiently high to generate radial tensile fractures in shale (Lavrov and Cerasi, 2013). It should be noted that 'shale' here means a rock with a relatively high thermal expansion coefficient, compared to 'sandstone' (Gilliam and Morgan, 1987).

A laboratory study of thermal fracturing in shale is initiated to investigate if and how such fractures can develop in shale. Since it is impractical to perform uniaxial test with cooling (instead of producing thermal cracks, the contracting sample will most likely separate from the loading pistons), a simple so-called Brazilian test is set-up, where the specimen is subjected to heating. In this test, also called indirect tensile test, a thin cylindrical sample is compressed axially inducing tensile fracturing in the disk's center. In the thermal version, tensile thermal stresses are generated in the central part of the disk, thus providing a laboratory model of the thermal cracking expected under in-situ cooling.

Finite element numerical simulations were performed to help plan the laboratory tests and showed that (Fig. 3), if the thermal state is allowed to equilibrate, heating from 0°C to 80°C is likely to produce tensile failure just as an ordinary (purely mechanical) Brazilian test would. The remaining question is whether such fracturing in shale would propagate far enough to be of concern in terms of initiating a leakage out of a storage site. These simulations show that thermal stresses are of concern for liquid CO_2 injection, but probably not relevant for injection of a gas, although this conclusion depends on tensile strength and thermal property variations.

CONCLUSION

The importance of sound geo mechanical analysis is getting more and more recognized. A certified CO_2 storage site in terms of sufficient capacity may still not be satisfactory due to concerns of fracturing risk and leakage. SINTEF is involved in research on several fronts concerning monitoring and qualification of storage sites. This includes laboratory work addressing fracturing and 4D rock physics aspects. Ongoing research activities include simulation work supplementing laboratory findings, and upscaling to field conditions. Near-well integrity issues and reservoir scale fracture risks are at the centre of both laboratory and simulation efforts.

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