Preliminary Report on Hydration-Induced Swelling of Shale in the Horn River Basin, Northeastern British Columbia

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Introduction

In the past decade, multistage hydraulic fracturing has become an essential completion technique, resulting in prolific development of low-permeability sandstone and shale reservoirs. Although such reservoirs are found to be abundant in many parts of the world, most of the developed ones are found in major North American basins (Energy Information Administration, 2013; Charlez, 2015). The practice of multistage hydraulic fracturing involves pumping water- or oil-based fluids at high pressure to create fracture networks in low-permeability rocks. As a result, a significant amount of water is used in such an operation (King, 2012, 2014). The range in volumes of water used for fracturing treatments varies significantly among formations. However, it is widely reported that up to 80% of the water pumped during a fracturing treatment is typically not recovered when the well is put back on production (Fan et al., 2010; King, 2012; Tipton, 2014).

Poor water recovery is attributed partly to spontaneous or forced imbibition of water into the rock matrix and clay system, particularly in clay-rich rocks (Makhanov et al., 2012; Roychaudhuri et al., 2013; Lan et al., 2014). Major mechanisms responsible for the spontaneous water uptake by shale rocks are high capillary suction (due to nanometre-size pores) due to sub-irreducible water saturation, diffusion, advection and surface-osmotic hydration (Al-Bazali, 2005; Zhang, 2005; Ghanbari, 2015; Roshan et al., 2016). Clay-rich shale can act as a membrane when immersed in water with lower ion concentration. This produces an osmotic potential (Zhang et al., 2004; Al-Bazali, 2005; Ghanbari and Dehghanpour, 2014). In addition to osmosis, diffusion results in ion transport in and out of the shale rock (Al-Bazali, 2005; Zhang, 2005; Ghanbari, 2015). This causes a change in electrical conductivity of the fluid.

Earlier studies examined the physicochemical changes that occur as a result of clay hydration in shales, but mostly in the context of drilling engineering. Chenevert (1970) conducted a comprehensive study on hydration of shales from various formations in the United States. He found that hydration of shales resulted in tensile stress and expansion in all rock samples. Adsorption of water by clay minerals also reduced the overall strength in his shale rock samples, which can be detrimental for wellbore-stability applications (Chenevert, 1970; Bol et al., 1994). In subsequent studies on shale hydration, researchers developed swelling or hydration indices to compare the swelling potential of various shales (Bol, 1986; Hayatdavoudi, 1999).

Recent studies have also connected the concept of clay hydration to wettability. Significantly higher uptake of water than of oil by oil-wet gas shales of the Horn River (HR) Basin has been attributed to water adsorption by clay minerals (Dehghanpour et al., 2012; Dehghanpour et al., 2013). Anisotropy in water imbibition, swelling stress and expansion, have also been shown as characteristics of laminated mudstones (Ghanbari and Dehghanpour, 2014; Makhanov et al., 2014). Furthermore, fabric changes, such as induced tensile microfractures and sample expansion have also been observed during imbibition (Dehghanpour et al., 2013; Ghanbari and Dehghanpour, 2014; Yang et al., 2015). Ghanbari and Dehghanpour (2014) reported a reduced spontaneous imbibition of water into samples confined with epoxy, raising questions on how much tensile stress and resultant expansion can be generated from hydration.

Furthermore, in the context of geomechanics, rock elastic properties (Young's modulus and Poisson's ratio) from laboratory compression tests are widely used as key inputs in creating hydraulic-fracture design models (Lacy, 1997; Dunphy and Campagna, 2011; Dong, 2016). However, most compression tests for unconventional rock samples in

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the laboratory still follow the workflow for conventional rocks. This workflow does not account for hydration-induced tensile stresses due to clay swelling. Incorporating hydration-induced stress and strain into geomechanical models can result in more realistic models for hydraulic fracturing.

Research Objectives

The goals of this study are to 1) extend previous work on water uptake of HR Basin shales and quantify its hydration-induced stress and expansion characteristics, 2) investigate the effects of fluid chemistry on water uptake and swelling, and 3) investigate the effects of hydration-induced stress and strain on enhancement of hydrocarbon production. In this paper are presented the preliminary results of the most direct measurements of hydration-induced tensile stress and strain in HR Basin shales.

Methodology

A three-step approach is taken to investigate the effects of hydration in the rock samples. Total water uptake by gas shales is due to a combination of high capillarity of nanopores and adsorption by clay minerals (Dehghanpour et al., 2012). Hence, all measurements will be linked to spontaneous imbibition and rock-mineralogy data.

In the first phase, spontaneous water- and oil-imbibition experiments are conducted on the shale samples. The purpose of the water-imbibition experiments is to obtain a relationship between the amount of ions that leach out of the sample and the mass of fluid that imbibes into the sample. By recording the imbibed mass and change in electrical conductivity, an imbibed mass–electrical conductivity crossplot (IM-EC crossplot) can be created to be used in phase 3. Imbibition and electrical conductivity are normalized to the mass of rock sample used. Comparisons are made between the imbibition of water and oil.

In the second phase, the expansion of the shale samples is measured during imbibition. During water imbibition, expansion is measured parallel and perpendicular to the plane of lamination, whereas expansion is measured only perpendicular to the plane of lamination for oil imbibition. This test does not restrain the sample, meaning the sample is free to expand during imbibition in customized imbibition cell 1 (described in the 'Materials and Equipment' section). Strain is computed from the displacement (as measured) and original length of the rock sample. The imbibition data from phase 1 are used to correlate the strain with the imbibed mass of fluid.

During the third phase, the hydration-induced tensile stress is measured in the samples when they are immersed in deionized water. Customized imbibition cell 2 (described in the 'Materials and Equipment' section) allows for the restriction of axial expansion and concurrent measurement of the expansive force generated by rock samples during imbibition of water. This test gives the hydration-induced tensile force with respect to the soaking time. Axial stress is computed from the force (as measured by the load cell) and the cross-sectional area of the rock sample. This phase will be extended by measuring the hydration-induced tensile stress (and change in water-uptake profile) of rock samples subjected to a constant axial compressive load during imbibition.

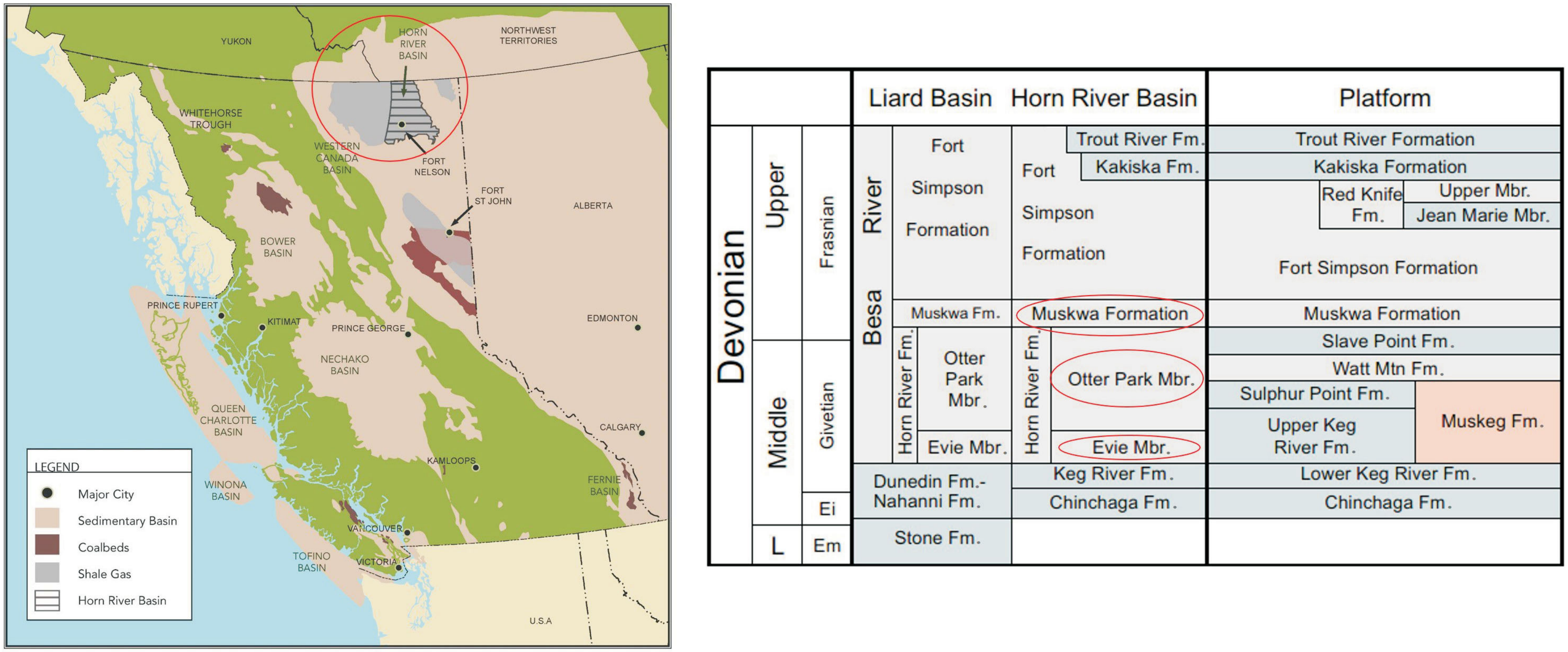
Since the sample is under an axial restraint, further fluid imbibition may be hindered as tensile force accumulates (Chenevert, 1970; Ghanbari and Dehghanpour, 2014). As a result, the imbibition profile in this test may not resemble that of a sample under zero accumulated-stress conditions (phase 1). Therefore, it is also of interest to determine the imbibed fluid mass that results in the recorded tensile force. However, the rock samples cannot be removed from the cell during the tests in this phase because that would create perturbation in the state of stress. To mitigate this problem, the electrical conductivity of the aqueous phase surrounding the rock sample in the imbibition cell is measured periodically. Subsequently, the electrical conductivity (normalized to the mass of the rock sample) is correlated with the imbibed mass of water using the IM-EC crossplot from phase 1.

Materials and Equipment

Core Samples

The core samples used in this study come from a well drilled in the Horn River Basin of northeastern British Columbia (BC). Figure 1a shows a geographic overview of Western Canada, indicating the Horn River Basin. Figure 1b shows the major formations of the Middle Devonian Elk Point Group in the Horn River Basin, with the three zones of interest outlined in red.

Tests are planned on rock samples from two formations of the Horn River Basin: the Muskwa (MU) and Horn River (HR) formations (Figure 1b). The Muskwa Formation is a siliceous pyritic shale with moderate to high total organic carbon (TOC). The Horn River Formation is further divided into the Otter Park (OP) and Evie (EV) members, both of them mid-Devonian shale units (Mossop and Shetsen, 1994; Hulsey, 2011; BC Oil and Gas Commission, 2014; Dong, 2016). The OP is a medium- to dark-grey, slightly calcareous mudstone with a lower TOC than the EV (McPhail et al., 2008). The EV is a dark grey to black shale with a higher average TOC than the MU and OP (Mossop and Shetsen, 1994; McPhail et al., 2008; Hulsey, 2011; BC Oil and Gas Commission, 2014; Dong, 2016). All MU and HR shales are brittle and exhibit strong fissility, mostly along the plane of lamination (Figure 2).



(a) (b)

Figure 1: a) Location of the Horn River Basin in northeastern British Columbia (modified from BC Ministry of Energy and Mines and National Energy Board, 2011). **b)** Partial stratigraphic table of the Middle Devonian period in the Horn River Basin (modified from Ferri et al., 2011); Muskwa Formation and Otter Park and Evie members outlined in red. *Abbreviations: Ei, Eifelian; Em, Emsian.*

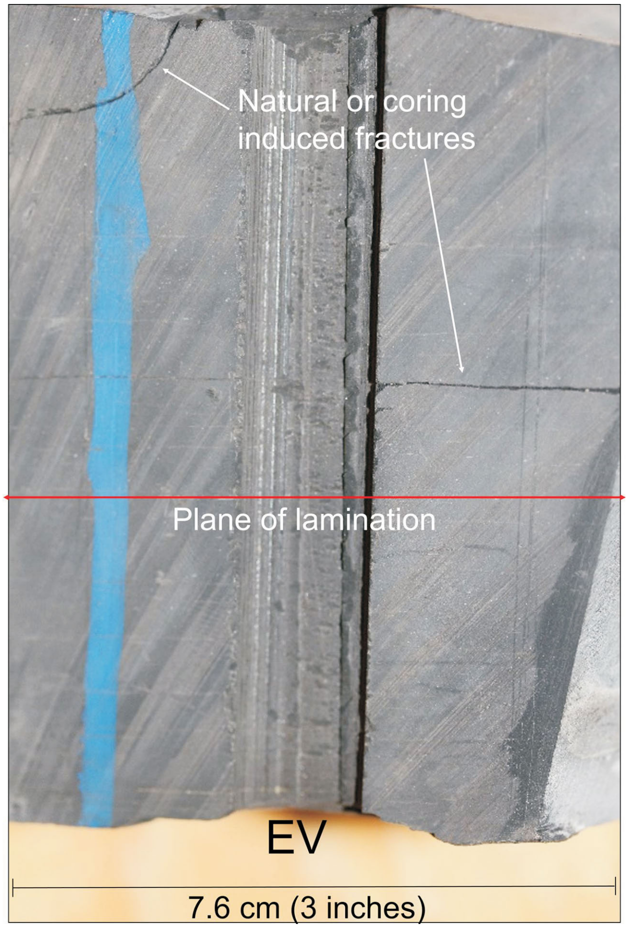


Figure 2: Shale sample from the Evie (EV) Member of the Horn River Formation, showing fissility along the plane of lamination, and natural and induced fractures.

Twenty-one samples are to be used in this study (seven each from the MU, OP and EV). Table 1 gives the depth, porosity and permeability for each sample. Representative mineralogy of powdered rock measured by X-ray diffraction (XRD) is shown in Table 2.

Rock samples used in all phases of this study were oven dried at 250°F to evaporate both capillary and clay-bound water (Luffel and Guidry, 1992). This ensures that all samples start at a similar water saturation (as capillary water evaporates first, followed by the water molecules electrostatically bound to the clay). Early water uptake by dried samples results from a combination of capillarity and adsorption by clay minerals. Hence, the oven-dried state of the samples provides the opportunity to capture the trends of imbibition and hydration swelling early in the soaking process.

Equipment

During the first phase, imbibition cells (Figure 3) are used to fully immerse the rock sample in water. A portable electrical-conductivity meter and mass balance are used to record the electrical conductivity and mass, respectively, of the rock sample during imbibition.

In the second phase, the rock sample is placed inside the glass chamber of a customized imbibition cell 1 (CIC-1; Figure 4), which is then filled with fluid until the rock is completely submerged. This cell is equipped with a linear variable differential transformer (LVDT) mounted on the side wall of the imbibition chamber. Stabilizer mounts prevent lateral movement of the rock sample. Any axial expan-

Table 1: Approximate depth, porosity and permeability of samples used in this study.

Sample ID	Approximate depth (m)	Formation/ member	Average porosity (%)	Average permeability (nD)
MU-1 MU-2 MU-3 MU-4 MU-5 MU-6 MU-7	2610	Muskwa	2.92	180
OP-1 OP-2 OP-3 OP-4 OP-5 OP-6 OP-7	2617	Horn River / Otter Park	3.25	271
EV-1 EV-2 EV-3 EV-4 EV-5 EV-6 EV-7	2681	Horn River / Evie	4.17	384

Table 2: Representative mineralogy of powdered shale samples from the Muskwa Formation (MU) and the Evie (EV) and Otter Park (OP) members of the Horn River Formation, as measured by X-ray diffraction.

Sample	Mineral (wt. %)								
	Quartz	K-feldspar	Plagioclase	Carbonate	Pyrite	Illite/smectite	Illite/mica	Kaolinite	Total clay
MU	65	3	3	10	3	5	11	0	16
EV	52	5	6	16	3	7	12	0	19
OP	76	0	3	6	3	4	9	0	13

sion exhibited by the rock causes a displacement of the LVDT core. The LVDT and its data acquisition system are set to acquire the displacement data every 10 seconds.

For the third phase, a specialized setup (customized imbibition cell 2) was designed to measure the hydration-induced tensile stress during spontaneous imbibition of fluid (Figure 5). Customized imbibition cell 2 (CIC-2) consists of an imbibition cell housed inside a load frame. The rock sample is placed in the imbibition cell filled with water. The sample is overlain by a circular spacer disk and a circular through-hole load cell. The spacer disk prevents rusting and damage to the load cell by eliminating direct physical contact between the fluid and the load cell. The shaft of the load frame firmly attaches into the through-hole load cell. At this point, from bottom to top, the rock sample, spacer disk, load cell and shaft are in rigid vertical alignment. This system prevents any axial expansion of the rock sample during the tests. Axial restraint at the top and bottom ends of the rock sample allows the swelling force generated within the rock sample to be directed toward the load cell. In addition to the axial restraint, the load frame allows for a constant compressive load to be applied to the rock sample through controlled downward motion of the shaft. Once the desired compressive load is reached, the shaft remains locked in position until manually unscrewed. The data acquisition system and associated computer program are set up to acquire the force on the load cell every 10 seconds. The portable electrical-conductivity meter from phase 1 is used to periodically measure the electrical conductivity of the fluid.

Experiments

This section describes the experiments for each phase. Table 3 summarizes the experiments to be performed on each rock sample.

Phase 1

Spontaneous imbibition experiments are conducted with water and kerosene on nine shales samples (three each from MU, OP and EV) for 7 days, to obtain three sets of imbibition data. The first and second sets of data (with water and kerosene, respectively) are used in conjunction with the free-expansion results (phase 2). The third set of imbibition data (with water), which includes electrical conductivity of the fluid, is used in phase 3.

Phase 2

Three sets of free-expansion experiments are conducted on MU, OP and EV rock samples. The first and second sets of experiments are carried out with water and kerosene, re-

Figure 3: Imbibition cells used in phase 1. Rock samples were immersed in aqueous or oleic phases. Change in mass of the rock samples and electrical conductivity of the fluid (for aqueous-phase experiments) were recorded periodically.

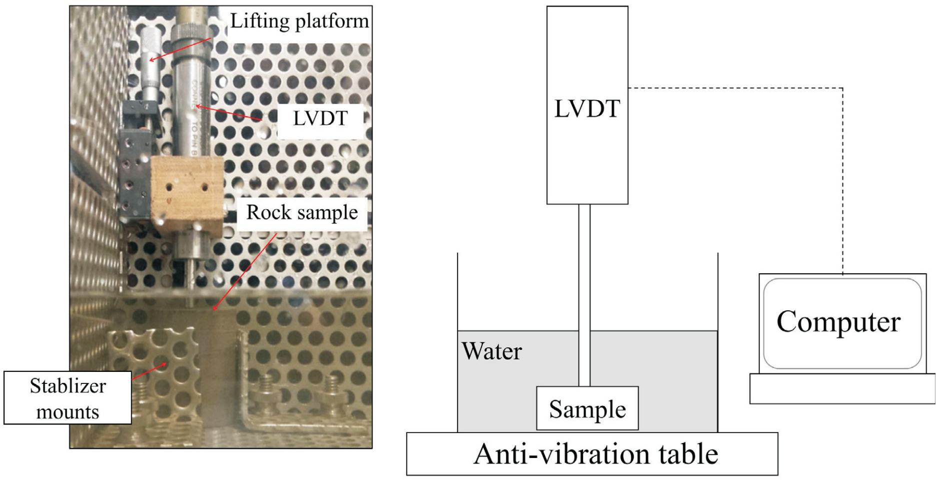
spectively. Rock samples are placed in the customized imbibition cell 1 such that planes of lamination are horizontal. Hence, the LVDT measures axial expansion along the direction perpendicular to the plane of laminations. The third set of experiments, carried out with water, are rotated 90° to align the axis of LVDT parallel to the plane of laminations. This arrangement measures axial expansion parallel to the plane of laminations.

Phase 3

One sample each from MU, OP and EV is tested for hydration-induced tensile stress. Force is measured in the direction perpendicular to the plane of laminations.

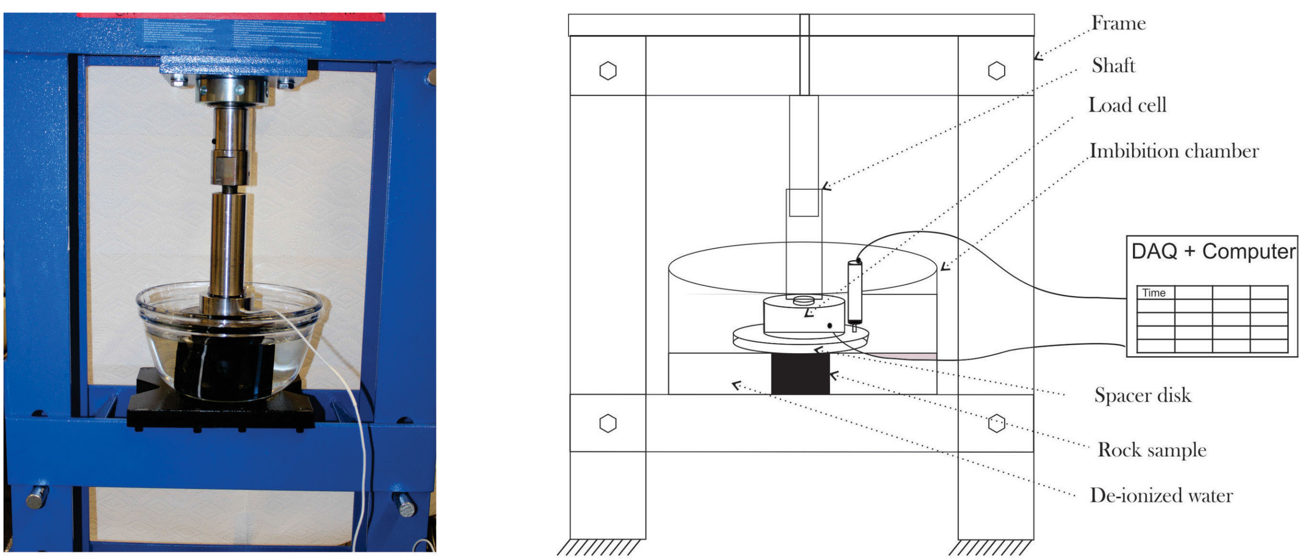
Preliminary Results and Future Work

From the rock samples tested thus far, it is apparent that imbibition-induced microfractures observed in previous stud-



(a) (b)

Figure 4: Photo **(a)** and schematic diagram **(b)** of customized imbibition cell 1, used in phase 2 of this study. The linear variable differential transformer (LVDT) records the axial displacement of the rock sample during imbibition.



(a) (b)

Figure 5: Photo **(a)** and schematic diagram **(b)** of customized imbibition cell 2, used in phase 3 of this study. The load cell measures the expansive (tensile) force generated by the rock sample during imbibition.

Table 3: Experiments to be performed on each rock sample.

Sample ID	Experiment	Test direction	Fluid
MU-1	Imbibition	-	Water
MU-2	Imbibition	-	Oil
MU-3	Imbibition + conductivity	-	Water
MU-4	Hydration stress	Perpendicular to lamination	Water
MU-5	Free expansion	Perpendicular to lamination	Water
MU-6	Free expansion	Perpendicular to lamination	Oil
MU-7	Free expansion	Parallel to lamination	Water
OP-1	Imbibition	-	Water
OP-2	Imbibition	-	Oil
OP-3	Imbibition + conductivity	-	Water
OP-4	Hydration stress	Perpendicular to lamination	Water
OP-5	Free expansion	Perpendicular to lamination	Water
OP-6	Free expansion	Perpendicular to lamination	Oil
OP-7	Free expansion	Parallel to lamination	Water
EV-1	Imbibition	-	Water
EV-2	Imbibition	-	Oil
EV-3	Imbibition + conductivity	-	Water
EV-4	Hydration stress	Perpendicular to lamination	Water
EV-5	Free expansion	Perpendicular to lamination	Water
EV-6	Free expansion	Perpendicular to lamination	Oil
EV-7	Free expansion	Parallel to lamination	Water

ies can, in fact, result in measurable expansion of rock samples. Strain of up to 0.75% is observed in the free-expansion imbibition cell (CIC-1). Expansion anisotropy is observed in directions parallel to and perpendicular to the plane of lamination. When the expansion is restricted, tensile stress of up to 18 psi accumulates in the samples, due to hydration (CIC-2). Rock samples will be tested under various added axial-compressive loads to investigate any changes in water-imbibition behaviour and accumulation of tensile stress. More samples will be incorporated into this study to assess the effect of fluid salinity on imbibition, expansion and tensile stress. It is projected that the work will be concluded by August 2017.

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