Evidence of localised gas propagation pathways in a field-scale bentonite engineered barrier system; results from three gas injection tests in the Large scale gas injection test (Lasgit)

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Three gas injection tests have been conducted during a large scale gas injection test (Lasgit) performed at the Äspö Hard Rock Laboratory, Sweden. Lasgit is a full-scale experiment based on the Swedish KBS-3 repository concept, examining the processes controlling gas and water flow in highly water-saturated compact buffer bentonite. Three preliminary gas injection tests have been performed. The first two tests were conducted in the lower array of injection filters (FL903). Both of these tests showed similar behaviour that corresponded with laboratory observations. The third gas test was conducted in an upper array filter (FU910), which gave a subtly dissimilar response at major gas entry with an initial pressure drop followed by a secondary gas peak pressure. Lasgit has confirmed the coupling between gas, stress and pore-water pressure for flow before and after major gas entry at the field scale. All observations suggest mechanisms of pathway propagation and dilatancy predominate. In all three gas tests the propagation was through localised features that tended to exploit the interface between the copper canister and the bentonite buffer. Considerable evidence exists for the development of a highly-dynamic, tortuous network of pressure induced pathways which evolves both temporally and geospatially within the clay, opening and closing probably due to local changes in gas pressure and or effective stress.

Highlights:

- Gas testing at a less-well hydrated location resulted in different behaviour at gas entry.
- Gas migrated through a localised network of gas pathways.
- Coupling between gas, stress and pore water pressure demonstrated at the repository scale.

Keywords

Gas flow; Äspö Hard Rock Laboratory; bentonite; KBS-3; Lasgit

1.0 Introduction

In the Swedish KBS-3 disposal concept for radioactive waste (SKB, 2009), copper canisters, with a steel insert, containing spent nuclear fuel will be placed in deposition holes (~ 2 m diameter) drilled into the floor of the repository tunnels. The space around each canister will be filled with pre-compacted bentonite blocks which, over time, will draw in the surrounding groundwater and swell, closing any construction gaps. Once hydrated, the bentonite will act as a low permeability diffusional barrier, severely limiting the migration of any radionuclides released from the canister after closure of the repository. While the waste canisters are expected to have a very substantial lifespan within the repository environment, it is important for purposes of performance assessment to consider the impact of groundwater penetration of one of the canisters. Corrosion of ferrous materials under anoxic conditions, combined with the radioactive decay of the waste and the radiolysis of water, will lead to the formation of hydrogen. If the rate of gas production exceeds the rate of gas diffusion within the pores of the barrier or host rock, a discrete gas phase will form and accumulate in the void space of the canister (Horseman, 1996; Horseman *et al.*, 1997; 1999; Weetjens & Sillen, 2006; Ortiz *et al.* 2002; Wikramaratna *et al*., 1993; SKB, 2011). Gas will then enter the bentonite when the gas pressure exceeds some critical entry pressure specific to this material. Since water penetration of the canister is a prerequisite for the generation of hydrogen gas in the buffer, the timing of gas movement in the clay might coincide with that of radionuclide release into the buffer. The possibility of an interaction between gas and radionuclide migration therefore emerges as an important issue in performance assessment.

The quantitative treatment of gas migration in compact clays is a highly complex issue (Rodwell *et al*, 1999). A number of laboratory studies of gas migration in repository buffer clays have been undertaken. These experiments have focussed on gas movement in initially saturated material (Donohew *et al*., 2000; Harrington & Horseman, 1999; Harrington & Horseman, 2003; Horseman & Harrington, 1994; Horseman *et al.,* 1999; Horseman *et al.,* 1999; Hume, 1999; Ortiz *et al.,* 1997; Tanai *et al*., 1997) and in unsaturated clays (Gallé, 1998; Gallé *et al.,* 1998; Gray *et al.,* 1996; Hume, 1999; Tanai *et al.,* 1997). Results from these studies indicate breakthrough pressure is strongly dependent on the degree of water saturation of the bentonite. At water saturations less than 70% (Tanai *et al.*, 1997) to around 80 – 90% (Hume, 1999), clay, such as bentonite, contains an interconnected network of air voids resulting in little or no pressure threshold for gas flow. As full saturation is approached, gas entry and breakthrough pressures increase rapidly (Gray *et al.,* 1996; Hume, 1999). Horseman *et al.* (1999) questioned whether gas flow occurred through the original porosity of the clay or through a network of crack-like pathways which opened and closed dependent on the magnitude of the gas pressure. Experiments reported by Donohew *et al*. (2000) on low density pastes indicate that a saturated clay must dilate (i.e. grow in volume) during gas entry and the initial changes in gas content are accommodated by an increase in the total volume of the clay. Although this is consistent with gas flow through a network of pressure-induced pathways, it cannot be reconciled with the more usual soil mechanics concept of desaturation by direct displacement of porewater. If all gas in the clay is accommodated by dilatancy, this raises the important question of sensitivity of the gas transport process to the boundary conditions of an experiment (Horseman *et al*., 1999).

While significant improvements in our understanding of the mechanisms governing gas migration in buffer bentonite have taken place, laboratory experiments (Horseman *et al.*, 2004) have highlighted a number of significant uncertainties, notably the sensitivity of the gas migration process to experimental boundary conditions and possible scale-dependency of the measured responses. As determined by Sellin & Harrington (2006), these issues are best addressed by undertaking a large scale gas injection test, or "Lasgit"; where large refers to a full-scale KBS-3 demonstration.

2.0 Experimental concept

Lasgit is a full-scale demonstration experiment operated by Svensk Kärnbränslehantering AB (SKB) at the Äspö Hard Rock Laboratory (HRL) at a depth of 420 m (Figure 1). The installation phase of Lasgit was undertaken from 2003 to early 2005 and consisted of the design, construction and emplacement of the infrastructure necessary to perform the experiment (Harrington *et al.*, 2007; Cuss *et al.*, 2010). The experiment was initiated on 1st February 2005 following the closure of the deposition hole.

The original aim of the Lasgit experiment was to perform a series of gas injection tests through water-saturated clay in a full-scale KBS-3 deposition hole. The objective of the experimental programme was to provide quantitative data to improve process understanding and test/validate modelling approaches used in repository performance assessment. Specific objectives included: perform and interpret a series of large-scale gas injection tests based on the KBS-3 repository design concept; examine issues relating to up-scaling and its effect on gas movement and buffer performance; provide information on the processes governing gas migration; and provide high-quality test data to test/validate modelling approaches. In essence, the Lasgit experiment consists of three operational phases: an installation phase, a hydration phase and a gas injection phase. The initial hydration phase began on 1st February 2005 with the closure of the deposition hole. The primary aim of this phase of the experiment was to fully saturate and equilibrate the bentonite buffer. The saturation and equilibration of the bentonite was monitored by measuring pore pressure, total pressure and suction at both the buffer/rock interface and key locations within individual clay blocks (see Figure 2). The hydration phase provided an additional set of data for thermo-hydro-mechanical (THM) modelling of water uptake under isothermal conditions in a bentonite buffer. When the buffer was considered to be fully hydrated, based on attaining stress and hydraulic equilibrium, the main gas injection phase would start. A series of detailed gas injection tests were to be performed and the processes and mechanisms governing gas flow under water saturated conditions in the bentonite would be examined. However, given the length of time required to equilibrate such a large quantity of clay (~ 25 tonnes), it was decided to augment the data by performing a series of preliminary gas and hydraulic measurements, undertaken at regular intervals in order to examine the effect of buffer maturation on the hydraulic and gas transport parameters of the buffer.

2.1 Experimental geometry

The Lasgit experiment was commissioned in deposition hole DA3147G01, which was the first emplacement borehole to be drilled at the Äspö HRL. The deposition hole is vertical, and has a length of 8.5 m and a diameter of approximately 1.75 m. Prior to the emplacement of Lasgit, the deposition hole was fully mapped (see Cuss *et al.*, 2011). The emplacement hole was capped by a conical concrete plug retained by a reinforced SS2172 carbon steel lid capable of withstanding over 5000 kN force. A full-scale KBS-3 copper canister with iron insert was modified for the Lasgit experiment with thirteen circular filters of varying dimensions located on its surface in three separate arrays (see Figure 2), to provide point sources for gas injection simulating potential canister defects. These filters could also be used to inject water during the hydration stages to help locally saturate the buffer around each test filter. As seen in previous field-scale studies, such as FEBEX (Huertas *et al.*, 2005), high water saturations in bentonite (> 95%) can take a considerable time to achieve. As a consequence, filter mats were placed in strategic positions both within the buffer and on the rock-wall to aid hydration. The canister was surrounded by specially manufactured pre-compacted bentonite blocks, all of which had initial water saturations in excess of 95 % (Cuss *et al.*, 2010). In the engineering void between the pre-compacted bentonite rings and the rock-wall, bentonite pellets were used. As the bentonite system began to saturate these swelled to fill the construction gaps and form a seal around the canister.

The deposition hole, buffer and canister were equipped with instrumentation to measure the total stress, pore-water pressure and relative humidity in 32, 26 and 7 positions respectively (see Figure 2 for the location of selected sensors). Additional instrumentation continually monitored variations in temperature, relative displacement of the lid and canister, and the restraining forces on the rock anchors. The experiment was monitored and controlled from a temperature controlled gas laboratory that allowed remote control and monitoring of the test. Figure 1 shows a photograph of the test site following the installation stage.

The boundary conditions of the experiment were those dictated by the pressures and stresses building up naturally within the bentonite buffer during re-hydration. The canister lid had been pre-stressed to 1300 kN to impose a similar force comparable with that which would be generated by the back-fill placed within the gallery above each deposition hole in a geological disposal facility. The experiment was conducted at ambient temperatures. The experiment is on-going and is expected to last a minimum of 10 years in total. The full test history to date is summarised in Table 1. The first 2 two-gas injection tests were conducted in a filter on the lower canister array (FL903; see Figure 2) in 2007 and 2009/10 and are described in Cuss *et al.* (2010; 2011). The key results from these tests are described below.

3.0 Results

The deposition hole was closed on 1st February 2005 with artificial hydration beginning 106 days later on 18th May 2005. The first preliminary gas injection test began on Day 813, in filter FL903 (see Figure 2) located on the lower array, as data indicated this section of the clay was more mature, i.e. exhibited higher swelling pressures and was in close proximity to the natural and artificial hydration sources, than the overlying material. The second preliminary gas injection test began on Day 1430, again in filter FL903. The third preliminary gas injection test began on Day 2072, in filter FU910 in the upper array of filters, in order to examine a location with a different hydration state. In all tests a known initial volume of gas was introduced to a 4.5 litre interface vessel. Water was pumped into the bottom of the interface vessel at a constant rate in order to steadily raise the gas pressure.

3.1 Gas injection test 1 (Day 813 – 1110)

The first preliminary gas injection test began on Day 813 in filter FL903. Pressures within the deposition hole and bentonite had increased substantially following the closure of the deposition hole and resulting hydration of the bentonite, with the average axial stress (monitored at separate locations throughout the clay) being around 4.9 MPa, the average radial stress (measured at the rock wall) being close to 4.0 MPa, the average total stress acting on the canister being around 4.2 MPa, the average porewater pressure (measured at the rock wall) being approximately 1.76 MPa and the average porewater pressure in the bentonite being around 0.26 MPa. Following a two-stage constant head test to determine the hydraulic properties of the buffer at FL903, gas (helium[1]) testing began on Day 917 with the introduction of an initial gas volume of 1.26×10^{-3} m^3 into the test system. This was slowly compressed raising the gas pressure in FL903, Figure 3a. Inspection of the graph indicates that during the first gas pressurisation event (Days 917 to 930), the measured pressure began to depart from the predicted pressure derived from the ideal gas law; this occurred at around

[1] Helium is used as a safe substitute for hydrogen (i.e. non-flammable), as the molecular diameters are comparable

Day 924. As gas pressure continued to increase, the departure in predicted versus measured gas pressure continued and was interpreted as gas penetration of the buffer. Analysis of the data suggests that gas flow into the buffer occurred at a pressure of about 0.65 MPa. This is much lower than the anticipated gas entry pressure for a saturated intact bentonite (Harrington & Horseman, 2003). Assuming an incomplete hydration state of the buffer and the heterogeneous nature of the stress field within the clay, it seems probable that the gas was exploiting these differences and was not penetrating fully resaturated bentonite. However, when gas pressurisation was stopped at Day 930 and the pressure held constant, flow into the clay dramatically reduced by around 98.5%, indicating that propagation of the main gas pathway(s) practically ceased when the pressure was held constant. The small continuous flux observed following this event may stem from the movement of gas along small-scale features which are only present because the bentonite was not fully mature. If correct, these fluxes should reduce in magnitude during later tests as the buffer equilibrates. Given the sudden reduction in flow, it suggests that gas failed to locate an adequate sink capable of accommodating the small in-flow of gas.

When gas pressurisation was reinstated on Day 952, the departure between measured and predicted gas pressure continued almost immediately (Figure 3b), indicating that the previous network of gas pathways continued to extend as soon as the pressure began to increase. Gas flow into the clay gradually increased with time until Day 970, at which point there was a marked increase in flow. This occurred when the gas pressure was marginally greater (by approximately 0.2 MPa) than the local total stress measured on the rock wall, but was marginally smaller (around 0.25 MPa) than the radial stress measured some distance away on the canister surface at PC903. Axial stress measured at PB902 was also marginally higher than the gas pressure, by around 0.3 MPa. Gas pressure continued to increase reaching a peak pressure of 5.66 MPa at Day 972.3. This was followed by a small spontaneous negative transient leading to a quasi-steady state at a gas pressure of around 5.5 MPa. Examination of the post peak gas flux shows it exhibits dynamic behaviour (over- and under-shooting flux into the system), suggestive of unstable gas flow. These observations are qualitatively similar to results reported by Horseman et al. (1999) and Harrington & Horseman (2003) performed on laboratory scale tests.

The injection pump was stopped (i.e. a shut-in test) at Day 974 and the gas pressure were allowed to decay, providing an estimate for the apparent capillary threshold pressure (i.e. when gas ceases to be actively mobile in the system, which was tentatively estimated to be around 4.9 MPa). This pressure was significantly higher than that required to initiate gas entry but was very similar to the average radial stress measured on the canister which was also close to the axial stress measured locally within the clay at PB902. This suggests a correlation between gas transport and total stress, and supports the observations reported by Harrington & Horseman (2003) based on laboratory scale tests.

Following peak gas pressure, a well pronounced increase in radial stress occurred around the entire base of the deposition hole, with the highest increase noted in the vertical plane below the point of injection. This strongly suggests gas preferentially moved downwards, probably along the interface between the canister and buffer. It is notable that the radial stress immediately adjacent to FL903 decreased during this time. Analysis of the porewater pressure sensors located within the buffer showed no obvious sensitivity to the injection of gas. In contrast, axial stress sensors located beneath and above the canister appear to register the passage of gas, a small inflection in the rate of increase in axial stress at the base of the canister occurred shortly after the peak in gas pressure. Such a reduction in stress can only be caused by the removal of load, suggesting some form of displacement had occurred as a result of gas injection.

3.2 Gas injection test 2 (Day 1430 – 2064)

Following the completion of gas injection test 1, an additional year of artificial hydration of all filters and filter mats was conducted. One question arising from Gas test 1 was whether the gas exited the deposition hole. In order to address this, in Gas test 2 neon was selected as the test permeant in place of helium, to facilitate tracking of gas through the host rock by gas sampling of the packered intervals in each of two nearby pressure relief holes (neon is absent from the natural pore waters of Äspö).

The second preliminary gas injection test began on Day 1430 in filter FL903, by which time pressures within the deposition hole and bentonite had increased; the average axial stress (monitored at separate locations throughout the clay) was around 5.5 MPa, the average radial stress (measured at the rock wall) was close to 4.5 MPa, the average total stress acting on the canister was around 5.2 MPa, the average porewater pressure (measured at the rock wall) was approximately 1.66 MPa and the average porewater pressure in the bentonite was around 0.39 MPa. Following a two-stage constant head test to determine the hydraulic properties of the buffer at FL903, gas (neon) testing began on Day 1606 from a starting pressure of 1.3 MPa. This was higher than the starting pressure in Gas test 1 as pore pressure at this location had increased with continued artificial hydration. Gas test 2 was planned to give more detail than Gas test 1, with four pressure ramps (instead of 2) and prolonged gas injection following gas breakthrough.

The first pressure ramp raised gas pressure from 1.3 to 2.55 MPa over a 9 day period, at which point the gas pressure was held constant for a further 15 days while flux into the clay was monitored with time (Figure 4a). Analysis of the data suggested that the gas entry pressure was close to the start value of 1.3 MPa, significantly higher than for Gas test 1. Once the injection pump was switched to constant pressure mode and the pressure in the filter held constant at 2.55 MPa, gas flow into the clay dramatically reduced by around 95%.

A second ramp raised pressure to 3.8 MPa over 9 days, followed by a period of constant pressure for 28.6 days. A third ramp raised pressure to a final target of 5.05 MPa over 16 days, and pressure was held constant for a total of 52 days (from Day 1690 to 1742). As with previous observations, the switch from pressure ramp to constant pressure resulted in a reduction of flux in excess of 95%.

The final gas injection stage was initiated on Day 1742 with a relatively slow injection rate, Figure 4b. At Day 1766.55, gas flow into the buffer spontaneously increased, exhibiting a well-defined peak before decreasing to a steady-state value of around 8×10^{-9} m^3 s^{-1} under STP (standard temperature and pressure) conditions. Gas pressure continued to increase reaching a maximum value of 5.87 MPa at Day 1767.3, 0.21 MPa higher than for the Gas test 1. Peak pressure was followed by a spontaneous negative pressure transient, which approached an asymptote of around 5.55 MPa. Figure 4b shows the response of the buffer to the ingress of gas during this phase of testing was very similar in form to that observed in the small-scale laboratory experiments reported by Harrington & Horseman (1999, 2003): post peak, both flux and pressure data initially “under-shoot” then “over-shoot” the ultimate asymptote value, symptomatic of unstable gas pathways (Harrington & Horseman, 1999).

At peak gas pressure, data from total stress and porewater pressure sensors indicated gas flow was both localised and a highly complex dynamic process, with pathways opening and closing probably in response to localised changes in gas pressure. Analysis of the data indicated conspicuous changes in value at and after peak gas pressure, providing strong evidence for the time-dependent evolution of a tortuous network of unstable gas pathways. While these data indicated that gas pathways initially propagated downwards and then across and upwards through the clay or clay/rock wall interface, later ‘breakthrough’ events from different sensor locations indicated that the gas pathway network continued to evolve, even though the system was at quasi steady-state. For example, the pressure recorded in filter

FL901 increased 6.5 days after gas peak pressure was recorded in injection filter FL903, as seen in Figure 5. A second increase in pressure occurred in FL901 10 days later (filter FL901 is 180° around the canister, with filters FL902 and FL904 90° around the canister, see Figure 2). It can be seen that gas propagated to the opposite side of the canister without intercepting either of the filters (FL902/904) between FL903 and FL901. This suggests that the gas pathway(s) was localised and tortuous, and that the entire canister/buffer interface was not conductive. Gas reached pressure sensor UB902, which is located towards the bottom of the deposition hole within bentonite block C1. This suggests that the gas propagated, at least in part, through the buffer and not only along the interface.

Gas sampling in the pressure relief holes after the completion of the gas-injection phase detected a trace amount of neon (117 ppm) in interval PRH1-2. All other PRH intervals showed undetectable (<50ppm) amounts of neon both before and after Gas test 2. Therefore the gas had exited the deposition hole and had entered a fracture in the host rock that was in hydraulic communication with one interval in the pressure relief holes.

3.3 Gas injection test 3 (Day 2257 – 2614)

In 2012, gas testing switched from the previously tested filter (FL903) to an upper array filter. Filter FU910 was selected; this filter was smaller in diameter (25 mm, compared to 50 mm for FL903), which meant that Gas test 3 would investigate neon movement under different stress conditions higher in the deposition hole and for a different hydration state, dictated by the size of the injection filter and total duration of artificial hydration.

The third preliminary gas injection campaign began on Day 2072 in filter FU910, by which time pressures within the deposition hole and bentonite had increased; with the average axial stress (monitored at separate locations throughout the clay) was around 5.78 MPa, the average radial stress (measured at the rock wall) was close to 4.8 MPa, the average total stress acting on the canister was around 5.66 MPa, the average porewater pressure (measured at the rock wall) was approximately 1.62 MPa and the average porewater pressure in the bentonite was around 0.45 MPa. Following a two-stage constant head test to determine the hydraulic properties of the buffer at FU910, gas (neon) testing began on Day 2257 with the introduction of an initial gas volume into the test system. Pressure started from 1 MPa, with four pressure ramps similar to Gas test 2, with the final stage conducted for a prolonged period of time. The first pressure ramp raised gas pressure to 2.25 MPa over a 17 day period, at which point the gas pressure was held constant for a further 31 days while flux into the clay was monitored with time (Figure 6a). Analysis of the data indicated that a small flux into the clay began at the onset of pumping, suggesting that the gas entry pressure was close to the start value of 1.0 MPa. Once the injection pump was switched to constant pressure mode and the pressure in the filter held constant at 2.25 MPa, gas flow into the clay dramatically reduced and remained low, resulting in a small STP background flux of around 2×10^{-11} $m^3 s^{-1}$; this equates to a reduction in flow in excess of 99%.

A second ramp raised pressure to 3.5 MPa over 17 days, followed by a period of constant pressure for 36 days. A third ramp raised pressure to a final target of 4.75 MPa over 16 days and pressure was held constant for a total of 100 days (from Day 2377 to 2477). As with previous observations, the switch from pressure ramp to constant pressure resulted in a reduction of flux in excess of 98%.

The final gas injection stage was initiated on Day 2477.25 with a relatively slow injection rate, Figure 6b. At Day 2490.36, gas flow into the buffer spontaneously increased, exhibiting a well-defined peak of 5.19 MPa and a pressure drop. As can be seen, the pressure response was dissimilar to that seen in Gas tests 1 and 2, initially gas pressure reduced by approximately 50 kPa to 5.14 MPa, and over the following 12 days recovered to a secondary peak of 5.3 MPa at Day 2502.3. The secondary peak had not been seen in previous tests in

Lasgit and had a magnitude over 0.1 MPa greater than the initial gas breakthrough. Pressure slowly progressed to a steady state of approximately 5.24 MPa and around 1×10^{-8} m^3 s^{-1} (STP) by Day 2524. As before, flux and pressure data initially "under-shot" then "over-shot" the ultimate asymptote value, symptomatic of unstable gas pathways (Harrington & Horseman, 1999).

On Day 2533 the logging computer failed, this resulted in the gas laboratory being isolated from the Lasgit experiment and artificial hydration was halted. The computer was re-instated on Day 2542; in the intervening 9 days the gas pressure had reduced approximately 100 kPa to 5.16 MPa due to the reduction in downhole stress caused by the cessation of artificial hydration.

At the time of initial gas breakthrough (Day 2490.36), radial stress sensor PR915 showed a 50 kPa increase, with smaller increases noted in PR917 (20 kPa), and PR916/918 (10 kPa). Radial stress sensors PR915 and PR916 were spatially closest to injection filter FU910, and were both positioned 45° around the deposition hole on Section 9 (Figure 2). Little to no stress change was seen on Section 7 of the deposition hole, suggesting that gas initially did not propagate downwards. Changes in porewater pressure were noted in some sensors.

Radial stress continued to rise in all four sensors located on Section 9, and peaked at the same time as the secondary gas peak. At this time, PR919 increased by 50 kPa, whilst PR920 and PR922 reduced by 15 kPa. This suggests that gas began to move upwards in the deposition hole. As seen in Figure 7, a series of pressure increases were noted in filter FU909, starting from Day 2495.28; 7 pressure increase events were seen. None of these pressure increases corresponded with a significant change in radial stress. On Day 2508.25, pressure increased in filter FU911; this event corresponded with a stress and porewater pressure change in several sensors.

Gas injection re-started on Day 2541 and pressure soon recovered. The classic under- and over-shooting of pressure and flow was seen for the remainder of the stage (Figure 6b). Figure 7 shows the pressure response of several sensors within Lasgit. As previously described, following gas breakthrough on Day 2490.36, pressure increased in filter FU909, starting on Day 2495.28. Over a period of approximately 5 weeks, the pressure in FU909 increased to become similar in magnitude to injection filter FU910. Filter FU911 was next to change, with an increase of 0.75 MPa on Day 2508.25; no further pressure increase occurred for the following 7 weeks, until a second increase of approximately 0.5 MPa occurred, followed by a significant rise of 4.5 MPa on Day 2568.43. Over a 13 day period, pressure in filter FU911 decayed by approximately 1.5 MPa until on Day 2580.59, filter pressure increased to approximate that of the injection pressure.

The third sensor to react was stress on the canister (PC903). Initially 2 pressure drops occurred on Day 2516.33 and 2517.95, followed by a stress rise on Day 2518.6. From this time onwards the response of PC903 mirrors FU910 and therefore it is deduced that gas propagated to this location on the canister face. The final sensor to change was filter FL904, at Day 2577.16, with an eventually rise of 1.7 MPa.

4.0 Discussion

In all three gas injection tests, there have been periods of constant-rate gas injection (CFR) and constant pressure (CP). In all occasions that the test was switched from CFR to CP, flow into the clay reduced by 95 % or more. In Gas test 2, a flux of 2.5×10^{-10}, 7.2×10^{-11}, and 1×10^{-12} m^3 s^{-1} was seen at constant pressure stages of 2.55, 3.8 and 5.05 MPa respectively. The large reduction in gas flux (ranging from 95 - 98.5%), when pressure was held constant, suggests an apparent reduction in gas permeability of the buffer. In classic concepts of two-phase flow (Aziz & Settari, 1979; de Marsily, 1986) the rate of gas flow is proportional to the gas pressure gradient and as such flow should continue into the clay when gas pressure was held constant (assuming gas is flowing to a sink). In the current experiments no such correlation was observed as gas flow showed no dependence on the driving gas pressure gradient. Therefore, two-phase flow is considered a poor model to explain these experimental observations. However, they can be explained by a pathway propagation model. According to Griffith crack theory, a crack will only propagate when the decrease in strain energy just balances the increase in surface energy (Griffith, 1921). In essence, this can be viewed as the slow time-dependent expansion of gas pathway(s), conceptually little different to that of inflating one or more tiny balloons within the bentonite, where the walls of the latter represent the pathway surfaces within the clay. As gas pressure increases the cracks (balloons) slowly expand and propagate resulting in a larger network of gas-filled pathways. If gas pressure is held constant, the capacity for further expansion of the cracks (balloons) is limited, by both the balance in strain and surface energies, and by the availability of inherent weaknesses within the buffer system. The observed reduction in gas inflow rate for the higher constant pressure steps strongly support this line of reasoning, and suggests that the availability or interconnectivity of such weaknesses within the clay (from small-scale transient features related to hydraulic/stress disequilibrium) is limited locally around the point of the injection zone.

In Gas test 3, a flux of 2.1×10^{-11}, 1.1×10^{-10}, and 1.7×10^{-10} m^3 s^{-1} was seen at constant pressure stages of 2.25, 3.5 and 4.75 MPa respectively. The large reduction in gas flow (ranging from 98.6 to 99.9%), when pressure was held constant, again suggests an apparent reduction in gas permeability of the buffer. As previously stated, while this does not conform to classic concepts of two-phase flow it can be explained by the pathway propagation model suggested above. However, in contrast with Gas test 2, a small increase in flow was observed during each successive constant pressure step. While these flows are very small it suggests that gas is still able to migrate into the clay and may be exploiting heterogeneities within the bentonite buffer that differ between filter FU910 and FL903 localities.

Gas entry pressures achieved in all three gas injection tests are much lower than those anticipated for saturated intact bentonite of a similar dry density (Harrington & Horseman, 2003). However, this can be explained by gas exploiting the incomplete hydration state of the buffer and the heterogeneous nature of the stress field within the clay. This could lead to heterogeneities within the clay that the gas can exploit, which are not present to the same degree in laboratory scale tests. However, this is unlikely the result in classical two-phase flow as work published by Donohew et al., (2000) on saturated low density bentonite clearly demonstrated that even under these conditions gas migration only occurred through the creation of pressure induced (dilatant) pathways. The increase in gas entry pressure between Gas test 1 and 2 is also indicative of the maturation of the clay, observed as increases in pore pressure and stress as hydration of the bentonite buffer continued. However major gas breakthrough occurred at a gas pressure close to the local stress magnitude, which is common with laboratory observations.

Figure 8 shows a summary of the major gas migration directions inferred from the three gas tests. Whilst gas may have migrated to other localities within the deposition hole, these are likely to be localised as no significant changes in stress or porewater pressure were observed. As can be seen, in Gas test 1 it is suggested that gas propagated along the interface between the canister and the bentonite blocks in a downwards direction in line with the prevailing stress gradient. It is probable in this test that gas exited the deposition hole along the interface between blocks R1 and R2. However, in Gas test 2 the same gas pathway was not exploited. In this later test, gas propagated 180° around the canister to filter FL901 and from there propagated downwards towards the bottom of the deposition hole. In Gas test 3, it was seen that it took considerable time for gas to reach a number of sinks and to fully pressurise these locations. The behaviour of the “pressurised” sensors mirrored the injection pressure, and this suggests that the system was behaving as if it were one large volume of gas. At the end of gas injection, a leak-off test was conducted from Day 2614.44 onwards and the three “pressurised” sensors reduced in a similar way to the gas injection filter (FU910). However, once PC903 reached 5.24 MPa there was no more decay; the sensor was therefore once again recording local stress at this locality.

The propagation of gas during tests 2 and 3 shows that gas pathways are localised. In Gas test 2, the gas propagated 180º around the canister and did not intercept the two filters that were located ±90º around the canister. In Gas test 3, gas propagated from the upper array of filters to the lower array without intercepting any of the four mid-plane filters. Therefore, gas propagation pathways must have been localised features. The behaviour of the four “pressurised” sensors seen in Gas test 3 shows that, once formed, the network of gas pathways continued to evolve and that multiple pathways were simultaneously forming. Once fully “pressurised”, the system behaved as if it were one inter-connected volume. Similar observations have been seen in laboratory testing (Graham *et al.*, 2014).

Figure 9a shows the local stress conditions around filter FL903 during the first two gas injection tests. Average stress is shown for radial stress [PR] and pore water pressure [UR] from the same level as the injection filter. Radial stress on the canister [PC] is also shown for Section 6 of the deposition hole. As can be seen, both gas breakthrough pressures are higher than the radial stresses observed. However, a close comparison was seen with gas breakthrough and PR910. As shown in Figure 9b for Gas test 3, the initial gas peak occurred once injection pressure was similar to the stress recorded nearby on the surface of the canister (PC903). This magnitude was much greater than the average radial stress at the Section 9 level.

All three gas tests have confirmed the link between local stress and gas breakthrough pressure, as previously observed in laboratory experiments. Figure 9c shows total stress plotted against the gas pressure at breakthrough. The dotted line represents the condition when applied gas pressure is equal to local stress: the gas breakthrough pressures plot close to this condition. This relationship has also been seen in laboratory data, with gas movement strongly controlled by the local stress state (see Graham *et al.*, 2011; 2014) However, predicting the precise magnitude and timing of the breakthrough pressure appears difficult given the anisotropy seen in stress within Lasgit and the uncertainty of the stress state at the injection filter. If stress at a given location was known then the magnitude of pressure for major gas entry could be predicted. The observed couple between major gas entry and total stress is consistent with observations from a field experiment testing the integrity of a borehole seal reported by Van Geet *et al.* (2007), who observed gas breakthrough pressures close to the measured value of radial stress. It is also consistent with previous small-scale laboratory experiments reported by Harrington & Horseman (1999, 2003) and Horseman *et al.* (1997), who observed qualitatively similar behaviour to that noted in this study.

Major gas entry into the bentonite buffer is associated with a rapid increase in gas flux. This is followed by a spontaneous negative pressure transient leading to a quasi-steady-state. There is considerable evidence for the existence of a highly-dynamic, tortuous network of pressure-induced pathways, which evolve both temporally and geospatially within the clay, opening and closing probably due to local changes in gas pressure and or effective stress. Further laboratory research is required to explore these interactions.

5.0 Conclusions

This paper reports on gas testing that occurred during the first 2,726 days (7.5 years) of continuous operation of the Large scale gas injection test (Lasgit) conducted at the Äspö Hard

Rock Laboratory. During this time the bentonite buffer has been artificially hydrated and this has given new insight into the evolution of the buffer under isothermal conditions.

Three gas injection tests have been conducted which illustrate the changes in response to gas propagation as the buffer matures. The first two tests were conducted in the lower array of injection filters at FL903. Both of these tests showed similar behaviour with a well-defined pressure peak; spontaneous negative transient; evidence of dynamic behaviour and unstable gas pathways; asymptote close to stress. The results were qualitatively similar to laboratory test results. However, the high gas entry pressures seen in the laboratory were not seen in Lasgit, as the stress state was much lower due to incomplete hydration of the buffer. The third gas test was conducted in an upper array filter (FU910). The response at the time of gas peak pressure was subtly dissimilar to that seen at FL903, with two peak pressures. However, major gas breakthrough has confirmed the coupling between gas, stress and pore-water pressure for flow before and after major gas entry at the field scale. All observations suggest mechanisms of pathway propagation and dilatancy predominate. In all three gas tests the propagation was through localised features and the general movement direction was towards the bottom of the deposition hole in the direction of the prevailing stress gradient. The injection tests have shown that the interface between barriers is a key part of the system. Gas appears to have exited the deposition hole in Gas test 2, but failed to find a way out during Gas test 3 (where gas continued to migrate along the canister/buffer interface).

Considerable evidence exists for the development of a highly-dynamic, tortuous network of pressure induced pathways which evolve both temporally and geospatially within the clay, opening and closing probably due to local changes in gas pressure and or effective stress. This is consistent with observations from previous experiments in particular those reported by Harrington & Horseman (2003), and given the incomplete hydration state of the buffer and the heterogeneous nature of the stress field within the clay, it seems probable that the gas is exploiting these differences in the tests discussed in this paper. As testing continues and the buffer evolves, greater insight into the processes governing the movement of gas within buffer bentonite, under evolving boundary conditions, will occur.

The important coupling between gas, stress and porewater pressure at the repository scale is well demonstrated by the Lasgit experiment. The importance and interdependencies related to this coupling will be investigated in future experiments currently planned for the Lasgit experiment.

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8.0 Acknowledgement

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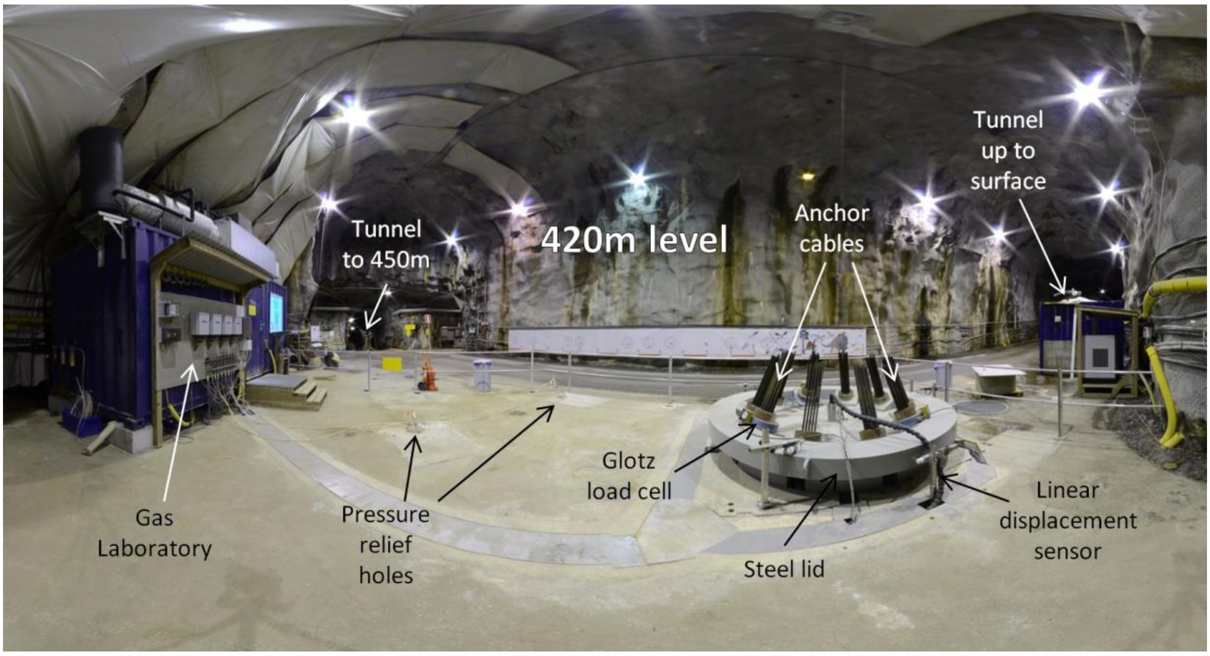

Figure 1 A panoramic view of the Lasgit test site located 420m below ground at the Äspö Hard Rock Laboratory in Sweden. The photo shows the position of the deposition hole, gas laboratory, pressure relief holes (containing a series of packered intervals in order to monitor porewater pressure in the surrounding fracture network) and some of the instrumentation attached to the steel lid.

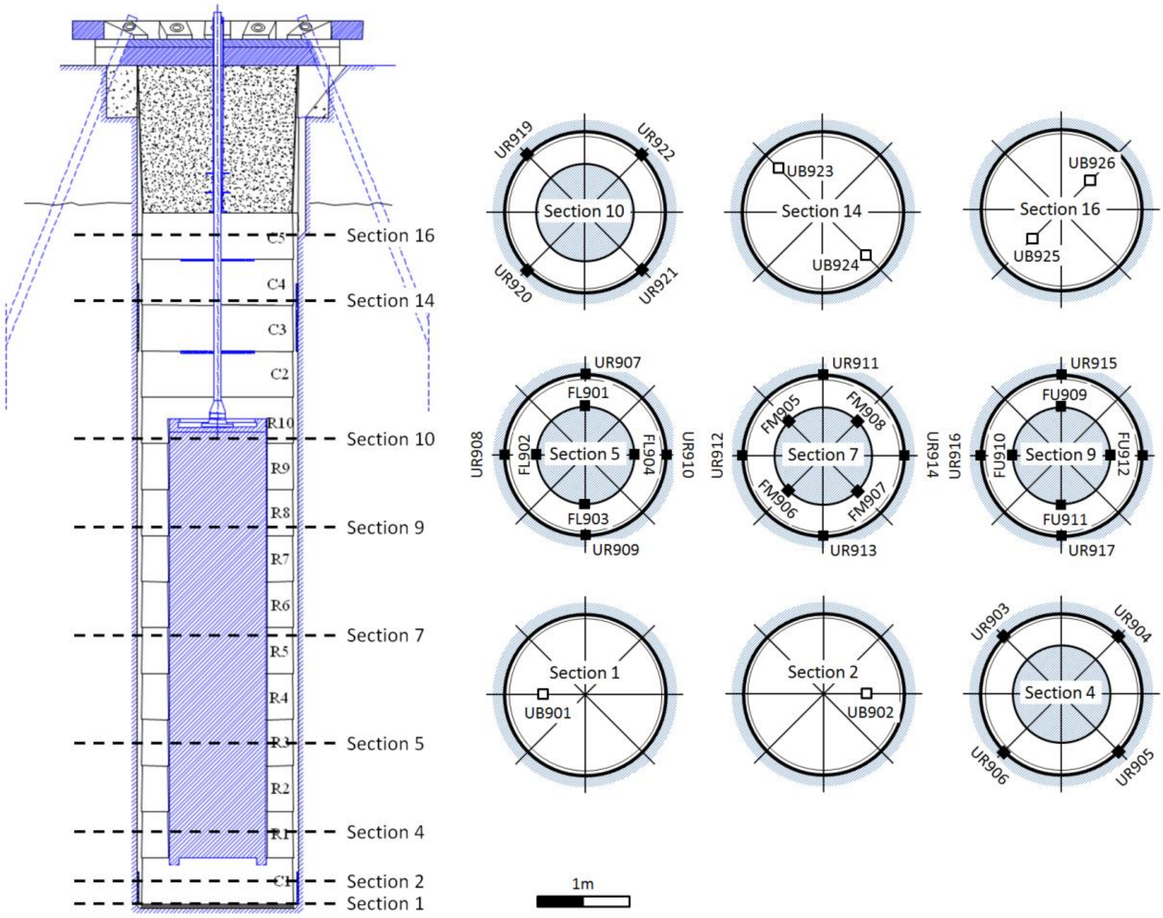

Figure 2 Schematic of the layout of the Lasgit experiment showing the locations of sensors. Sensors are placed in 14 of a total of 17 sections, filter mats for artificial water saturation in 4 sections and gas injection filters in 4 sections (UB9xx = pore-pressure sensor within the bentonite buffer; UR9xx = pore-pressure sensor at the rock wall; FL90x = injection filter on the lower array; FM90x = injection filter on the mid-plane array; FU9xx = injection filter on the upper array; Cx = bentonite block; Rx = bentonite ring).

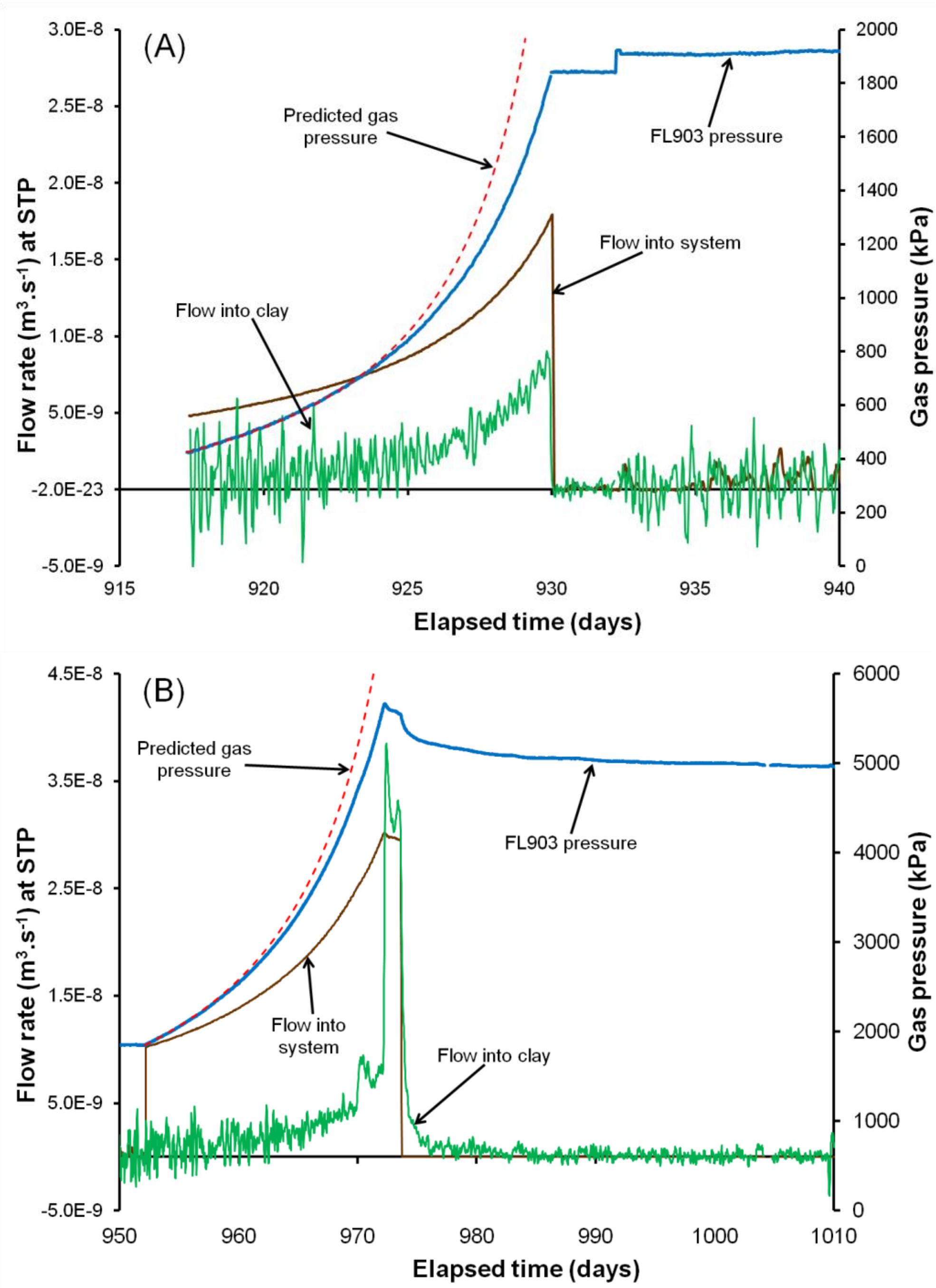

Figure 3 Plots (A) and (B) show the entire injection history for Gas test 1. STP flow rates into the injection system and the clay as well as measured and predicted gas pressures are plotted against elapsed time. Flow into the clay is calculated using a combination of weighted moving average and time moving average (mean). For plot (A) the departure between measured and predicted gas pressure is symptomatic of gas penetration of the buffer. In plot (B) the peak pressure response is symptomatic of the development of 'major' gas pathways

within the buffer and is qualitatively similar in response to small-scale experiments reported by Horseman *et al.* (1997, 1999, 2004) and Harrington & Horseman (2003).

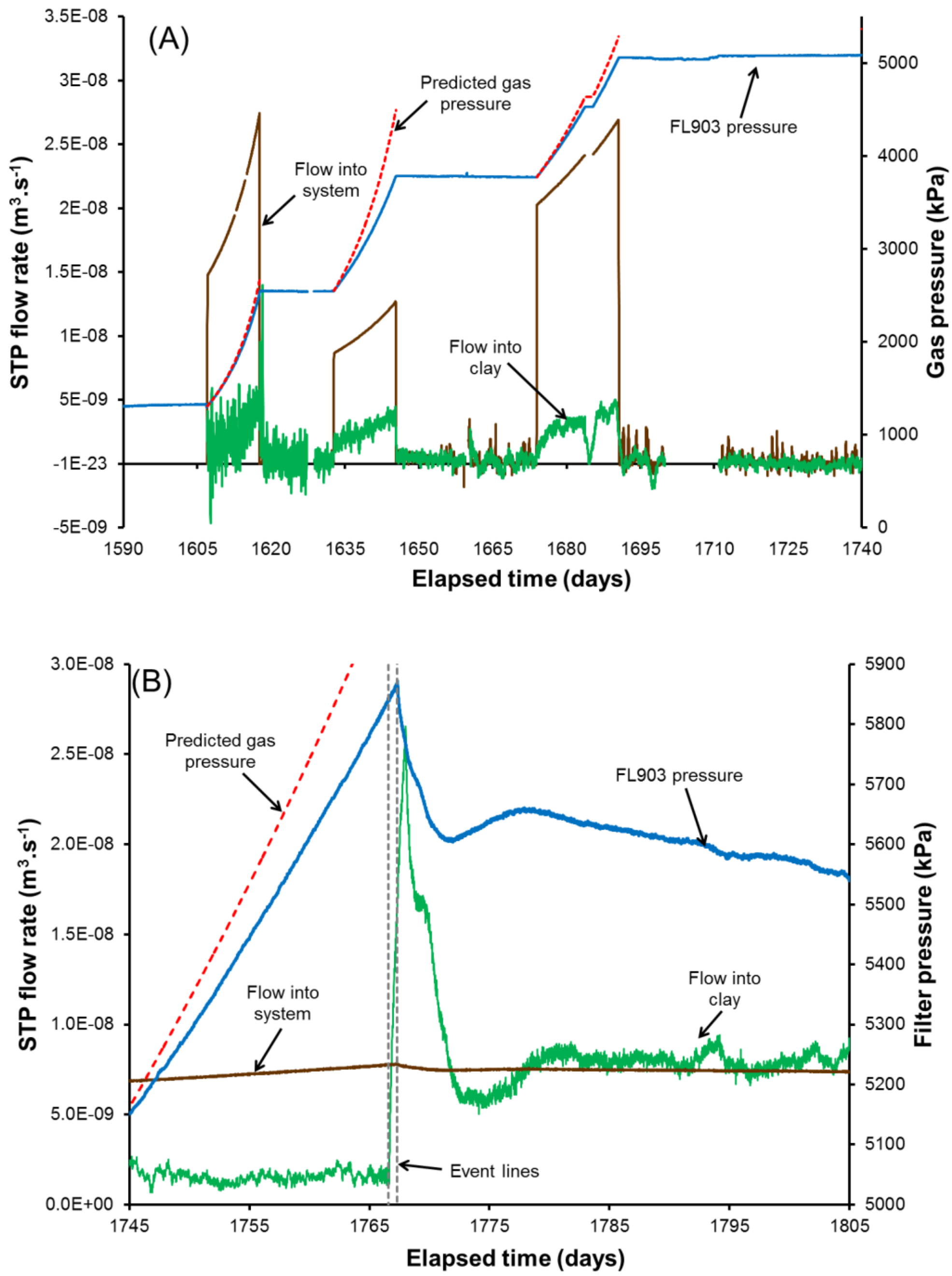

Figure 4 Plots (A) and (B) show the entire injection history for Gas test 2. STP flow rates into the injection system and the clay as well as measured and predicted gas pressures are plotted against elapsed time. Inspection of plot (A) shows the reduction in flux into the clay during each constant pressure step. Plot (B) shows the 'major' gas entry event signified by the rapid increase in flux into the clay. This is followed by a well-defined negative flux transient which first under- and then over-shoots the injection flow rate into the system. This is symptomatic of unstable gas pathways.

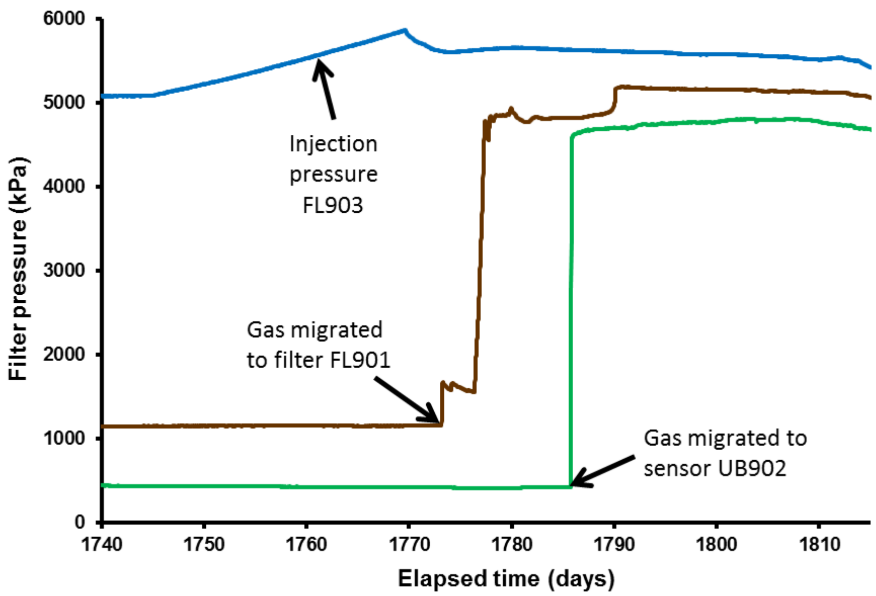

Figure 5 Results for Gas test 2, data showing prolonged gas injection in FL903. As gas injection continued it resulted in an increase in pressure at FL901; pressure in sensor UB902 sometime later. This shows that gas propagated to these locations and that the network of gas pathways continued to dynamically evolve following major gas entry.

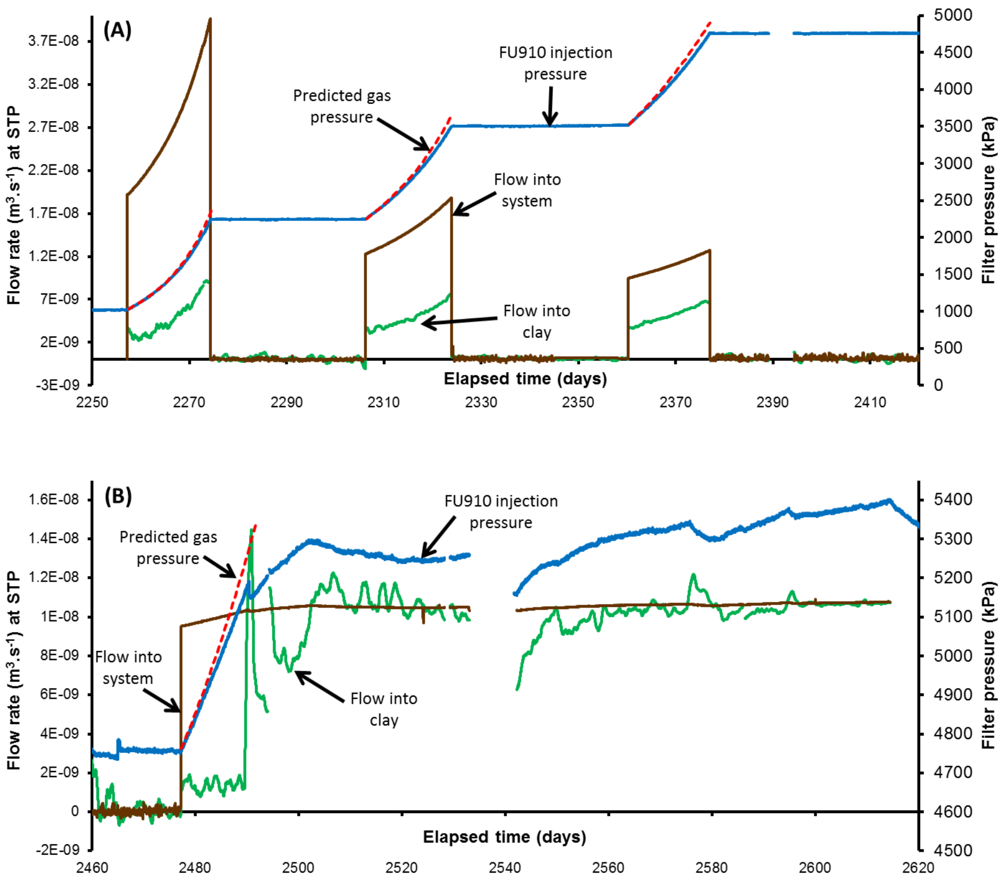

Figure 6 Plots (A) and (B) show the entire injection history for Gas test 3. Inspection of plot (A) shows the reduction in flux into the clay during each constant pressure step. Plot (B) shows the 'major' gas entry event signified by the rapid increase in flux into the clay. This is followed by a secondary gas peak and an eventual transient which first under- and then over-shoots the injection flow rate into the system. This is symptomatic of unstable gas pathways.

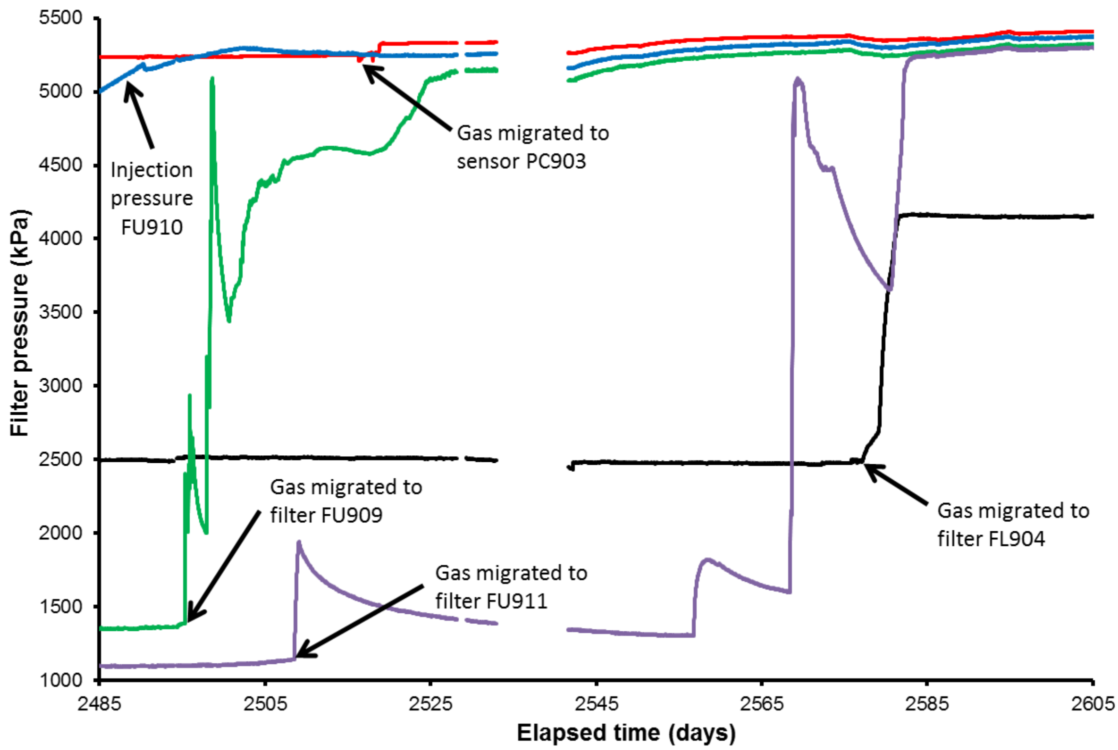

Figure 7 Response of selected sensors during prolonged gas injection (Gas test 3). In order of first change, gas reached sensors FU909, FU911, PC903 and FL904. The evolution of pressure shows that several gas pathways must have formed and that these continued to evolve spatially and temporally.

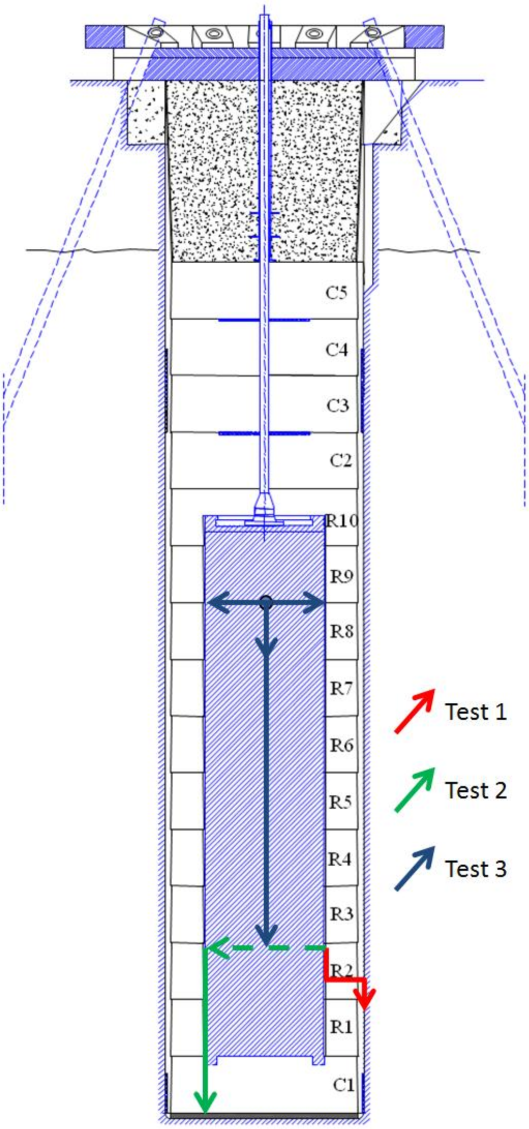

Figure 8 Gas migration direction for the three gas injection tests.

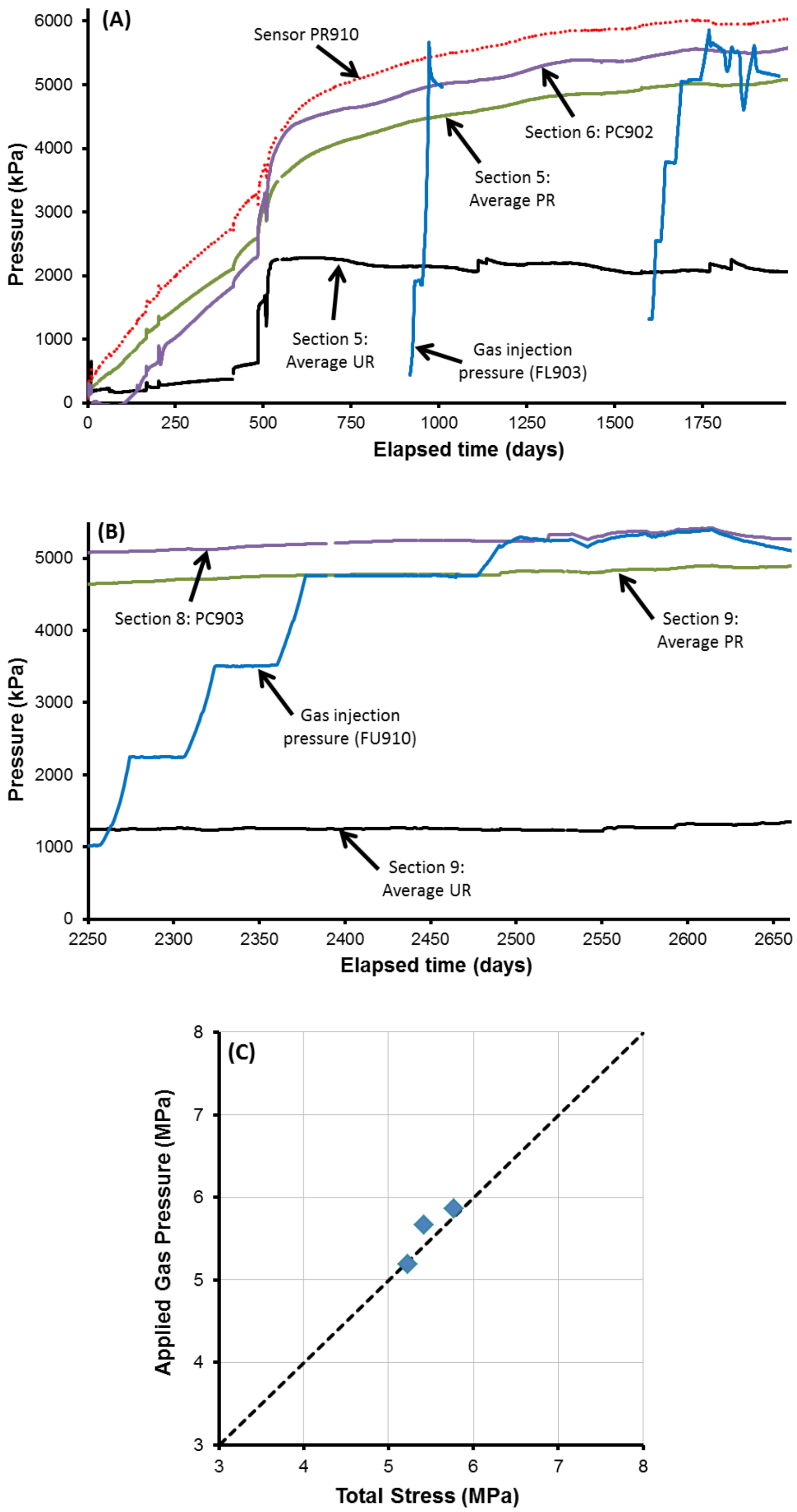

Figure 9 Gas breakthrough and local stress. Plot (A) shows the results from Gas test 1 and 2, where both tests had gas breakthrough at a pressure greater than the average radial stress on the corresponding level. However, a close relationship is seen between gas breakthrough and

radial stress on the deposition hole wall at PR910. Plot (B) shows breakthrough in Gas test 3 occurred at a pressure close to PC903. Plot (C) shows the close relationship between stress state close to the gas injection filter and gas breakthrough pressure.

Test stage	Duration
Artificial hydration of filter mats	Day 0 – on-going
• Artificial hydration phase 1	• Day 0 – 843
• Gas test 1 in filter FL903	• Day 813 – 1110
○ Hydraulic test	○ Day 843 – 917
○ Gas injection test	○ Day 917 – 1010
○ Hydraulic test	○ Day 1010 – 1110
• Artificial hydration phase 2	• Day 1110 – 1430
• Gas test 2 in filter FL903	• Day 1430 – 2064
○ Hydraulic test	○ Day 1473 - 1577
○ Gas Injection test	○ Day 1577 - 1964
○ Hydraulic test	○ Day 1964 - 2019
• Gas test 3 in filter FU912	• Day 2019 -2072
○ Hydraulic test	○ Day 2072 Abandoned
• Gas test 3 in filter FU910	• Day 2072 - 2726
○ Hydraulic test	○ Day 2085 – 2141
○ Leak off test	○ Day 2141 – 2257
○ Gas injection test	○ Day 2257 – 2673
○ Hydraulic test	○ Day 2673 – 2726

Table 1 List of test stages during the complete history of Lasgit