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Is Pressure-induced Mineral Dissolution the Dominant Factor Propelling Fracture Closure?

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ABSTRACT

Fractures are significantly important for the utilization of low-permeable geothermal reservoirs. The long-term sustainability of fracture aperture determines the lifespan and economic efficiency of a reservoir. In an aqueous fluid, chemical reactions between fluid and minerals are time-dependent under P and T conditions, yielding an irreversible impact on the fracture's evolution. Pressure solution at the propping asperities results in a decrease of aperture, while mineral dissolution on the void walls enlarges the fracture. To investigate the effects of this coupled process, a long-term intermittent flow-through experiment was conducted with distilled water under a pore pressure of 1 MPa and confining pressure of 10 and 30 MPa at a temperature of 140 and 32 °C. A monomineralic sedimentary rock (Fontainebleau sandstone) with a composition of > 99.5% quartz and an extremely low permeable matrix was used. A tensile fracture along the central long axis of the sample core was artificially produced and the two halves were assembled with a pre-offset of 0.75 mm. Permeability was intermittently measured after the flow was stopped for time intervals of 8 and 16 days, respectively. Before each permeability measurement, the effluent was continuously sampled from the outlet capillary with a sub-sample volume of 0.5 ml and a flowrate of 0.5 ml/min. The peak silica concentration of the subsamples represented the fluid's composition within the fracture and indicated an ion diffusion process from the fracture towards the capillaries. Pre- and post-experiment µCT scans of the sample at atmospheric pressure illustrated the overall aperture and contact ratio changes before and after the experiment.

The theoretically dissolved amount of quartz on the free fracture walls as accounted for by PHREEQC (1.73 mmol/l at 140 °C) was significantly smaller than the measured total silica concentration of the effluent (8~9 mmol/l), revealing that pressure solution mainly contributed to the dissolution process. However, it showed that confining pressure and the respective time intervals of stagnant flow had a negligible effect on the final peak effluent concentration, inferring that a chemical equilibrium has been reached rapidly at constant temperature consequently impeding pressure solution from proceeding. In addition, permeability showed to remain approximately constant throughout the 137 days of the experiment.

In summary, it is concluded that the silica concentration of the pore fluid increased predominantly due to pressure solution at fracture asperities. The dissolution and diffusion of quartz (silica) within the water film between the stressed contacting asperities may be restricted by the ion concentration of the surrounding fluid, alleviating pressure solution creep. In contrast, continuous flow-through would disturb the chemical equilibrium within the pore fluid accelerating pressure-induced mineral dissolution.

1. INTRODUCTION

Improving the understanding of the long-term behavior of fluid and mass transport in fractured rock masses with low matrix permeability under crustal conditions is of significant importance for the deep geothermal energy utilization. Studies show that water-saturated quartz sands have substantial time-dependent compaction at constant pressure rather than dry compacted grains (Schutjens, 1991). In addition, elevated temperature also significantly affect the compaction process of propping fractures (Polak et al., 2003; Yasuhara et al., 2006). The mechanism behind these phenomena is considered due to pressure-induced mineral dissolution. Their combined effects are typical in hydrothermal systems as well as in enhanced geothermal systems (EGS) when injecting fluids to the hot dry rocks, which determine the sustainability and lifespan of geothermal reservoirs.

Stress-induced mineral dissolution has been studied on unconsolidated aggregates (e.g. quartz grains) at diagenetic conditions (De Boer, 1977a; b; Robin, 1978; Weyl, 1959) and on rock fractures (e.g. novaculite and granite) at hydrothermal conditions (Polak et al., 2004; Yasuhara et al., 2004; Yasuhara et al., 2006) for decades. They gained insight into the procedure of pressure-induced solution, which incorporates three processes; minerals on propping asperities (in fractures or described as grain-to-grain contacts in aggregates) dissolve inside the contact areas, after which the dissolved minerals diffuse from the inside contact areas to the peripheries through the intervening thin water film between the adjacent asperities, and may ultimately deposit on the free pore walls (Tada et al., 1987; Yasuhara and Elsworth, 2008). This process consequently drives irreversibly time-dependent porosity reduction in aggregates and/or permanent fracture aperture closure in rock fractures. In essence, the compaction of aggregates and fracture closure are due to the same mechanism. Pressure solution is described by a rate-limiting process, therefore the progress is determined by the lowest of the above three processes (De Boer, 1977b; Yasuhara and Elsworth, 2008). In addition to the stress-induced mineral dissolution, the solid phases on free surfaces can also dissolve in the solvent, which is called free-face dissolution yielding the retreat of free surfaces. The two processes have opposite effects on the geometric alteration on fracture aperture channels, determining the evolution of fracture permeability.

Most of the previous studies of fracture aperture focused on the compaction of the fracture aperture in an open system with water circulation (Polak et al., 2004; Polak et al., 2003; Yasuhara, 2003). To our knowledge, in an opened system with water circulation, the equilibrium of rock-fluid (distilled water) interactions is not reached as a result of the fluid flow. Therefore, the reaction between rock and the fluids can somehow continuously proceed. While in a closed system without pore water circulation, the chemical equilibrium may achieve with time, diffusion of the solute may be inhibited due to the decrease of concentration gradients, which

brings up a question; can the rate-limiting process of pressure solution reach equilibrium and consequently restrict the progress of fracture closure?

Three main factors should be seriously considered for the experimental procedure on the investigation of pressure solution creep. Small contact area ratio and sufficient effective stress are needed; the volume of each effluent sample should be equivalent to the fracture aperture volume. In addition, brittle damage and plastic deformation of fracture due to mechanical compaction need to be foreclosed. This study presents a long-term experiment with intermittently flow-through permeability measurements in conjunction with effluent element analysis. The rock sample was scanned by a μCT scanner before and after the experiment to quantitatively analyze fracture aperture variations.

2. SAMPLE AND EXPERIMENTAL PROCEDURES

2.1 Sample Preparation

Fontainebleau sandstone was used for the investigation, which is a monomineralic rock with more than 99.5% of quartz. It has an extremely low matrix permeability (<0.1 mD), the porosity is roughly 3%. A cylindrical sample with a diameter of 30 mm and a length of 40 mm was split along the long axis by a Brazilian setup. Due to the geometry of the two halves, the fracture may immediately close under pressure when the two surfaces are aligned. On the other hand, the matched fracture surfaces lead to high contact area, the stresses on the bridging asperities may be insufficient even under a high confining pressure. Therefore, the two halves are shifted by 0.75 mm along the longitudinal axis with two spacers on the two ends of the sample. Fracture aperture is consequently self-propped by the contact asperities.

2.2 Experimental Apparatus

The sample is mounted in a hydrostatic pressure vessel, where the confining pressure is produced by a cylindrical pump through silicon oil. The oil within the pressure vessel can be heated up by electrical resistance heaters and controlled by a controller. The sample bottom is connected to an upstream pump and the upper side is connected to either a downstream pump or a relief valve. The downstream pump is designed for maintaining constant pore pressure during permeability measurement, and the differential pressure between the sample ends is monitored as well. With the relief valve, effluents can be sampled under certain constant pressures. The spiral capillary soaked in cold water (~20 °C) between the relief valve and the sample is to cool the fluid during sampling.

2.3 μCT Scan

The microstructure of the assembled fracture sample was observed by an X-ray μCT scanner (ultra-high resolution nano CT system) prior to and after the experiment under the atmospheric condition. Fracture aperture is extracted from the reconstructed 3d model and analyzed. Due to the extremely low matrix permeability and the low porosity, we ignored the pore connections and only focused on the fracture aperture.

2.4 Pre-Confining Pressure Cycles and Temperature Variations

Distilled water was used as the permeant throughout the experiment. When first applying confining pressure on the rock sample, the contact asperities will be subject to high-stress concentration yielding brittle damage and plastic deformation. To apply non-hydrostatic thermodynamics to pressure solution and free-face dissolution include the assumption that all solid deformations are elastic and reversible (Engelder, 1982). Therefore, in this study, three times loading-unloading confining pressure cycles between 5 MPa and 30MPa were operated. Pore pressure was maintained constant under 1 MPa throughout the experiment. The temperature was varied stepwise between room temperature and 140 °C. Permeability was measured at constant P and T conditions.

2.5 Procedure of Long-term Observation

After pre-pressure and temperature variations, constant confining pressure and pore pressure, as well as temperature, were applied for the long-term observation for 137 days. Permeability was measured after the flow was stopped for time intervals of 8 or 16 days under each constant P and T conditions. The effluent was sampled before each permeability measurement.

2.6 Effluent Sampling and Chemical Analysis

After the flow was stopped for time intervals of 8 or 16 days, the fluid within the fracture aperture may progressively reach a high element concentration due to fluid-rock interactions. The fluid that directly contacts the solid phases within fracture voids should be equivalent to the aperture volume, which is significantly small. However, the pore fluid within the flow-through system has plenty amount of volume comparing to the aperture volume. The large volume of the effluent will definitely dilute the actual fluid concentration and mix the fluid within the aperture and other fluids in the systems (e.g. the fluid in the capillaries), leading to incorrect results of element concentration. On the other hand, one cannot estimate the volume within the relief valve and capillaries in the downstream side, a sample with an improper volume may cause a completely wrong result.

To better sample the effluent from fracture aperture instead of from the capillaries or any space in the flow-through system, we continuously sample the effluent from the outlet capillary (the relief valve) with each volume of 0.5 ml for 20 subsamples in total and a constant flow rate of 0.5 ml/min. A permeability measurement was subsequently conducted, and therefore the pore system was completely flushed with distilled water, causing a sort of reset of the pore fluid concentration. The segmented subsamples were diluted by 10 times and silica concentration was immediately measured by a photometer (photoLab-S12). In addition, two series of them were analyzed with inductively coupled plasma-optical emission spectrophotometer (ICP-OES).

2.7 Determination of Hydraulic Aperture

The downstream side was switched from the relief valve to the downstream pump after effluent sampling. Permeability was subsequently measured with a higher constant flow rate Q. The differential pressure, Δp, along the sample ends, was monitored

meanwhile. The overall sample permeability can be expressed based on the well-known Darcy's law as,

$$k_{sample} = \frac{Q\mu \cdot L}{\Delta P \cdot A} \tag{1}$$

Where μ, A, L are fluid viscosity, cross-sectional area, and length of the rock sample, respectively. By assuming the matrix permeability is negligible (<0.1 mD), the fluid completely flows through the fracture aperture, which has the cross-sectional area, $2a_h R$, the relationship between the fracture permeability, k_f, and k_{sample} is established by the hydraulic aperture, a_h. The fracture permeability is also described using "cubic law" by assuming laminar flow between two parallel plates.

$$k_f = \frac{a_h^2}{12} \tag{2}$$

Therefore, combined the above calculations, the hydraulic aperture can be expressed using the overall sample permeability and the sample radius, R, as follows (Witherspoon et al., 1980),

$$a_h = \sqrt[3]{6\pi k_{sample} R} \tag{3}$$

After each permeability measurement, all the valves were closed except the valve on the inlet of the downstream pump to introduce a closed pore fluid system. The downstream pump was maintained at constant pore pressure of 1 MPa.

3. RESULTS AND DISCUSSION

The hydraulic aperture decreased from 57 µm to 54 µm when increasing the confining pressure from 5 MPa to 30 MPa at room temperature. Unloading stepwise to 5 MPa led to a slight increase of the hydraulic aperture to 62 µm. This could result from the migration of the brittle particles within the fracture during unloading. The temperature cycle under the confining pressure of 10 MPa caused a reversible hydraulic aperture variation between 58 µm (at room temperature) and 41 µm (at 140 °C). Further two loading-unloading cycles showed that hydraulic aperture was ultimately constant at 58 µm under a confining pressure of 10 MPa.

After the pre-treatment of the sample, the brittle damage and the plastic deformation of the sample seems like to be foreclosed. Confining pressure was subsequently increased to 30 MPa ($a_h \approx$57 µm at 33 °C), and the temperature was increased to 140 °C. The hydraulic aperture was, therefore, ~37 µm under this P and T conditions.

3.1 Effluent Concentration and Hydraulic Aperture Variations

We observed a significant mass dissolution and diffusion in the fracture aperture and the surrounding fluid. Figure 1 shows the representative silica concentration distribution in the fracture aperture and other spaces in the pore fluid system under different P and T conditions after time intervals of 8 days or 16 days, respectively. Fig. 1 (a), the first effluent measurement after the flow was stopped for 16 days clearly reveals that the peak concentration is reached at the sixth subsample. Therefore, we can infer that the sixth subsample is the fluid within the fracture aperture. For further effluent sampling, all the continuous subsamples (segmented) were collected, but only the fifth, sixth and seventh subsamples, as well as some selected subsamples, were analyzed. The procedure is sufficient to determine the highest fluid concentration after each time interval. Therefore, Fig. 1 (b), (c) and (d) show less and/or sparse spots.

The peak silica concentration can be found in all effluents at 140 °C (Fig. 1 (a), (b) and (c)) except at 32 °C (Fig. 1 (d)). The concentration distribution illustrated the dissolved silica transfers from fracture aperture to the upstream and downstream capillaries resulting from diffusion. There is no significant difference between the samples after 16 days interval (Fig 1. (a)) and 8 days interval (Fig 1. (b)) at the same P and T condition (Pe=29 MPa and T=140 °C). We still observed a similar concentration distribution under the confining pressure of 10 MPa after 8 days. After decreasing the temperature from 140 °C to room temperature (32 °C), the effluent concentration distribution shows a completely different behavior after 8 days. There is no obvious peak concentration in all subsamples, the silica concentration within the fracture aperture decreased to 0.22 mmol/l. Measured silica concentrations are clearly temperature dependent. They show less effective-stress effects while temperature seems like the main factor on the silica concentrations.

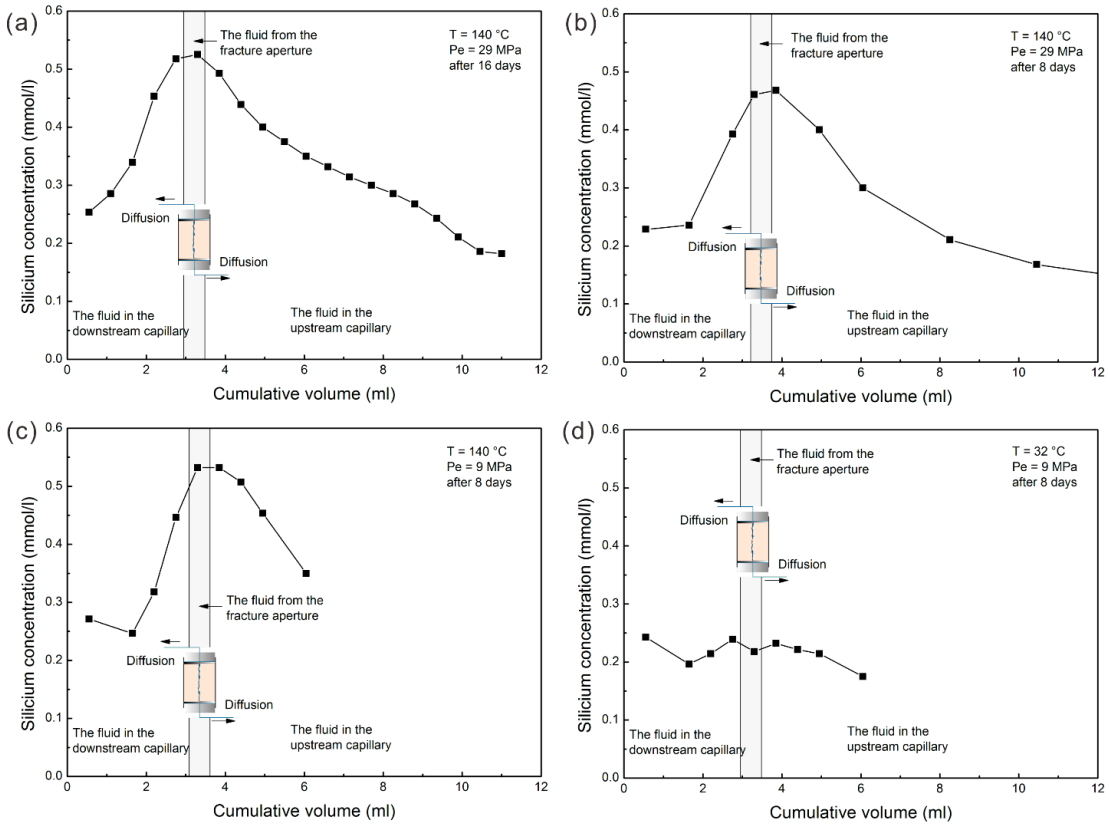


Figure 1: Silica concentrations of the subsamples from the relief valve as a function of cumulative volume, the gray background indicates the silica concentration of the fluid from the fracture aperture, and all the other spots illustrate the silica concentration of the fluid in the downstream and upstream capillaries; the sample is (a) at 140 °C under the effective stress of 29 MPa for 16 days, (b) at 140 °C under the effective stress of 29 MPa for 8 days, (c) at 140 °C under the effective stress of 9 MPa for 8 days, and (d) at 32 °C under the effective stress of 9 MPa for 8 days, respectively.

Figure 2 shows the overall peak silica concentrations as a function of time. It is noticed that after a certain time interval, silica concentration reaches a higher value compared to the distilled water from the upstream pump. The reaction between rock and the fluid within the fracture aperture is obvious at all conditions. While comparing all analyses using a photometer (spots in black), the silica concentrations seem to be not variable (0.41~0.54 mmol/l) at 140 °C even under different stress conditions, but decreases to 0.22 mmol/l when the temperature is 32 °C.

There are two series of effluent measurements conducted with ICP-OES. The peak concentrations are 9.14 mmol/l after a 16 days interval and 8.04 mmol/l after an 8 days interval, respectively (Fig. 2), which are significantly larger than other peak concentrations measured using the photometer. Again, it shows that the influence of different time intervals on the final concentrations is not significant.

It is noticed that the results measured with ICP-OES are more than an order of magnitude larger than the results analyzed using the photometer. This could be as a result of monomeric silica and polymeric silica in the solutions. ICP-OES measures the total silica concentration of the effluent, while only the silica monomers are detected by the photometer as the reagent reacts only with monomeric silica in the solution. The dissolved silica within the fracture aperture may reach equilibrium at 140 °C after the time intervals applied. When we sampled the effluent through the cooling spiral capillary from the outlet, the temperature of the effluent significantly decreased to room temperature forming supersaturated silica. The total sampling took about 20 mins (flowrate=0.5 ml/min, total effluent volume 10 ml) and the preparation of the concentration measurement (with photometer) took about 2 hours each time. Silica concentration exceeds the solubility of silica at room temperature, forming silica polymers due to the polymerization of dissolved monomer silica before analysis. It has to been noticed is that 10 times dilution for effluents with distilled water is not capable to decrease the concentration of monomeric silica below the solubility limit at room temperature. In addition, there were about 2 hours 20 mins each time before dilution. The supersaturated silica solution may progressively form polymers, which is also a time-dependent process.

The procedure of sampling and the concentration measurement was the same for all effluents, meanwhile, the peak concentration of the total silica (ICP-OES) is also observed. Therefore, the monomeric silica distribution can somehow response the diffusion process of the total dissolved silica.

The variation of the hydraulic aperture is negligible (a_h : 37 µm ~38 µm) throughout the experiment. When the temperature decreased to 32 °C, the hydraulic aperture ultimately increased to 63 µm. The significant hydraulic aperture increase resulted from the changes of thermal-induced deformation of the rock matrix, which is not considered in the current study.

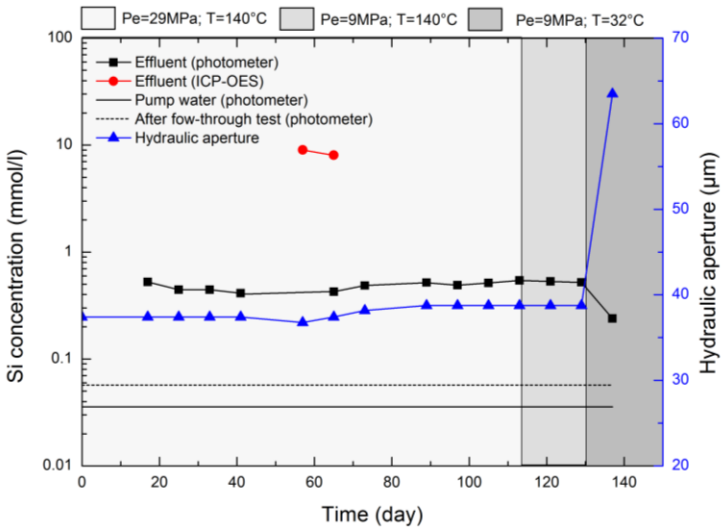


Figure 2: The maximum silica concentration of each series of subsample effluent and the measured hydraulic aperture as a function of the duration of the experiment under different pressure and temperature conditions.

3.2 Mineral Dissolution

To distinguish the effects of free face dissolution and pressure-induced solution on silica concentration of effluents, we assume that the kinetic quartz dissolution has reached equilibrium after the respective time intervals, which is 1.73 mmol/l at 140 °C and 0.13 mmol/l at 30 °C calculated using PHREEQC. Therefore, the measured silica in the effluent consists of two components; dissolved silica from the free face of quartz and the lithostatic stress-induced dissolved silica from contact asperities. Since pressure solution rate is significantly faster than the kinetic reaction rate of quartz (De Boer, 1977b), the concentration increases due to the diffusion of the dissolved silica from the stressed asperities to the pore fluid, which may inhibit the dissolution of the free fracture walls.

It is found that all peak silica concentrations (monomer) are larger than the quartz solubility at 30 °C, whereas smaller than that at 140 °C. Since the polymerization is a time-dependent process, samples were diluted about 2 hours later after sampling. The supersaturated silica did not reach equilibrium; dilution made the oversaturated-monomeric silica to become undersaturated, and therefore the measured silica monomer concentration is significantly greater than the quartz solubility at room temperature.

The rate of mechanical fracture aperture variation, db/dt is related to the pressure solution rate, $\dot{m}_{str}(t)$, of the stressed asperities (negative, leads to fracture closure) and the free face dissolution rate, $\dot{m}_{fre}(t)$, of the fracture walls (positive, enlarge fracture voids), which may be expressed as,

$$\frac{db}{dt} = -\frac{\dot{m}_{str}(t)}{A \cdot R_c \rho} + \frac{\dot{m}_{fre}(t)}{A \cdot (1 - R_c) \rho} \tag{4}$$

Where A is the geometric area of the fracture, R_c is the contact area ratio of the two fracture surfaces, and ρ is the density of quartz. Here we use the total silica concentration (measured by ICP-OES) to estimate the dissolved mass resulting from pressure-induced quartz dissolution and use the theoretical kinetic quartz solubility to calculate free face dissolution. Due to the diffusion of the dissolved silica from fracture aperture to the upstream and the downstream capillaries, the entire closed system needs to be accounted for, which can be defined by the accumulation of the concentration distribution after the respective time intervals.

$$\Delta b = -\frac{\sum_{i=1}^{n} V_s \left(C_{total}^i - C_{Si}^i\right)}{A \cdot R_c \rho} + \frac{\sum_{i=1}^{n} V_s C_{Si}^i}{A \cdot (1 - R_c) \rho} \tag{5}$$

Where V_s is the subsample's volume, which is equivalent to the fracture aperture volume, C_{total}^i and C_{Si}^i are the total silica concentration and the silica concentration due to free face dissolution of the ith subsample, respectively. For an assumed contact area ratio in the range of 20% to 50% this yields $\Delta b \approx$ -3.59 to -1.12 µm after a time interval. We assume that the contact area ratio is constant throughout the experiment. Therefore, the total mechanical aperture reduction during the experiment is 14.56 to 46.67 µm depending on the contact area ratio. The calculated mechanical aperture reduction is significantly greater than the hydraulic aperture variations as measured.

3.3 Microstructural Analysis

The total fracture volume decreased from 0.403 ml to 0.204 ml after the experiment based on the 3d-µCT model analysis. However, one cannot distinguish the effects of mechanical compression at the beginning loading-unloading stage and of pressure solution on fracture closure. By assuming that the ultimate fracture aperture is 0.204 ml, for the final contact area ratio in the range of 20% to 50%, the mechanical aperture a_m can be calculated by,

$$a_m = \frac{V_f}{A \cdot (1 - R_c)} \tag{6}$$

Therefore, the final average mechanical aperture is 212.5 to 340 µm. Compared to the final mechanical aperture, the fracture aperture degradation (14.56 to 46.67 µm) during the experimental duration is not drastic. We still observed well-connected fracture voids in the 3d model after the long-term experiment, which allow the fluid to flow through. These flow paths are enlarged by the surface retreat of fracture walls and are also subject to closure due to the pressure solution creep of the propping asperities. In summary, these variations are not sufficient to affect the hydraulic aperture within the duration of the experiment as hydraulic aperture maintained almost constant throughout.

4. CONCLUSIONS AND FURTHER WORK

It is concluded that the silica concentration of the pore fluid increased predominantly due to pressure solution at fracture asperities and can reach a substantial level within a short period of time (several days). The total dissolved silica concentration can be significantly higher than the silica solubility at the same P and T conditions. Different time intervals seem not to significantly affect effluent concentrations and a macroscopic silica diffusion in the closed system was clearly observed. The dissolution and diffusion of quartz (silica) within the water film between the stressed contacting asperities may be restricted by the ion concentration of the surrounding fluid, alleviating pressure solution creep. In contrast, continuous flow-through would disturb the chemical equilibrium within the pore fluid accelerating pressure-induced mineral dissolution, which was observed in previous investigations (Polak et al., 2003; Yasuhara et al., 2006).

Open questions to be addressed in further work are that: 1. the mechanical aperture is significantly larger than the hydraulic aperture, the fracture closure could be insufficient to trigger variations of the hydraulic aperture within the experimental duration; 2. The silica concentration distribution was obtained by a monomer detector (photometer) while it may not show a completely similar behavior for the total silica distribution.

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