A Preliminary Study on Fluid-Rock Interactions of the Hot Fractured Rock Geothermal System in Cooper Basin, South Australia

Gideon B. Kuncoro[1], Yung Ngothai[1*], Brian O'Neill[1], Allan Pring[2], Joël Brugger[2]
[1] The University of Adelaide, School of Chemical Engineering, North Terrace, Adelaide, SA, 5000
[2] South Australian Museum, North Terrace, Adelaide, SA, 5000
*Corresponding author: yung.ngothai@adelaide.edu.au

A study of the interactions between rock and circulating fluid is essential to determine the chemical changes and mineral alteration of a geothermal system. Preliminary mineralogical investigation and geothermal experiments have been performed to investigate the hydrothermal alteration of the Habanero geothermal system in the Cooper Basin, South Australia. Samples of drill cuttings from a borehole 5 km deep were contacted with reverse osmosis water in a thermosyphon induced loop reactor at 250°C and 50 bar. Fluid and rock samples were analysed prior to, and after circulation of the water through crushed sample of the rock (100 – 200 µm diameter) for 1, 2, 3, 7, 14 and 21 days. Water analysis was performed using ICP-MS, and rock analyses were conducted using an optical microscope, SEM and XRD. The experimental results indicated that mineral dissolution was more rapid in the early stages of the experiment. This may be a consequence of the dissolution of finer rock particles. SEM observations showed evidence of etching of the mineral surfaces consistent with partial dissolution. XRD results indicated that quartz was stable throughout the experiment, and that the albite-feldspar ($NaAlSi_3O_8$) in the rock had partially dissolved. ICP-MS analysis on the water sample confirmed that some mineral dissolution has occurred. The concentrations of most elements increased with the exception of Ca, Ba and Mg. Future work will quantify concentrations (ppm) of the dissolved minerals.

Keywords: hot fractured rock, fluid-rock interaction, geothermal, Cooper Basin, Habanero

Introduction

Hot fractured rock (HFR) geothermal energy has great potential as a future supply for electric power generation by harnessing stored thermal energy from high temperature granitic rocks in the Cooper Basin and North Flinders Ranges. This route provides opportunities for power generation with minimal greenhouse gas emissions or long-lasting nuclear wastes, at a cost competitive with those for energy generated from fossil fuels if carbon costs are considered. The geothermal heat exchange occurs at great depth, up to 5 km, and the thermal energy source is radioactive decay rather than volcanism (Geodynamics, 2009). Existing reservoir granites are currently in equilibrium with the surrounding ground water. The injection of fresh water to extract thermal energy from the host rock will alter this fluid-rock equilibrium and may cause partial chemical dissolution or mineral species alteration, which may potentially increase the dissolved solids such as silica and other metals in the water. These dissolution products of the components have different equilibria, which will be a function of temperature and pressure, thus precipitation or scaling of pipe work and closure of fractures in the granite body are possible. The saturation of metals in fluid is volume-dependent, where very small volumes of fluid may require slight under-cooling before precipitation occurs. Clearly, characterization of fluid geochemistry is important in the evaluation of the performance of geothermal systems (Grigsby et al., 1989). Moreover, understanding the chemical interactions due to the injection of fluid into hot granite is crucial for problems concerning clogging by precipitation and heat loss caused by dissolution (Azaroual and Fouillac, 1997).

The study of fluid-rock interaction will allow determination of mineral alteration and dissolution of minerals to the circulating water. Unfortunately, relatively little information is available on the rates and chemical mechanisms of mineral reactions in hydrothermal solutions (Posey-Dowty et al., 1986). Furthermore, it is impossible to generalize the actual field experience of mineral deposition in geothermal systems into one consistent theory due to the vast chemical and operational variation between field sites (Robinson, 1982). Therefore, although there have been a number of studies on fluid-rock interactions for different geothermal sites (Rimstidt and Barnes, 1980; Robinson, 1982; Posey-Dowty et al,. 1986; Savage et al., 1987; Grigsby et al., 1989; Savage et al., 1992; Azaroual and Fouillac, 1997; Yangisawa et al., 2005), these are probably not directly applicable to the hot granite-based geothermal systems in the Cooper Basin.

Flow-through Cell

A hydrothermal reaction cell has been developed to observe chemical changes in the host rock and the circulating fluid. A diagram and a photograph of the flow through cell are provided in Figure 1. The cell is designed to operate in a flow-through configuration where the fluid flows continuously inside the cell. The total cell volume is 345 ml. All tubing is made from ¼ inch titanium and connected with standard Swagelok titanium fittings, with the reservoirs in stainless steel

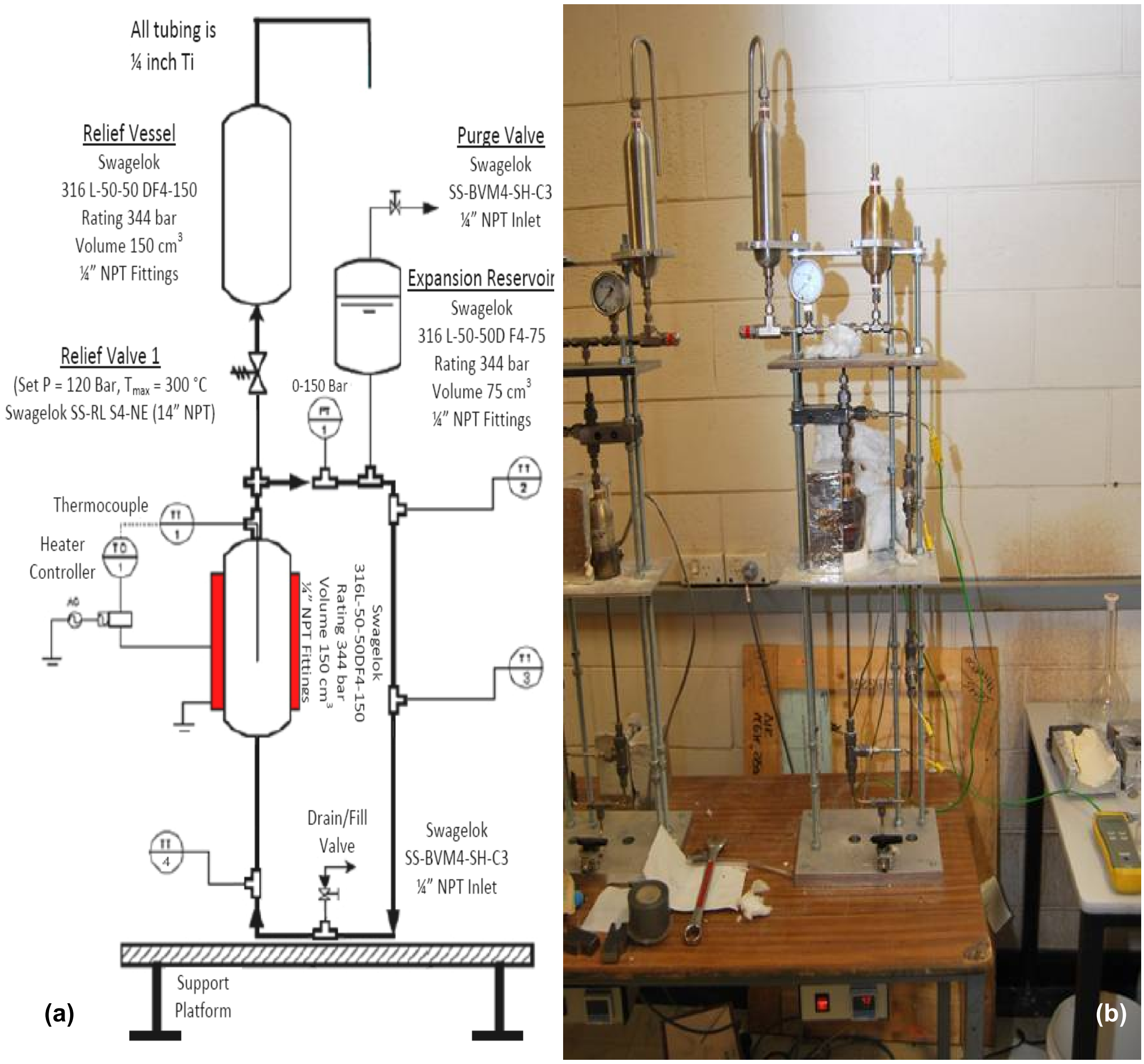

Figure 1: (a) Diagram of the flow through cell (b) Photograph of the geothermal flow through cell

(SS316). The total length of the cell loop is approximately 1800 mm. The volume of the main reservoir is 150 cm^3. A pressure relief system consisting of a relief valve and a relief vessel is employed to the cell for safety. The volume of the relief vessel is 300 cm^3 and the relieve valve was set to open at a maximum pressure of 100 bar. An expansion reservoir is employed to compensate for changes in volume as the fluid is heated. The volume of the expansion reservoir is 75 cm^3. All vessel are rated at 344 bar. Four thermocouples are installed to monitor the temperature changes throughout the cell. A pressure transducer is installed to monitor the pressure. The operating temperature and pressure are 250^{o}C and 50 bar, respectively. Temperature is controlled by a simple relay controller and two heaters were used and arranged in parallel. The heaters are intact with the main reservoir and insulated with ceramic bricks.

Experimental

Samples of drill cuttings were provided by Geodynamics from the Habanero 3 well. The samples were analysed using optical microscope, scanning electron microscope (SEM) at the Adelaide Microscopy Centre to observe both surface and cross-sectional area, and powder X-ray diffraction (XRD) at the South Australian Museum to identify and semi-quantify the minerals. A preliminary set of experiments to observe the fluid-rock interaction were performed in batch mode. The drill cutting was used as the rock sample. The rock sample was crushed and sieved to give 100 – 200 µm size fraction and approximately 0.7 grams of rock were used in each batch. The sample was contained in a pre-weighed wire basket made from stainless steel and placed in the sample holder of the cell. The cell was filled through a valve in the base of the cell with reverse osmosis (RO) water and then 90 ml of water was drained from the cell to allow for fluid expansion upon heating. The velocity of the thermosyphon circulating fluid is estimated to be approximately 0.1 m/s. The fluid-rock interaction periods were 1, 2, 3, 7, 14, and 21 days. At conclusion of this interaction period, the rock sample was dried (105°C for 48 hours), cooled in a desiccator, and weighed to determine any weight loss.

The rock samples were analysed using SEM and XRD, and the water samples were stored and preserved with 4% w/w of 1M nitric acid until analysis by ICP-MS to identify the dissolved metals. The silica content was quantified using heteropoly blue method (HACH, 2009).

Results and Discussion

Preliminary results from the geothermal cell experiment illustrate that the dissolution of the rock (% w/w) increases with time (Figure 2).

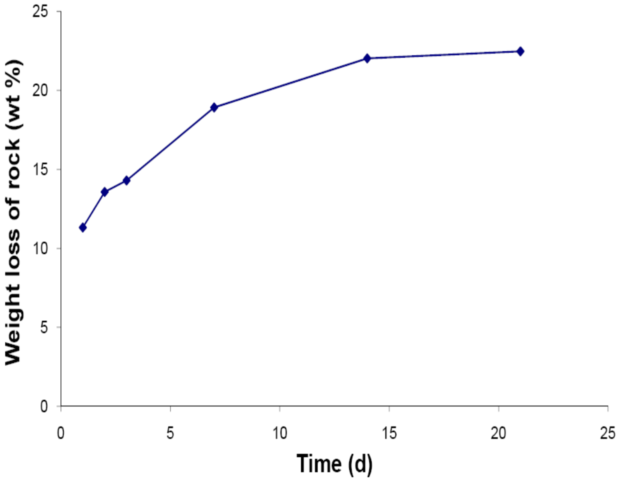

Figure 2: Change in weight loss of rock (% w/w) versus time

However, dissolution appears more rapid in the early stages of the experiment. It is probably an artefact of the rapid dissolution of fine particles present in the rock sample (Savage et al., 1987).

The later stage of the experiment approached a steady state value. However the fluid is not necessarily saturated with minerals (feldspar), but due to the low dissolution reaction rate between the remaining phases causes this behaviour..

Detailed analyses of the mineralogical changes in the host rock are currently underway and will be reported at a later date.

Rock Analysis

Petrographic analysis was performed on the drill cuttings from Habanero 3 well. The rock is a feldspar syenite, containing albite (NaCa)AlSi$_3$O$_8$, and microcline (KAlSi$_3$O$_8$) with carbonate alteration, which has been subjected to hydrothermal alterations (Pring, pers. comm. 2009), as shown in Figure 3.

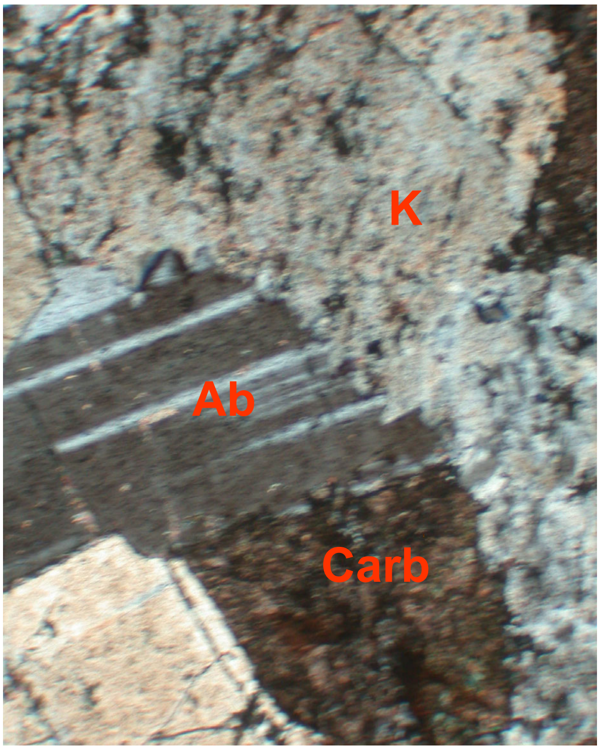

Figure 3: Host rock Habanero 3 – “syenite” consisting of albite (Ab), microcline (K) with extensive carbonate (carb) alteration – field of view 2mm across

SEM images of the surface particles were obtained using the secondary electron detector (SE) of the XL30 in Adelaide Microscopy. The SEM images of the rock sample surfaces before and after the experiments are shown in Figure 4. It can be seen that fine particles adhered on the surface of the starting rock. The fine particles rapidly dissolved during the early stages of the experiments and the roughness of the rock surface also becomes more apparent with longer interactions with the fluid. Etching is evident on the surface of the rocks and again developed in the later stages of the experiment. This indicates that a dissolution reaction has occurred in the interaction period.

SEM analyses of the cross section of the rock samples (images not presented) were also conducted. These images were obtained using the backscattered electron detector (BSE) and analysed using the energy dispersive x-ray spectrometer. The results suggest that the rock is composed of albite-feldspar, microcline and quartz. The feldspar was variably veined and was replaced by patches of fine grained carbonate with a magnesium and iron-rich composition. The rock also contains minor amounts of pyrite (FeS$_2$), sphalerite (ZnS), fluoropatite (Ca$_5$(PO$_4$)$_3$F and a number of other accessory minerals. Preliminary observation of the SEM analysis on the rock samples after the experiment indicates minimal alteration. However, it was evident that the carbonates have dissolved in the early stages of the experiment.

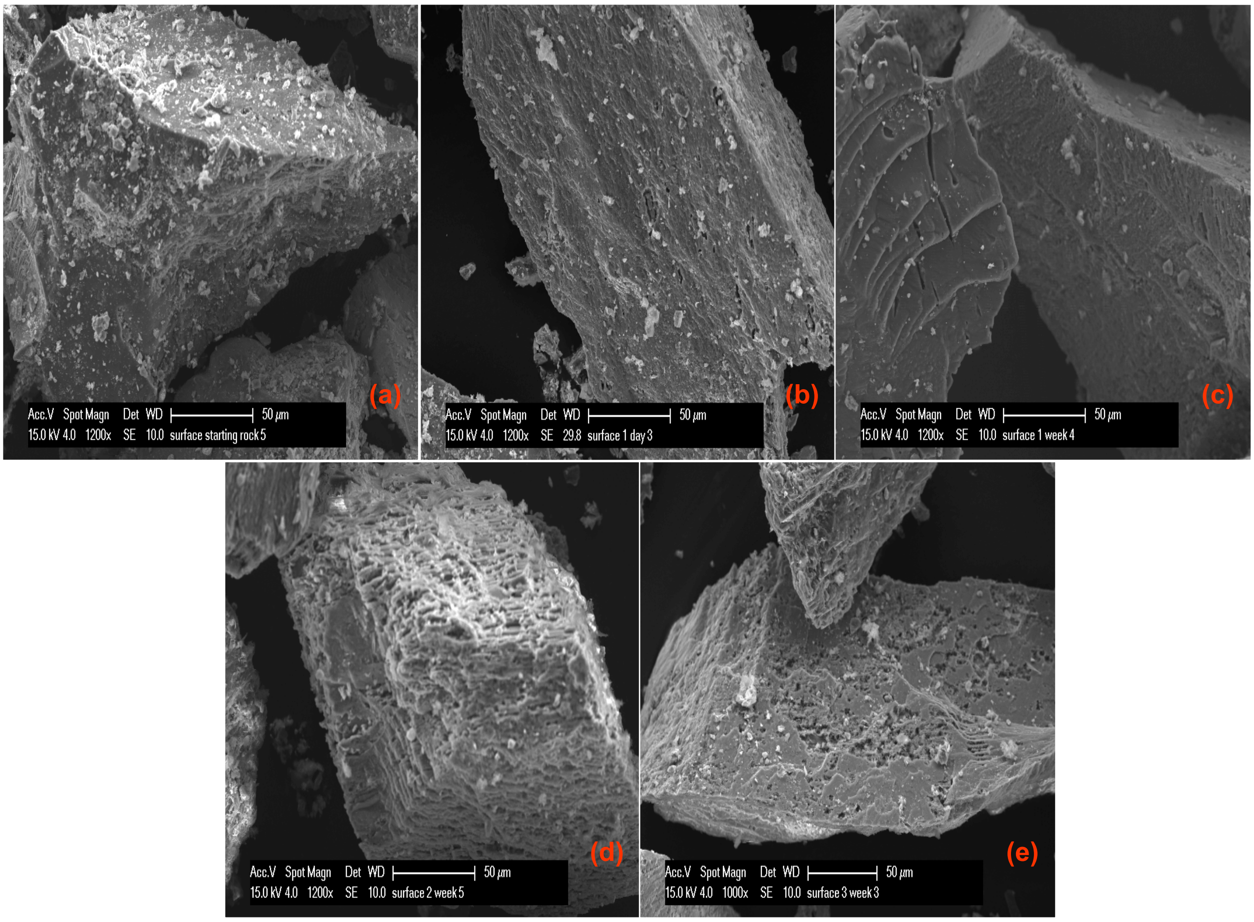

Figure 4: SEM images of the rock sample surface (a) starting rock (b) after 1 day experiment (c) after 1 week experiment (d) after 2 weeks experiment (e) after 3 weeks experiment

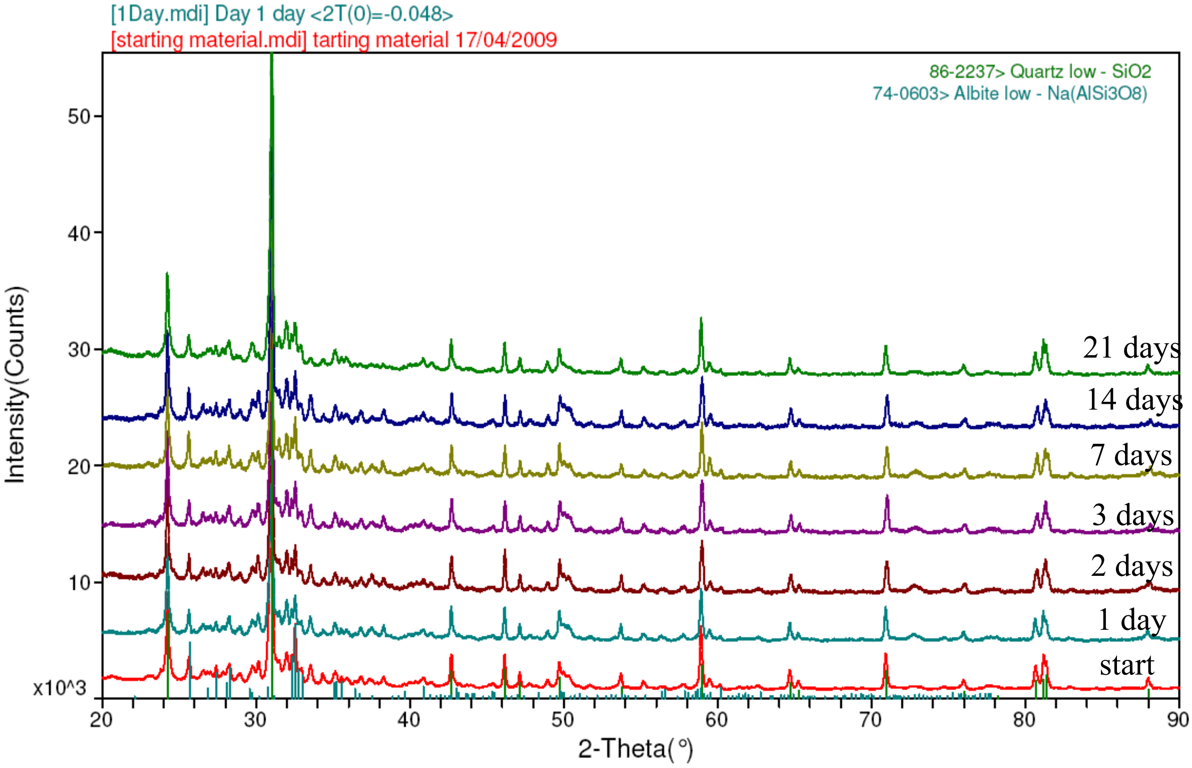

Figure 5: Compiled XRD analysis results from geothermal cell experiments

Traces of iron, manganese, magnesium, and strontium were found in the solutions after the experimental runs. Some of the iron may be contaminants from partial dissolution of metals from the stainless steel basket and/or the stainless steel reservoir of the geothermal cell. The results from the X-ray diffraction analysis of the rock sample from different stages of the experiment are presented in Figure 5. It is seen that the peaks showing intensity do not change significantly in different experimental runs. The lines in the XRD trace for albite and microcline show slight decrease compared to those of quartz, which is quite stable. Quantitative phase analysis using the X-ray diffraction data is planned for future work.

Water Analysis

The initial pH of the water was 5.5. This did not change significantly in all batch experiments. Figures 6 – 9 show the concentration of elements versus time from the ICP-MS analysis on the circulating water after 1, 2, 3, 7, 14, and 21 days of fluid-rock interactions.

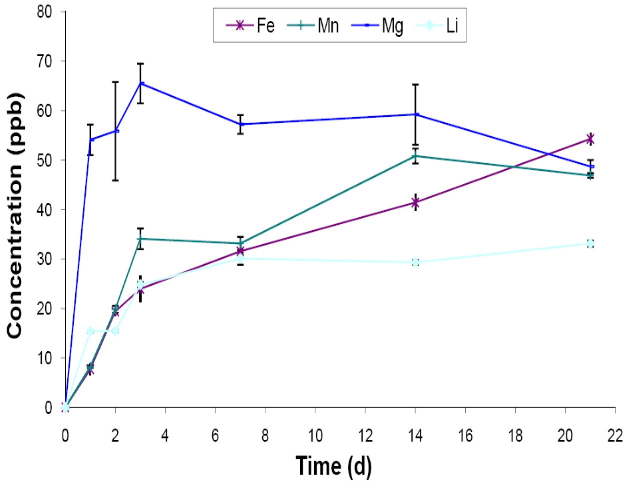

Figure 6: Concentration of Fe, Mn, Mg and Li in experimental liquid versus time

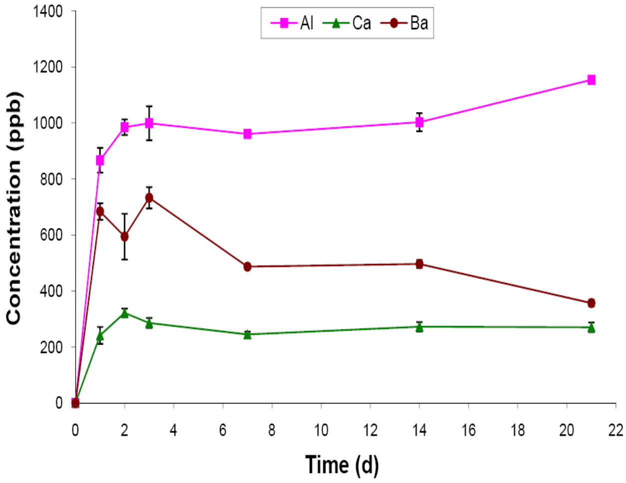

Figure 7: Concentration of Al, Ca and Ba in experimental liquid versus time

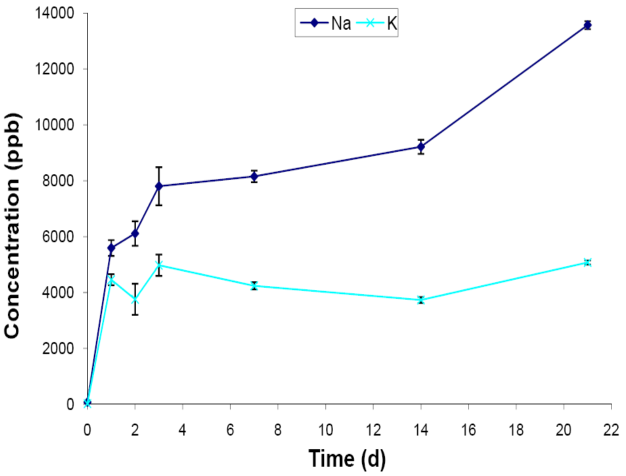

Figure 8: Concentration of Na and K in experimental liquid versus time

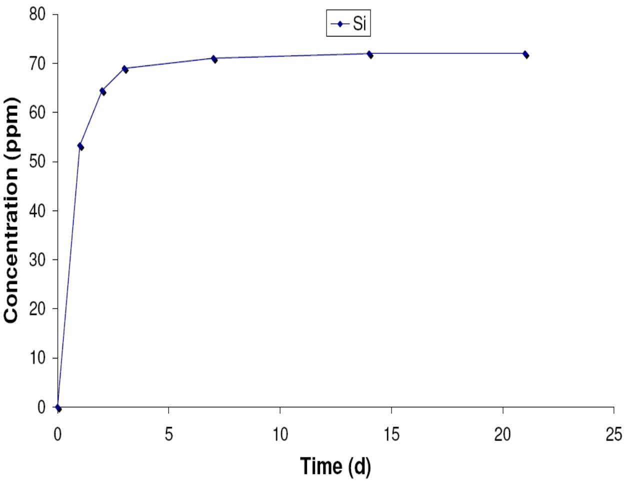

Figure 9: Concentration of Si in experimental liquid versus time (standard deviation 0.0067)

Water analysis results showed that there was enhanced release of the minerals, indicated by the concentration increase of minerals in the liquid phase. The rapid dissolution is probably a consequence to the dissolution of fine particulates which adhere to the mineral grains of the rock sample to the fluid phase (Figure 4a). The use of pure water (very low concentration of dissolved mineral) would also explain the rapid dissolution reaction. The increase in concentration of elements Si, Na, and K in the water would indicate the dissolution of albite and microcline feldspars. The increase in the concentration of Fe and Mn may be the consequence of the carbonate dissolution to the liquid. Traces of Al, Fe, Mn and Mg may be contaminants from the dissolution of accessory minerals. Concentration of all analysed elements showed a net increase during the experiment, except for Ca, Ba, and Mg.

Conclusion

The petrographic and diffraction analysis showed that the rock is composed chiefly of feldspar syenite, quartz, albite and microcline with carbonate alteration. The fluid-rock interaction experiment showed that dissolution reactions occur predominantly in the early stages of the experiment probably due to the dissolution of fine particulates in the rock. In addition, the carbonates have also dissolved in the early stages of the experiment. Results of XRD showed that feldspar experienced a slight reduction; however, quartz remained stable throughout the experiment. Liquid analysis showed higher concentrations of Na, K, Si, and Al compared to other analysed elements. These results suggest that the dissolution reaction occurs primarily for the feldspars.

The dissolution of feldspar would suggest potential silica scaling. The concentration of silica (72 ppm released from 0.7g rock sample) was released to the liquid phase throughout the experiment. Unfortunately the quantification of the minerals has not been concluded, therefore the mass balance and mass transfer rates are still unclear at this stage.

Future Work

The current work has used reverse osmosis water for the fluid-rock interaction and does not represent the actual interaction. Therefore future work will conduct the experiment using a more complex fluid system Na – Cl – H_2O and will progress with the actual fluid from the field. Quantification of the minerals will be performed using electron microprobe to understand the mass transfer occurring in the interaction. Modelling of the fluid-rock interaction will be performed in the later stage of this research using Geochemist Workbench.

Acknowledgments

The research described in this paper has been supported by The Department of Primary Industries and Resources of South Australia (PIRSA) and Geodynamics. The author would like to thank Geodynamics for supplying the drill cuttings, and the South Australian Museum and Adelaide Microscopy for the equipment access.

References

Azaroual, M., and Fouillac, C., 1997, Experimental Study and Modelling of Granite-Distilled Water Interaction at 180°C and 14 Bars: Applied Geochemistry, V. 12, pp. 55-73.

Geodynamics, 2009, Power from the Earth. Habanero 3, http://www.geodynamics.com.au/IRM/Company/ShowPage.aspx?CPID=1403, accessed 10 January 2009.

Grigsby, C. O., Tester, J. W., Trujillo JR., P. E., and Counce, D. A., 1989, Rock-Water Interactions in the Fenton Hill, New Mexico, Hot Dry Rock Geothermal Systems I, Fluid Mixing and Chemical Geothermometry: Geothermics, V. 18, 629-656.

HACH, 2009, DR/2010 Portable Spectrophotometer Procedures Manual. http://www.hach.com/fmmimghach?/CODE%3A4930022286|1, p 767 – 772, accessed September 2008

Posey-Dowty, J., Crerar, D., Hellerman, R., and Clarence, D. C., 1986, Kinetics of Mineral-Water Reactions: Theory, Design, and Application of Circulating Hydrothermal Equipment: American Mineralogist, V. 71, pp. 85-94.

Pring, A., 2009, personal communication.

Rimstidt, J. D., and Barnes, H. L., 1980, The Kinetics of Silica-Water Reactions: Geochimica et Cosmochimica Acta, V. 44, pp. 1683-1700.

Robinson, B. A., 1982, Quartz Dissolution and Silica Deposition in Hot Dry Rock Geothermal Systems, Thesis, Cambridge, Massachusetts Institute of Technology.

Savage, D., Cave, M. R., Milodowski, A. E., and George I., 1987, Hydrothermal Alteration of Granite by Meteoric Fluid: An Example from the Carnmenellis Granite, United Kingdom: Contributions to Mineralogy and Petrology, V. 96, pp. 391-405.

Savage, D., Bateman, K., and Richards, H. G., 1992, Granite-Water Interactions in a Flow-through Experimental System with Applications to the Hot Dry Rock Geothermal System at Rosemanowes, Cornwall, U.K.: Applied Geochemistry, V. 7, pp. 223-241.

Yangisawa, N. Matsunaga, I., Sugita H., Sato, M., and Okabe T., 2005, Scale Precipitation During Circulation at the Hijiori HDR Test Field, Yamagata, Japan: Proceedings World Geothermal Congress 2005, Antalya, Turkey, 24-29 April 2005.