FRACTURE GENERATION IN ARTIFICIAL GEOTHERMAL RESERVOIRS UNDER SUPERCRITICAL WATER CONDITIONS

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SUMMARY – This paper discusses the generation of micro-fractures in a granite under a super critical water environment. In order to create an artificial pathway of water in a geothermal reservoir with limited permeability, hydraulic stimulation technology is commonly employed. In this study, simulated hydraulic stimulation tests were performed using thick-walled cylindrical specimens of 45 mm outer diameter, under temperatures up to 600 °C and confining pressures up to 100 MPa. The experimental results showed that there was no macroscopic fracturing in the high temperature regime where the predominant fluid flow occurred. The permeability of the granite was also measured using the same cylindrical specimen configuration as was used in the simulated hydraulic stimulation tests. The permeability test results showed that the permeability of the granite was enhanced drastically when the temperature exceeded the critical point of water, whilst no significant increase in the permeability was observed under the subcritical water condition. Optical microscopy of the microstructural change revealed that the enhanced permeability was due to the formation of micro-fractures under the supercritical water environment. This laboratory-scale test result suggests that it may be possible to generate a micro-fracture network by injecting water into a high temperature rock mass whose conditions exceed the critical point of water and to extract the heat energy through the generated fracture network from the supercritical rock mass.

1. INTRODUCTION

Geothermal energy is one of the "green" energy resources that is expected to play a significant role in sustainable development. In order to increase the amount of geothermal energy available, new extraction systems which are called HDR (Hot Dry Rock) and HWR (Hot Wet Rock) systems are being investigated (Abé *et al.,* 1999). A recent survey at the Kakkonda geothermal field in Japan discovered very hot granite rock just beneath the existing hydrothermal reservoir (Ikeuchi *et al.,* 1996, Kato *et al.,* 1996, Uchida *et al.,* 1996). In the Kakkonda geothermal field, the rock temperature has been shown to reach 500 °C at a depth of approximately 3500 m. This thermal condition is not unique to the Kakkonda field. Hot rock masses having a temperature well above 350 °C have been also found in Italy (Cappetti *et al.* 1985), Iceland (Staingrimsson *et al.* 1990) and other countries. If we could use the heat energy stored in this class of high temperature rock, the total amount of geothermal energy could increase significantly.

As demonstrated by the field survey at the Kakkonda geothermal field, the temperature and pressure conditions of the deep-seated high temperature rock exceeds the critical point of water. It has also shown that no significant natural fracture network and no significant water is present in the rock mass. The rock mass underlying the existing geothexmal reservoir is a neo-granitoid pluton. This observation at the Kakkonda field suggests that an artificial water pathway will have to be formed, for example by hydraulic stimulation, in order to extract the heat energy from the deep-seated rock mass.

In this paper, simulated hydraulic stimulation tests were performed on a granite under high temperature and pressure water conditions up to 600°C and 100 MPa in order to discover the fracture behavior under a supercritical water environment. The permeability of the granite was also determined to characterise the fluid flow characteristics at various water conditions above the critical point. The effects of temperature and fluid pressures on the observed fracture and permeability behaviour were examined based on thin section observations of microstructural change. In this paper, we call high temperature rock masses whose conditions exceed the critical point of water "supercritical rock mass".

2. EXPERIMENTAL, PROCEDURE

2.1 Hydraulic Stimulation Test

The rock used in this study was Iidate Granite, which was taken from a quarry in Fukushima Prefecture, Japan. Iidate Granite is a coarse-grained rock, average grain size of 1.5 mm and composed of 37.1% quartz, 34.0% K-feldspar, 6.3% plagioclase and other minerals.

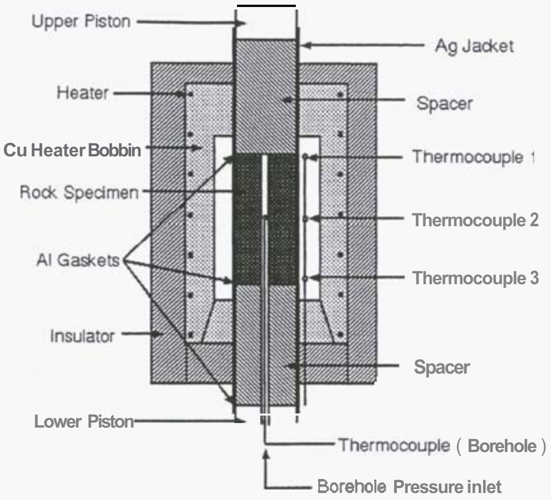

Figure 1 – Schematic diagram of triaxial pressure vessel for simulated hydraulic stimulation test and permeability test under supercritical water conditions

Simulated hydraulic stimulation tests were conducted on the granite using thick-walled cylindrical specimens. The outer and inner diameter of the cylindrical specimens were 45 mm and 5 mm, respectively, and the specimen height was 90 mm. Schematic illustration of the hydraulic stimulation test apparatus used is given in Fig.1. The maximum temperature and confining pressure achievable with this triaxial apparatus are 600 "C and 150 MPa, respectively. The cylindrical specimen and metallic spacers were inserted into a 0.3 mm thick silver jacket to form a specimen assembly, as shown in Fig. 1. The specimen assembly was then placed between the upper and lower pistons. Sealing tapes were attached to the end of the silver jacket to prevent the fluid flow between the jacket and pistons during the simulated hydraulic stimulation tests. After applying confining pressure onto the cylindrical specimen, the temperature was elevated at a constant rate of 3 °C/min up to a predetermined value. The heating of the specimen was achieved using an internal heater. The temperature control was conducted using a thermocouple placed in the middle of the specimen, and the temperature distribution was monitored at the upper and lower positions. The temperature difference was less than 3 % with respect to the central vertical position. The borehole temperature was also measured using a thermocouple during the hydraulic stimulation tests. The temperature drop at the borehole was approximately 5% compared with the testing temperature. After the temperature reached the predetermined level, water was then injected into the borehole at a constant flow rate. The flow rate used in this study is in the range of 0.5 mm^3/sec - 300 mm^3/sec.

2.2 Permeability Test

Permeability tests were performed using the same test apparatus as the simulated hydraulic stimulation tests. Water was injected into the cylindrical specimen at a constant flow rate, while the confining pressure was kept constant. The flow tests were conducted at reduced injection rates to prevent macroscopic fracture of the specimen. The injection was continued until steady state flow was achieved, and the borehole pressure under the steady state was determined at various temperatures and pressures.

The permeability of the rock k was calculated from the measured borehole pressure, confining pressure and flow rate using the following equation,

$$\Delta P = \frac{Q}{2\pi l(k/\nu)} \ln \frac{r_o}{r_i} \qquad (1)$$

where ΔP is the difference between the borehole pressure and confining pressure, Q is the constant flow rate, l is the height of the specimen, r_o, r_i is the outer and inner radius of the specimen, ν is the viscosity of pure water at various temperatures and pressures was taken from literature.

In order to investigate the microstructural change in the granite specimens after the permeability tests, thin sections of 100 µm thickness were prepared from the tested specimens and examined under a petrographic microscope. From these, the micro-fracture density in individual rock forming minerals was determined.

3. RESULTS AND DISCUSSION

3.1 Hydraulic Stimulation Test Result

The experimental results of the simulated hydraulic stimulation tests are shown in Fig. 2. Fig. 2(a) shows the variation of the borehole pressure with respect to time for the testing temperature of 25 "C, under the confining pressure of 100 MPa. As indicated by the breakdown behavior, macroscopic fracturing took place when the pressure exceeded the confining pressure (113.5 MPa) at room temperature.

Fig. 2(b) shows the pressure change for 600 "C. The injection rate (5.0 mm^3/sec) is the same as for room temperature. In this high temperature condition, no macroscopic fracture formed and no significant difference between the borehole and confining pressure was observed, indicating that flow dominant behaviour was occurring. It should be mentioned here that a macroscopic fracture was induced at an injection rate greater than 200 mm^3/sec at 500 "C, and no macroscopic fracture formed at 600 "C within the range of flow rates used in this study (max. 300 mm^3/sec). This observation suggests that the fracture behavior of the granite is brittle at the supercritical temperature regime for the strain rates employed in the hydraulic stimulation tests. Thus it is feasible to create macroscopic fiactures in the rock at the supercritical temperature conditions if sufficiently high injection rates are employed to build-up the borehole pressure. Typical flow rates employed in field-scale hydraulic stimulations are equivalent to the flow velocity at the borehole wall on the order of 0.01-0.1 mm/sec. The flow velocity corresponds to the injection rate of 10-100 mm^3/sec for the simulated hydraulic stimulation tests in this study. It can be seen that, for the high temperature regime, macroscopic fracturing took place in the laboratory-scale tests at the injection rate equivalent to that of field-scale hydraulic stimulations. Thus we investigated the flow dominant behavior observed at the high temperature in more detail.

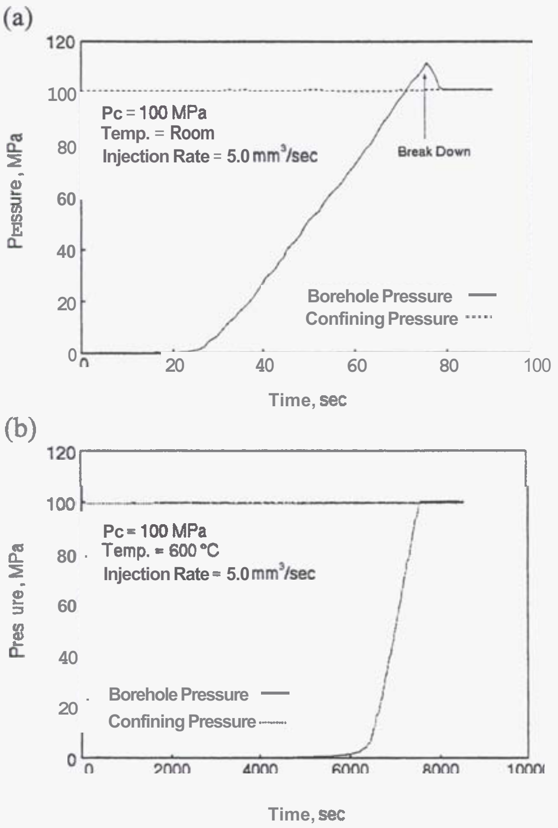

Figure 2 – Pressure behavior in simulated hydraulic stimulation tests. (a) 25 °C and (b) **600** "C. The injection rate is **5.0** mm^3/sec and the confining pressure is 100 MPa.

3.2 Permeability Test Result

The permeability data obtained from the flow tests are shown in Fig. **3**. Fig. 3(a) shows the temperature dependency of the permeability for various confining pressures. The borehole pressure in the flow tests, conducted at the reduced injection rates, was close to the confining pressure indicated in the figure. Above the critical point of water, the pressure difference was less than 1.0 MPa. Thus, the confining pressure value can be taken as that of the borehole pressure. It can be seen that the permeability increases rapidly when the temperature exceeds the critical temperature **of** water (374 °C), whilst **no** significant increase of the Permeability is observed under the subcritical water condition. We have conducted cyclic measurements **and** monitored the permeability during the cooling stage as well **as** during the heating stage. No significant change in the permeability **has** been observed and the permeability attained at the **maximum** temperature **has** been shown to be maintained during the cooling stage, particularly in the supercritical water regime. The cyclic measurements indicate that the permeability enhancement at the high temperatures is due to **an** irreversible process. It can **also** be noted in Fig. 3(a) that there is some pressure dependence of the penneability.

In Fig. 3(b), the permeability is plotted as a function of the confining pressure (water pressure). The permeability remains extremely **small** with the water pressure less than 20 MPa. However, the permeability shows a drastic increase at the pressure of 25 **MPa,** which is above the critical pressure point of water **(22.1 MPa).** Thus, the rapid increase in the permeability occurs when the water reaches supercritical conditions.

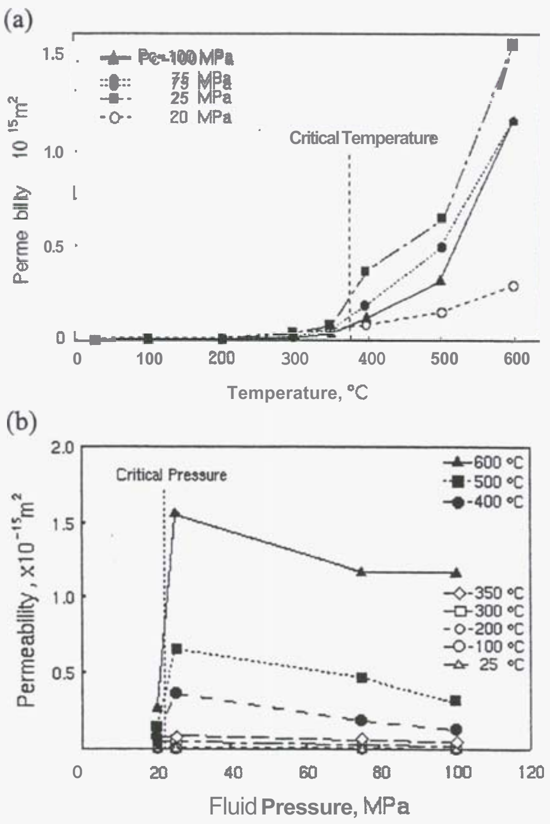

Figure **3** – Permeability changes. (a) Temperature dependence (b) Fluid pressure dependence.

3.3 Effect of Micro-fracturing Behaviour

We studied the microstructural change due to the hydraulic injections using thin sections in order to examine the cause of the permeability increase. Figs. 4(a) and (b) show photographs of the thin sections of the specimens used in the flow tests. As illustrated in Fig. 4(a), no significant change was observed in the microstructure up to 300 °C. In contrast, a number of micro-fractures at grain-scale were generated at higher temperatures as shown in Fig. 4(b). The micro-fractures can be seen in all the minerals of the granite and their orientation is random.

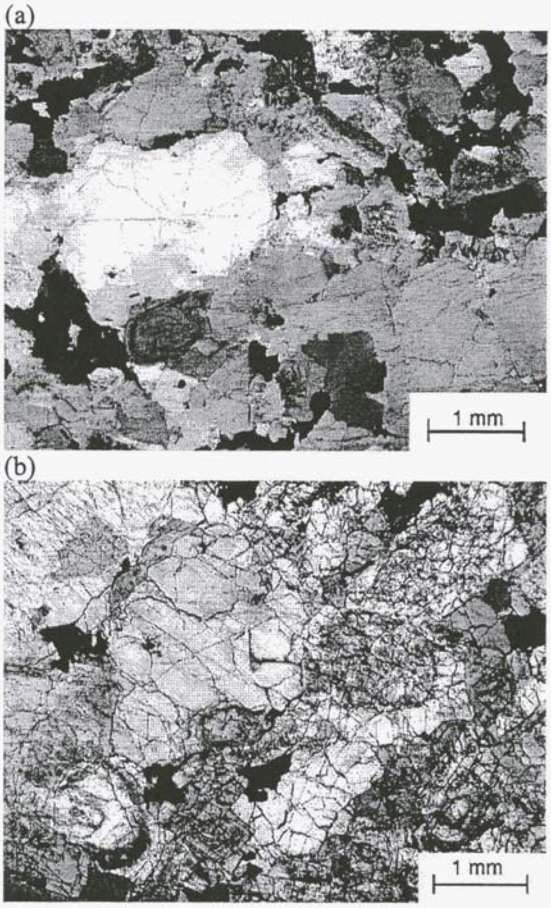

Figure 4 – Thin section photograph of the granite after flow test. (a) 300 °C and (b) 600 °C

From the thin section observations, we determined the micro-fracture density in tested specimens and compared with the permeability measurements. In order to evaluate the micro-fracture density, a trace of micro-fractures was constructed using the thin section observations, including both intra-granular and grain-boundary micro-fractures. It has been shown that the number of the grain-boundary micro-fractures is much smaller than that of the intra-granular micro-fractures.

Crack density, S_v, may be computed using the following equation (Underwood, 1969),

$$S_v = \frac{\pi}{4}\frac{L}{A} \qquad (2)$$

where L is the fracture length and A is the area of observation.

Figure 5 shows the measured micro-fracture density as a function of the testing temperature for various water pressures. As mentioned above, the micro-fracture density includes both intra-granular and grain-boundary micro-fractures. The initial micro-fracture density in the intact specimen was approximately 5 mm^{-1}. It was demonstrated that the micro-fracture density increases significantly at temperatures greater than the critical temperature, except for the water pressure of 20 MPa. The increase of the micro-fracture density is less at 20 MPa, compared with the result for the water pressure above the critical point of water. It appears that the micro-fractures are induced when the temperature and pressure exceeds the critical point of water.

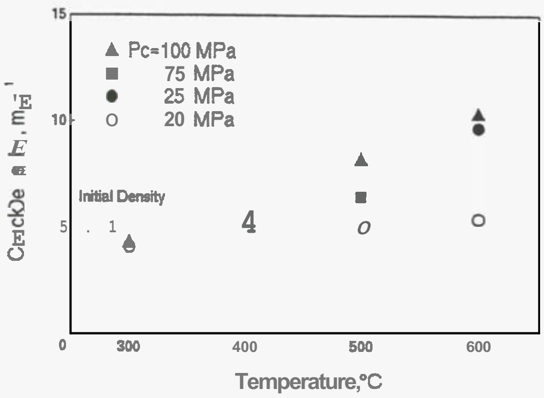

Figure 5 – Micro-fracture density vs. testing temperature.

The variation in the micro-fracture density correlates very well with the permeability increase shown in Fig. 3. Thus, it is concluded that the permeability enhancement observed in the supercritical water conditions is due to the generation of the micro-fracture network. As discussed above, supercritical water plays an important role in the occurrence of micro-fracturing in rock forming minerals. If we are to develop a deep-seated geothermal reservoir using hydraulic stimulation, a fracture network will develop because of the micro-fracturing, and hence, the permeability of rock mass will increase. It is also suggested that the supercritical rock mass may be a volume-like porous reservoir which is the most advantageous type of reservoir to extract heat *energy*. Hence, it can be said that a supercritical rock mass has the potential to become a renewable energy resource. However, this mechanism for supercritical water-induced microfracturing needs further investigation.

4. CONCLUSIONS

Simulated hydraulic stimulation tests were performed on Iidate Granite using cylindrical specimens under a supercritical water environment to investigate the reservoir formation mechanisms in supercritical rock masses. In addition, flow tests were conducted to determine the Permeability of the granite. The testing temperature was up to 600 "C and the confining pressure up to 100 MPa. The following conclusions can be drawn fiom the present study:

- In the simulated hydraulic stimulation tests, no macroscopic fracture was initiated and flow dominant behavior took place at relatively higher temperatures and lower injection rates.

- The measured penneability increased drastically when the temperature and pressure of the injected water exceeded the critical point of water.

- The microstructural observation revealed that the micro-fracture network was generated in the granite under the supercritical water environment. The generated micro-fracture network was shown to be responsible for the dominant flow behavior and the permeability enhancement in the supercritical water condition. It was also demonstrated that the variation in the micro-fracture density correlates well with the permeability increase.

- The experimental observation suggests that it may be possible to generate a volume-like reservoir by hydraulic stimulation and to extract the heat energy fiom supercritical rock masses.

5. ACKOWLEDGEMENTS

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6. REFERENCES

Abé, H., Niitsuma, H. and Baria, R. (ed.), (1999) Special Issue on Hot Dry Rock/Hot Wet Rock academic review, *Geothennics*, **28.**

Cappetti, G., Romano, C., Cigni, U., Squarci, P., Stefani, G. and Taffi, L., (1985). Development of deep explotariotn in the geothexmal areas of Tuscany, Italy. ***Geothermal Resources Council. Int. Symp. on Geothermal Energy.*** **303-309.**

Ikeuchi, K., Komatsu, R., Doi, N., Sakagawa, Y., Sasaki, M., Kamenosono H. and Uchida, T. **(1996)** Bottom **of** hydrothermal convection found by temperature measurements above 500 "C and fluid inclusion study of **WD-1** in Kakkonda geothermal field, Japan. ***Geothermal Resources Council Transactions,*** Vol. **20,** pp. **609-616.**

Kato, O., Doi, N., Ikeuchi, K., Kondo, T., Kamenosono, H., Yagi, M. and Uchida, T. **(1996)** Characteristics of temperature curves and fracture **systems** in quaternary granite and tertiary pyroclastic rocks of NEDO WD-la in the Kakkonda geothermal field, Japan, ***Proc. 8th Int. Symposium on the Observation of the Continental Crust through Drilling,*** pp. **241-246.**

Staingrimsson, B., Gudmundsson, A., Franzon, H. and Gunnlaugsson, E., **(1990)** Evidence **of** a supercritical fluid at depth in the Nesjavallir field. ***Proc. 15th Workshop on Geothermal Reservoir Engineering,*** Stanford University, California, SGP-TR-130, **81-88.**

Uchida, T., Yagi, M., Sasaki, M., Kamenosono, H., Doi, N. and Miyazaki, S. **(1996)** Investigation of deep-seated geothermal reservoir by NEDO's 4000m well in Kakkonda, Japan, ***Proc. 8th Int. Symposium on the Observation of the Continental Crust through Drilling,*** pp. **73-78.**

Underwood, E. E., **(1969)** Quantitative Stereology, ***Addition-Wesley Publishing Company***