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HIGH PERMEABILITY OF QUATERNARY GRANITES IN THE KAKKONDA GEOTHERMAL AREA, NORTHEAST JAPAN

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ABSTRACT

Kakkonda geothermal area is one of the most active geothermal areas in Japan, accompanying a young and hot granitic intrusive underlying 2 km below the surface as a heat source. Deep geothermal well WD1a encounters the heat source granite below 2860m depth and recovered core samples from the hot region. The logging temperature of the Kakkonda granite in WD1a ranges from 375 to more than 500 ºC. Core permeability, porosity and pore size of Quaternary unaltered granite from Kakkonda geothermal area were measured to evaluate the hydraulic properties of the heat source region. The measured permeability, when the Pe (effective confining pressure) is at about 2 MPa, ranges from 58 to 500 μd for unaltered Kakkonda granite whereas it is less than 10 μd for the altered samples. The core permeability of the Kakkonda granite is order of 100 μd, which is order of magnitude higher than the reported laboratory permeability of various granitic rocks. Mean crack-width, which ranges from 0.25 to 2.84 μm, has a positive correlation with the measured permeability. Geometry of the permeable pore can be simplified as a platy crack and permeability mostly depends on crack width rather than crack density. SEM observation revealed that the grain boundaries are open. The granite is considered permeable just after the solidification and subsequent alteration, and/or compaction reduces the permeability and crack-width. Grain boundary may play an important role as a migration of vapor phase in degassing process.

1. INTRODUCTION

Kakkonda geothermal area is one of the most active geothermal areas in Japan, accompanying a young and hot granitic intrusive underlying 2 km below the surface as a heat source. NEDO (New Energy and Industrial Technology Development Organization) drilled a deep borehole (WD1a) to investigate the deep-seated geothermal resources. WD1a encounters the Kakkonda granite (Kanisawa et al., 1994) from 2860 m depth to the bottom (3729m depth). The borehole temperature exceeds 500 ºC at the bottom. This is probably the first experience to drill through the thermal convection zone and to get the samples of a heat source. Subsurface geology, geophysical studies and geochemical studies are summarized in a special volume of Geothermics (Sasada et al (eds., 1998)). Fig.1 is a schematic cross section of the Kakkonda Geothermal system after Komatsu et al. (1998).

Kakkonda geothermal system is considered to be an active magmatic-hydrothermal system, of which study is very important since most of the study has been focused on the fossil system such as porphyry copper deposits. We pay attention to the permeability of the heat source region, as the transport of water is one of the essential processes in heat and mass transfer in magmatic-hydrothermal stage. No data has obtained yet due to lack of the appropriate sample. Fujimoto et al. (1998) measured the core permeability of the heat source granite and mentioned that the permeability is higher than 100 μd, which is one order of magnitude higher than the reported laboratory permeability of various granitic rocks. In this paper, we add new data of permeability, porosity, and pore size of Kakkonda granite to confirm the hydraulic properties of the heat source.

2. EXPERIMENTAL AND RESULTS

2.1 Samples

Five samples (M, N, O, #1 and #6) were analyzed. Four of them (M, N, O, and #1) come from the drilled core of the Kakkonda area and the one (#6) is a surface sample of Takidani granite. As for the two samples (#1 and #6), Fujimoto et al. (1998) already reported preliminary results and this paper clarified a dependence of pore pressure. The characteristic features of the samples are summarized in Table 1.

As for the samples from Kakkonda, three samples (M, N and O) are from WD1a and the rest is from well 21. Three spot cores of the Quaternary granite were recovered from WD1a (#11 from c.a. 2938m depth, #12 from c.a. 3230m depth and #13 from c.a. 3729m depth respectively). The test specimens M, N and O come from cores #11, #12 and #13 respectively. The rock temperatures are 375ºC for core #11, 420 ºC for core #12 and hotter than 500 ºC for core #13. Core #11 belongs to the hydrothermally convective zone, core #13 belongs to thermally conductive zone, and core #12 belongs to the boundary zone.

A core #11 is granodiorite with weak porphyritic textures. Miarolitic cavities are distributed. Fine grained potassium feldspar, quartz and biotite fill intergranular space. It suffers weak metamorphism characterized by secondary biotite. Core #12 is tonalite with weak porphyritic texture. The characteristics are similar to Core #11. It suffers both weak metamorphism and alteration. Alteration minerals are actinolite, sericite, and chlorite. Core #13 is equigranular tonalite and suffers neither metamorphism nor alteration. Many open cracks densely developed horizontally. The description of the cores is given in Sasaki et al. (1999).

The sample (#1) is granodiorite from the well 21 at the depth of 2568.5m in the Kakkonda area. The temperature exceeds 400 ºC. It suffers neither metamorphism nor alteration.

The radiogenic ages of the Kakkonda granite are reviewed in detail by Doi et al. (1998).

The granodiorite sample #6, the only surface sample, is from the Takidani granodiorite which is the youngest exposed granite in the world, with the age of about 1.0 Ma (Harayama, 1992). It appears unaltered in hand-specimen and in thin section.

2.2 Permeability

Permeability of the test pieces was measured by the Transition Pulse method (Brace et al., 1968), following the method described by Takahashi et al. (1990). After the pore pressure equilibrated within the specimen, the fluid pressure was raised instantaneously by a few bars at one end of the specimen. The pore pressure then decreased exponentially with time as water flowed through the specimen. The permeability can be calculated from the pore pressure decay rate. This method has superior precision and independent control of pore pressure (Pp) and confining pressure (Pc) compared to other methods. The latter is important, as the pressure release effect can be minimized for core samples.

The specimens were cylindrical in shape, with a 30 mm radius and 30 mm length, without any apparent cracks. Length of the specimens was parallel to the original core.

The temperature was kept at 22ºC, within 1ºC fluctuation. First, the Pc is set at about 5 MPa and Pp at about 3 MPa for the measurement at the effective confining pressure (Pe = Pc - Pp) at 2 MPa. After that, the Pc is increased up to 40 MPa (up to 85 MPa as for #6 sample) slowly, and then the Pp is raised slowly to measure permeability at several Pc values. The pressure conditions and measured permeability are listed in Table 2. 40 MPa, nearly the maximum Pc of our apparatus, corresponds to lithostatic pressure of about 1.6 km depth, if the rock density is 2.5 g/cc.

The measured permeability, when the Pe is at 2 MPa, ranges from 58 to 500 μd for unaltered Kakkonda granite whereas it is less than 10 μd for the sample #6 (Table 3). Quaternary unaltered Kakkonda granodiorite is more than one order of magnitude higher than the permeabilities of the other samples reported in Fujimoto et al. (1998).

Fig. 2 shows the relation between Pe (effective confining pressure) and core permeability. The diagram shows that the logarithmic core permeability linearly decreases with Pe. This is due to the narrowing of the fluid pathway as increasing Pe.

2.3 Porosity and crack-width

Porosity and crack-width distributions were measured by a mercury intrusion method. The porosity was obtained from the cumulative volume of the intruded mercury. The maximum injection pressure was about 414 MPa and we used the interval between 1.4 and 590 MPa. Pore size estimates are based on the relation between the pore volume versus intrusion pressure, as the mercury can be intruded into narrower pore spaces at higher pressures. Assuming the pore spaces to be platy cracks, the crack-width can easily be calculated from the intrusion pressure, the contact angle and the surface tension, to get a histogram of the crack width (Table 3). Table 3 includes the previous results (Fujimoto et a., 1998).

Porosity ranges from 1.8 to 4.3 %. Quaternary unaltered granodiorite samples, which are permeable as mentioned before, show relatively large porosities of 2 %, whereas, the other samples have porosities lower than 2%, except the tonalite sample #3. Mean crack width, which ranges from 0.12 to 1.30 μm, has a positive correlation with the measured permeability (Fig. 4). Porosity of the Sample M is higher probably due to the presence of miarolitic cavities.

Pore size is large for the sample O, which arises from horizontal cracks. These horizontal cracks do not largely influence the permeability as we analyzed the permeability parallel to the core.

2.4 SEM observation

SEM (scanning electron microscope) observation was performed to see the fluid migration path. Fig. 4 shows the surface of mildly polished surface of the specimens. The grain boundaries are distinct and sometimes open for the Kakkonda granite comparing to the altered granite. Fujimoto et al. (1998) observed the fractured surface of the specimens and the grain boundaries are open and contain only a little precipitate as for Kakkonda granite. The opening widths are at micron scales and concordant with the measured mean crack-width. The mineral surfaces show euhedral growth and some dissolution etch pits exist, which indicates that the grain boundaries were filled with hydrothermal fluid. Blue dyed epoxy impregnated thin sections of the specimens also demonstrate that the grain boundaries are open and interconnected (Takahashi et al., 1992). Fujimoto et al. (1998) also observed that the grain boundaries of the altered specimens are not as open as Kakkonda granite.

3. DISCUSSIONS

3.1 Permeability versus pore size

The logarithmic relations between permeability and mean pore size are shown in Fig. 3. If the permeable pore are open cracks, permeability can be represented by the following equation (e.g., Norton and Knight, 1977).

$$K = n D^3 / 12,$$

Where, K, n and D represent permeability, crack density and crack aperture respectively.

Assuming n is 10 cracks per cm and D is 1μm, then K should be 100 μd, this is the same order of magnitude as our measured values. This coincidence suggests that the geometry of the permeable pores can be simplifies into platy cracks. In this case, the slope should be 3 on Fig.3, whereas it is about 2.2, smaller than the theoretical value. This might arise from the difference in the crack shape and complexity of the networking. Modeling of the crack networking is a future problem.

As for the sample O, permeability is not so high comparing the large crack width. The horizontal cracks are not so important for the fluid flow perpendicular to the cracks.

3.2 Implications for mass transfer during magmatic-hydrothermal stage

Permeabilitis of the unaltered Kakkonda granite were about 100 μd. They are an order of magnitude higher than those of the altered granite in the Kakkonda area (Fujimoto et al., 1998). They are much higher compared to those of other well known exhumed and old granites, such as Westerly granite or Barre granite, which range from 0.001 to a few tens μd (Brace, 1980).

A positive correlation between permeability and pore size indicates that the difference in permeability arises from crack-width rather than crack density. A simple model calculation reveals that the permeable cracks can be simplified as platy cracks as a first approximation. Grain boundaries are major pathways of fluid penetration considering open grain boundaries shown in Fig. 4.

Simulation studies showed that the critical permeability for generation of hydrothermal convection is about 30 µd (i.e., Norton and Cathles, 1979). The obtained permeability of Kakkonda granite is higher than the critical value under low Pe conditions, where pore pressure is close to lithostatic pressure. On the contrary, they are lower than the critical value under high Pe conditions, where pore pressure is significantly lower than lithostatic pressure (i.e., hydrostatic pressure).

Temperature logging data of WD1a indicates that hydrothermal convection occurs above 3100 m depth (Ikeuchi et al., 1998). The obtained permeabilities of Kakkonda granite are not clearly different with depth or whether the sample belongs to hydrothermally convective zone or conductive zone. This suggests that fracturing might be necessary for generating hydrothermal convection in a heat source granite as the measured permeability represents matrix permeability. Sasaki et al. (1998) mentioned that evidence of fracturing is clear in the cores (#11 and #12) from a convective zone, whereas the signature of brittle deformation is scarce in the core #13 which comes from a conductive zone.

The matrix permeability of Kakkonda granite is considered small for generation of hydrothermal convection, however, it is large enough for degassing process. Hypersaline fluid was sampled near the bottom part of WD1a (Kasai et al., 1998). The hypersaline fluid is considered to be of magmatic origin. The fluid is separated into vapor rich phase and dense brine due to cooling and/or ascending. Vapor phase selectively goes up through permeable cracks such as grain. Brine remained in the grain boundaries in Kakkonda granite as it is dense and much more viscous.

4. CONCLUSIONS

1. The measured permeability, when the Pe is at 2 MPa, ranges from 58 to 500 µd for unaltered Kakkonda granite whereas it is less than 10 µd for the altered samples. The core permeability of the Kakkonda granite is order of 100 µd, which is order of magnitude higher than the reported laboratory permeability of various granitic rocks.

2. Mean crack-width, which ranges from 0.25 to 2.84 µm, has a positive correlation with the measured permeability. The permeable pore can be simplified as a platy crack as a first approximation and permeability mostly depends on crack width rather than crack density.

3. SEM observation revealed that the grain boundaries are open. The granite is considered permeable just after the solidification and subsequent alteration, and/or compaction reduces the permeability and crack-width. Grain boundary may play an important role as a migration of vapor phase in degassing process.

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(JE: in Japanese with English abstract)

Table 1. Brief description of the samples. The age and temperature data of the samples (M, N, O, #1, #2 and #3) are after Doi et al(1998). The age of the sample #6 is after Harayama (1992). The data of the sample #5 is after NEDO(1992). Samples (M, N, O, #1, and #2) are unaltered Kakkonda granite.

No.	locality/well-depth	rock facies	alteration/metamorphism	age(Ma)	temperature
M	WD1a-2937m	granodiorite	very weak	0.11-0.19	375°C
N	WD1a-3229m	tonalite	very weak	0.11-0.14	420°C
O	WD1a-3727m	tonalite	none	0.01-0.02	>500°C
#1	well 21-2568.5m	granodiorite	none	0.34-0.07	>400°C
#2	well 13-2346.4m	granodiorite	very weak	0.16-0.21	350°C
#3	well 5-1740.3m	tonalite	weak	0.08	320°C
#4	well 20-2764.7m	tonalite	weak	?	>350°C
#5	Nyuto TZ7-1493.5m	granodiorite	intense alteration	~1.7	~140°C
#6	Takidani / surface	granodiorite	very weak	~1.0	

Table 2 Pressure conditions and permeability of core samples. Pc is confining pressure, Pp is the pore pressure and Pe is effective confining pressure (Pe = Pc – Pp) respectively.

Sample	Pc (MPa)	Pp (MPa)	Pe (MPa)	K (10^{-6}darcy)	Sample	Pc (MPa)	Pp (MPa)	Pe (MPa)	K (10^{-6}darcy)
M	5	3.1	1.8	96.3		39.5	30.1	9.4	69.2
	5.3	3	2.2	88.4		39.7	20.3	19.4	44
	5.4	3.1	2.3	93.3		39.9	10.2	29.7	25.3
	5.6	3.1	2.5	91.6		39	2.9	36.1	17.2
	9.6	7.5	2.1	89.6					
	19.6	17.3	2.3	82.5	#1	5.8	2.9	2.8	513
	29.7	27	2.7	91.4		6.1	2.9	3.2	509
	41.1	36.9	4.2	80.4		6.1	2.9	3.2	512
	40.8	30.3	10.5	51.1		10.1	7.4	2.7	523
	40.8	20.9	19.8	18		19.2	17.4	1.8	565
	40.2	20.3	19.9	21		19.7	17.4	2.3	541
	39.2	10.2	29.1	16		19.4	17	2.4	499
	40.4	10.2	30.2	15.7		29.2	27.5	1.6	546
	39.3	3.3	36	11.5		39.9	37.1	2.8	492
						39.8	37.1	2.7	517
N	5.7	3	2.7	57.4		39.6	30	9.6	283
	5.8	3.1	2.8	57.7		39.8	30.3	9.5	286
	6.2	3.2	3	61.3		39.2	20	19.2	158
	14.5	3.4	11.1	30.3		39.2	9.7	29.6	110
	28.9	3.7	25.3	14.3		39.3	3	36.3	90
	39.1	3.6	35.5	9.6					
	39	13.3	25.7	12.8	#6	6.7	4	2.8	7.35
	39.8	13.1	26.7	12.6		9.4	7.1	2.3	8.31
	39.8	20.8	19	16.7		19	17	2	8.27
	40.7	30.4	10.3	24.4		29.3	26.8	2.5	8.35
	41.1	38.4	2.7	44.5		39.4	36.8	2.6	7.97
	40	37.9	2.1	57.7		40	29.9	10.1	3.16
						40.9	20.3	20.5	1.27
O	27.6	25.1	2.5	122		42.3	10.2	32.1	0.606
	27.6	25.1	2.5	123		40.5	3.2	37.2	0.365
	27.6	25.1	2.5	111		49.3	3.3	46	0.247
	27.6	25.1	2.5	103		59.8	3.2	56.5	0.176
	39.5	37.1	2.4	110		70.2	3.3	66.8	0.097
	39.5	37.1	2.4	110		79.3	3.3	76.1	0.0619
	39.5	30.1	9.4	80.8		90.8	4.4	86.5	0.0544

Table 3 Permeability (Pe is about 2MPa), porosity, and mean crack width. Permeability of the samples (#2, #3, #4 and #5 are after Fujimoto et al.(1998).

No.	Permeability (10^{-6} darcy)	Porosity (%)	Mean crack width (10^{-6} m)
M	90	3.46	0.79
N	60	2.17	0.86
O	110	2.44	2.84
#1	370	4.33	1.31
#2	116	2.68	1.33
#3	2.5	3.0	0.3
#4	11.7	1.8	0.22
#5	0.86	2.2	0.13
#6	7.4	1.7	0.25

Fig.1 Location and cross section of the Kakkonda geothermal area after Komatsu et al.(1998).

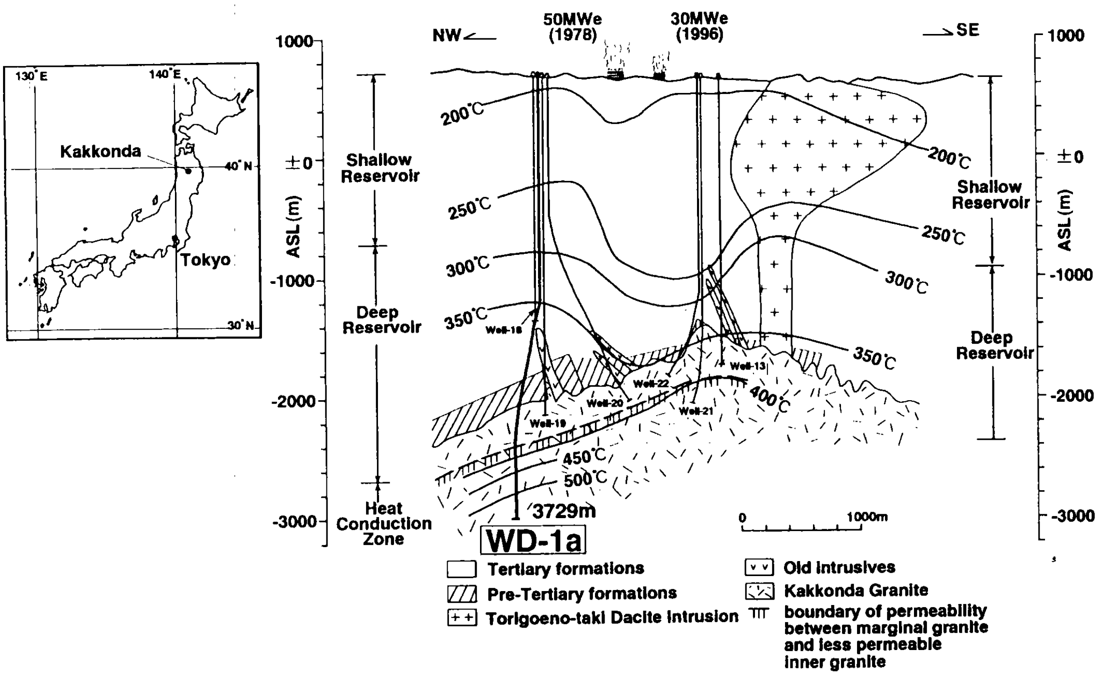

Fig.2 Permeability changes with effective confining pressure Pe (Pe= Pc – Pp).

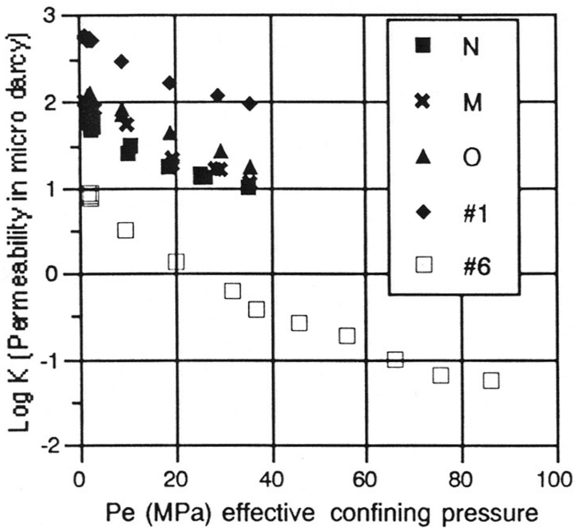

Fig.3 Logarithmic relations between mean crack-width (D) and permeability (K). The slope of the best fit line is 2.2.

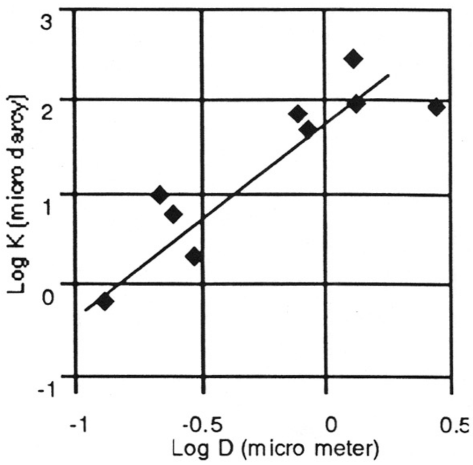

Fig.4 SEM photomicrographs of mildly polished surface of the test pieces. Scale bar is shown in each photograph. Photos a & b are sample #4, and c&d are sample N. Photos b and d are close up of the boxes in the photos a and c respectively. *Q* and *F* represent quartz and feldspar respectively. Sample #4 is weakly altered and grain boundary is not clearly open, whereas, Sample N is unaltered and grain boundary is clearly open.