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STUDY ON SURFACE AREA ESTIMATION OF THE OGACHI HDR RESERVOIR BY GEOCHEMICAL METHOD

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ABSTRACT
Characterizing the Hot Dry Rock (HDR) reservoir is a very important issue for the practical use of the HDR geothermal power. As one of the reservoir characterization methods, we have been conducting a geochemical study at the Hijiori and Ogachi HDR test sites, to develop a geochemical method for estimating the reservoir surface area.

As part of the development of a geochemical estimation method for the reservoir surface area:
(1) We estimated dissolution values (dissolved weights of Na and K) in the production water due to water/rock interactions.
(2) We conducted preliminary laboratory test to measure the apparent rate constant of the reservoir rock dissolution and to assess the relationship between the dissolution value and the grain size of the rock sample.
From these two studies, the surface area of the Ogachi HDR reservoir was preliminarily estimated.

Estimated contents of sodium and potassium contributed by the dissolution of reservoir rock into the production water from the OGC-2 well during each circulation are summarized as follows;
The estimated sodium contents were 225 ppm, 218 ppm, 210 ppm and 200 ppm, and the estimated potassium contents were 18.3 ppm, 19.2 ppm, 21.0 ppm and 16.0 ppm, in 1993, 1994, 1995 and 1997, respectively.

The following results were obtained from the laboratory interaction experiments:
(1) Under the limited experiment condition but like the Ogachi reservoir, the apparent sodium dissolution rate constant of the reservoir rock sample for different grain sizes was obtained. The following relationship between the apparent rate constant for Na and the rock/water ratio (A/M ratio: A represents the surface area of the reservoir and M represents the water volume in the reservoir) was derived;
$$K(ppm/min)=0.001368(A/M)+0.00728$$
(2) Considering this rate constant for Na and the estimated Na content in the production water during each circulation period at Ogachi, the rock/water (A/M) ratio in the Ogachi reservoir was estimated. Using the A/M ratio and values obtained from tracer tests, the surface area of the Ogachi reservoir in each year was estimated as 6463×10^3 m^2 in 1994, 6656×10^3 m^2 in 1995 and 4174×10^3 m^2 in 1997.

1. INTRODUCTION

To realize a hot dry rock geothermal power generation system, it will be necessary to develop techniques for creating an artificial reservoir and estimating its characteristics as well as its configuration. A geochemical survey method for analyzing the chemical changes in the injection and production water during a circulation test is likely to be very useful as a method to evaluate the characteristics of the engineered reservoir.

The Central Research Institute of Electric Power Industry (CRIEPI) has been conducting an HDR project at Ogachi, Akita Prefecture, Japan., since 1990. After creating upper and lower reservoirs and drilling a production well (OGC-2) to intersect both reservoirs, circulation tests were performed in 1993, 1994, 1995 and 1997 at the Ogachi HDR test site. During these tests, sampling and chemical analysis of the production and injection water were carried out.

This study is mainly based on the understanding that one of the factors affecting dissolution due to water/rock interactions in the reservoir is rock/water ratio. If the relationship between the dissolution value and the rock/water ratio can be evaluated, we can calculate the rock/water ratio in the reservoir. Furthermore, the surface area of the reservoir together with the reservoir volume can be deduced from the results of tracer tests.

From this point of view, we have been carrying out following two sub studies;
(1) A study to assess dissolution values of the chemical elements deduced from the water/rock interaction, in the production water during circulation tests, since the fluid chemistry of the production water is mainly based on mixing of the injection water with formation water and water/rock interaction.
(2) Laboratory water/rock interaction experiments with various grain size of rock sample under the same conditions as the circulation tests, to obtain data concerning the rate dissolution constant of the host rock (granodiorite) and to clarify the relationship between apparent rate constant and sample grain size (rock/water ratio).

This paper describes:
(1) The estimated dissolution values of sodium and potassium in the production water collected during circulation tests conducted in 1993, 1994, 1995 and 1997 at the Ogachi HDR site.
(2) The analytical results of preliminary laboratory experiment using rock samples at Ogachi and Hijiori to collect data concerning the apparent dissolution rate constant and the relationship between the apparent rate constant and rock/water ratio.
(3) Results of the surface area estimation for the Ogachi reservoir.

2. DISSOLUTION VALUE ESTIMATION IN THE PRODUCTION WATER

During circulation tests, some chemical constituents are assumed to be added to the injected water through two chemical processes. These are mixing of low saline injected water with high saline formation water, and dissolution due to water/rock interactions. After these processes have occurred, the injected water flows out from the production well as the production water.

A chloride ion can be used as a mixing indicator based on the following factors:

(1) The chloride ion is non-reactive and soluble, and exists little in the granite.

(2) The injected water has a low chloride content compared to the high chloride content that can be expected in the formation water of the Ogachi reservoir.

(3) Sodium chloride, the usual salt of chloride, has high solubility, so the chloride content of the production water is well below the saturation point.

Many chemical constituents can be expected to be dissolved from the granite in the reservoir through the water/rock interactions. Among these many chemical constituents, sodium and potassium usually exist, and thus these elements can be used to produce an index of the dissolution. The increase of these constituents in the production water results not only from the mixing of the injection water and the formation water but also from the dissolution due to water/rock interactions.

Bivariate plots of Na-Cl and K-Cl are very useful for estimating the amount of sodium and potassium added to the injected water by dissolution. Cross plots of Na-Cl and K-Cl in the production water during circulation tests display a linear relationship as shown in Fig. 1. This straight line relationship can be explained as a mixing line of the two ion source, injection water with low chemical concentration and formation water with high chemical concentration. If the production water is affected by only mixing in the reservoir, the cross plot displays line A connecting both single-source end members. On the contrary, if sodium or potassium is added to the injected water not only by mixing, but also by water/rock interactions in the reservoir, the Na-Cl/K-Cl cross plot of the production water shows line B, and the value of Y intercept can be estimated as the sodium and potassium concentrations added by dissolution of the rock.

Using the above approach, the sodium and potassium dissolution values in the production water of each field circulation test were estimated (Fig, 2(a), (b)). The data for sodium and potassium in the production water from the OGC-2 well are summarized as follows:

(1) The estimated sodium contents were 225 ppm, 218 ppm, 210ppm and 200 ppm, and the estimated potassium contents were 18.3 ppm, 19.2 ppm, 21.0 ppm and 16.0 ppm, in 1993, 1994, 1995 and 1997, respectively (Table 1).

(2) The sodium content was higher than the potassium content in every year.

(3) The sodium content decreased gradually year by year.

3. OUTLINE OF THE WATER ROCK INTERACTION EXPERIMENT

The chemical content of the production water contributed by the dissolution due to water/rock interactions depends on various reservoir conditions, such as temperature, pressure, rock type, chemistry of the injection water, rock/water ratio and so on. To measure the apparent rate constant of the reservoir rock dissolution under the reservoir conditions, and evaluate the relationship between the rate constant and rock/water ratio, we performed laboratory water/rock interaction experiment using rock samples with different grain sizes.

The rock sample used for these experiments were granodiorite that were collected from drilled core at the depth of the deeper reservoir of the OGC-1 well (injection well) at the Ogachi HDR site, and the HDR-3 well (production well) at the Hijiori HDR site (Table 2).

We developed a flow through type autoclave which can simulate water/rock interactions under simulated reservoir conditions of temperature, pressure, rock type, residence time, rock/water ratio and so on. This system is composed of a cell where water and rock interact, a heater unit which heats up and keeps a constant temperature in the cell, plunger pumps and flow meters, pressure control syringes which can keep a constant pressure in the cell even as the water flows, and a control panel which can control this system. The outline of this system is shown in Fig. 3.

Using this apparatus, several water/rock interaction experiments were performed. In order to estimate the relationship between the dissolution value and the grain sizes of the rock sample (so to speak, the A/M ratios), seven experiments with different grain sizes, OGC-#2, #6, #9, #13 (series A) and HJR-#1, #2, #4 (series B), were conducted under the same conditions of pressure, temperature and flow rate. Six experiments with different flow rates in each series, OGC-#5, #6, #7 (series C) and HJR-#4, #5, #6 (series D) were also conducted to measure the apparent dissolution rate constant of the reservoir rock. To simulate the reservoir conditions, all experiments were conducted at 240ºC and under 250 kg/cm^2 pressure. The term of each experiment was about 2 to 3 weeks. The experimental parameters are shown in Table 3.

Tested water was collected from a sampling port through a pressure control valve. Water samples were collected every three hours in the early stages, and once a day or twice a week near the end of the experiments. The sodium and potassium were analyzed by atomic absorption, the silica was analyzed by spectrophotometry.

4. RESULTS OF EXPERIMENTS

Sodium and potassium concentrations in the series A and B increased quickly in the early stage of the experiments , and then decreased gradually to stable values. The maximum sodium concentrations of the OGC-#2, #6, #9, #13 experiments were 63.5 ppm at 38 ml of total flow volume, 36.0 ppm at 42 ml, 36.1 ppm at 43 ml and 78.3 ppm at 117 ml, respectively. Those of HJR-#1, #2, #4 experiments were 71.6 ppm at 102 ml of total flow volume, 83.6 ppm at 114 ml and 79.1 ppm at 109 ml, respectively. After that, the sodium concentrations of both series decreased and reached stable concentrations at points around 500 ml to 2000 ml from the end of the experiment. The sodium concentrations of the last water samples were 7.2 ppm, 7.9 ppm, 9.8 ppm and 26.7 ppm in series A (Fig. 4(a)), and 13.4 ppm, 27.6ppm and 32.0 ppm in series B (Fig. 4(b)), respectively. The potassium concentrations of the last samples were 4.2 ppm, 4.6 ppm, 4.5 ppm and 11.4 ppm in series A, and 13.2 ppm, 14.2 ppm and 17.1 ppm in series B, respectively.

Sodium and potassium concentrations of series C and D varied like those of series A and B, except for the HJR-#6 experiment, because HJR-#5 and #6 experiments were conducted sequentially using the same rock sample. The sodium concentrations of the last water samples of OGC-#6, #7 and #5 in series C were 7.9 ppm, 7.2 ppm and 6.4 ppm (Fig. 5(a)), and those of HJR-#4, #5 and #6 in series D were 32.0 ppm, 29.3 and 28.2 ppm (Fig. 5(b)), respectively. The potassium concentrations of the last water samples of series C were 4.6 ppm, 3.9 ppm and 3.8 ppm, and those of series D were 17.1 ppm, 15.8 and 15.9 ppm, respectively (Table 3).

The results of these experiments are summarized as follows:

(1) Contents of sodium and potassium increased quickly in the early stage of most experiments, and then decreased gradually to stable values.
(2) From the results of series A and B, the fluid from the experiment with bigger grain size rock samples, (so to speak, smaller A/M ratio), had smaller sodium and potassium contents. This tendency was more marked in the Hijiori sample.
(3) From the results of series C and D, the fluid from the experiment with smaller flow rates, (so to speak, longer residence times), had higher sodium contents. Compared to the sodium contents, the potassium contents were not affected strongly by residence time.

5. DISCUSSION

5.1 Rate constant and A/M ratio

The apparent rate constant for the dissolution of reservoir rock from Ogachi and Hijiori was determined using experimental results from series C and D. As shown in Fig. 6, cross plots of the sodium contents and the residence times from both series show linear relations. These relations can be recognized as indicating 0-order reaction. From these lines, the apparent rate constant k, for limited water/rock contact times of both series can be estimated as follows:

$k(A/M=0.78)=8.33x10^{-3}$

$k(A/M=9.28)=19.9x10^{-3}$

Assuming the k value changes in proportion to the A/M ratio, the relation between the k value and the A/M ratio can be expressed by the following formula:

$k\ (ppm/min)=0.00136(A/M)+0.00728$ (1)

From this formula, sodium dissolution value, C, under the limited experimental condition can be derived as shown below:

$C=kt+2.48(A/M)+2.99$ (2)

From the formulae 1 and 2, the A/M ratio can be recognized as a function of the dissolution value, C, and residence time, t, and expressed by the following formula:

$A/M=(C-(0.00728t+2.99))/(0.00136t+2.48)$ (3)

5.2 Surface area estimation

In order to estimate the A/M ratio of the Ogachi reservoir by formula 3, it is necessary to know the residence time of the injection water in the reservoir. Furthermore, to estimate the A value which represents the surface area of the reservoir, it is necessary to know the value of M which represents the water volume in the reservoir

The values, t and M, can be obtained by tracer tests (Kiho et al., 1999) conducted during circulation at Ogachi. The value t can be recognized as the modal time of the tracer response curve, and was calculated at Ogachi as 4080 min. in 1994, 1140 min. in 1995 and 2520 min. in 1997. The value M can be recognized as the modal volume of the tracer response curve, and was calculated as 280 m^3 in 1994, 135 m^3 in 1995 and 138 m^3 in 1997. Using these values, the surface area of the Ogachi reservoir during circulation in each year can be evaluated as $6463x10^3\ m^2$ in 1994, $6656x10^3\ m^2$ in 1995 and $4174x10^3\ m^2$ in 1997 (Table 4).

6. CONCLUSIONS

As a part of the development of the geochemical estimation method for the reservoir surface area, we estimated dissolution values in the production water caused by water/rock interactions, and conducted preliminary laboratory tests to measure the apparent rate constant for the dissolution of the reservoir rock and to assess the relationship between the dissolution value and the grain sizes of the rock samples.

The estimated sodium contents were 225 ppm, 218 ppm, 210 ppm and 200 ppm, and the estimated potassium contents were 18.3 ppm, 19.2 ppm, 21.0 ppm and 16.0 ppm, in 1993, 1994, 1995 and 1997, respectively. The sodium content was higher than the potassium content in every year. The sodium content decreased gradually year by year.

The results of the laboratory experiments are summarized as follows:

(1) Contents of sodium and potassium increased quickly in the early stages of most experiments, and then decreased gradually to stable values.
(2) From the results of series A and B, fluid from the experiments with bigger grain sizes, (so as to speak, smaller A/M ratio), had smaller sodium and potassium contents. This tendency was more marked in the Hijiori sample.
(3) From the results of series C and D, fluid from the experiments with lower flow rates, (so as to speak, longer residence time), had higher sodium contents. Compared with the sodium contents, the potassium contents were not affected strongly by residence time.

The following significant results were obtained from the laboratory interaction experiments:

(1) Under the condition simulating the Ogachi reservoir, the apparent sodium dissolution rate constants of the reservoir rock sample with different grain sizes were obtained. The relationship between the apparent rate constants for Na and the rock/water ratio (A/M ratio) was deduced according to the following formula:
$K(ppm/min)=0.001368(A/M)+0.00728$
(2) Based on the apparent rate constants of Na and the estimated Na contents in the production water during each circulation period at Ogachi, the rock/water (A/M) ratio in the Ogachi reservoir was estimated. Using the A/M ratio and values obtained by tracer tests, the surface area of the Ogachi reservoir in each year was estimated as $6463x10^3\ m^2$ in 1994, $6656x10^3\ m^2$ in 1995 and $4174x10^3\ m^2$ in 1997.

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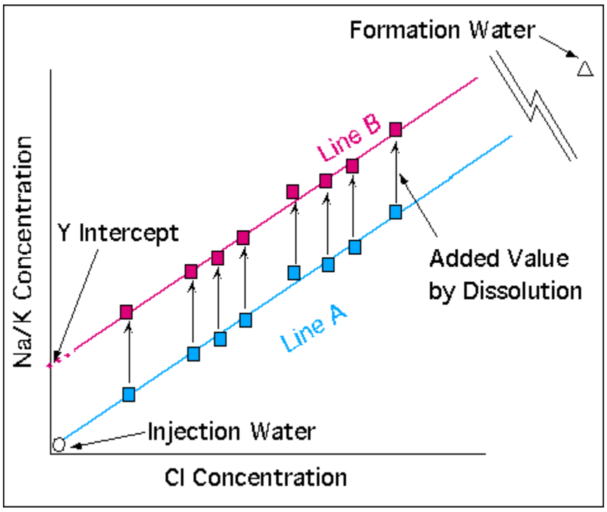

Fig. 1 Estimation method for determining the dissolution value in the production water

Table 1 Estimated Na and K contents in the production water from rock dissolution

Field Experiment (Name and Year)	Y Intercept (Dissolution value)	
	Na (ppm)	K (ppm)
22 days Circulation in 1993	225	18.3
1 months Circulation in 1994	218	19.2
5 months Circulation in 1995	210	21.0
10 days Circulation in 1997	200	16.0

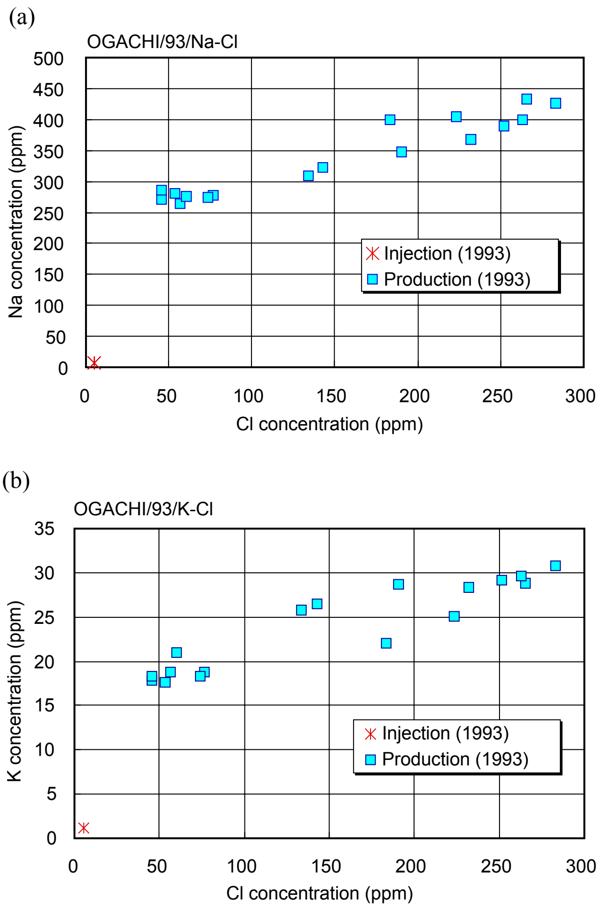

Fig. 2 Na/Cl and K/Cl cross plots during 1993 circulation at Ogachi
top: Na/Cl (a) bottom: K/Cl (b)

Table 2 Mineralogy of the rock sample

(after NIRE 1994)

Sampling Depth (m)	2184.40
Rock Type	Granodiorite
Mode Ratio (%)	
Quartz	24.5
Plagioclase	52.5
K-Feldspar	11.1
Biotite (altered)	0.9
Allanite	0.0
Chlorite	0.0
Sericite	8.5
Carbonate mineral	0.7
Epidote	1.9
Anhydrite	0.0
Sphene	0.0

Table 3 Conditions of laboratory experiments and dissolution values of Na and K

Experiment No.	Series	Temp. (°C)	Pressure (kg/cm^2)	Flow rate (ml/h)	Grain size (mm)	A/M ratio (m^2/Kg)	Concentration of last sample Na (ppm)	K (ppm)
OGC-#2	A	240	250	10	3.30	2.23	7.2	4.2
OGC-#5	A, C	240	250	20	5.73	0.79	6.4	3.8
OGC-#6	C	240	250	10	5.73	0.79	7.9	4.6
OGC-#7	C	240	250	15	5.73	0.79	7.2	3.9
OGC-#9	A	240	250	10	1.52	2.15	9.8	4.5
OGC-#13	A	240	250	10	0.61	9.10	26.7	11.4
HJR-#1	B	240	250	10	3.31	2.07	13.4	13.2
HJR-#2	B	240	250	10	1.32	5.05	27.6	14.2
HJR-#4	B, D	240	250	10	0.64	9.29	32.0	17.1
HJR-#5	D	240	250	20	0.64	9.29	29.3	15.8
HJR-#6	D	240	250	30	0.64	9.29	28.2	15.9

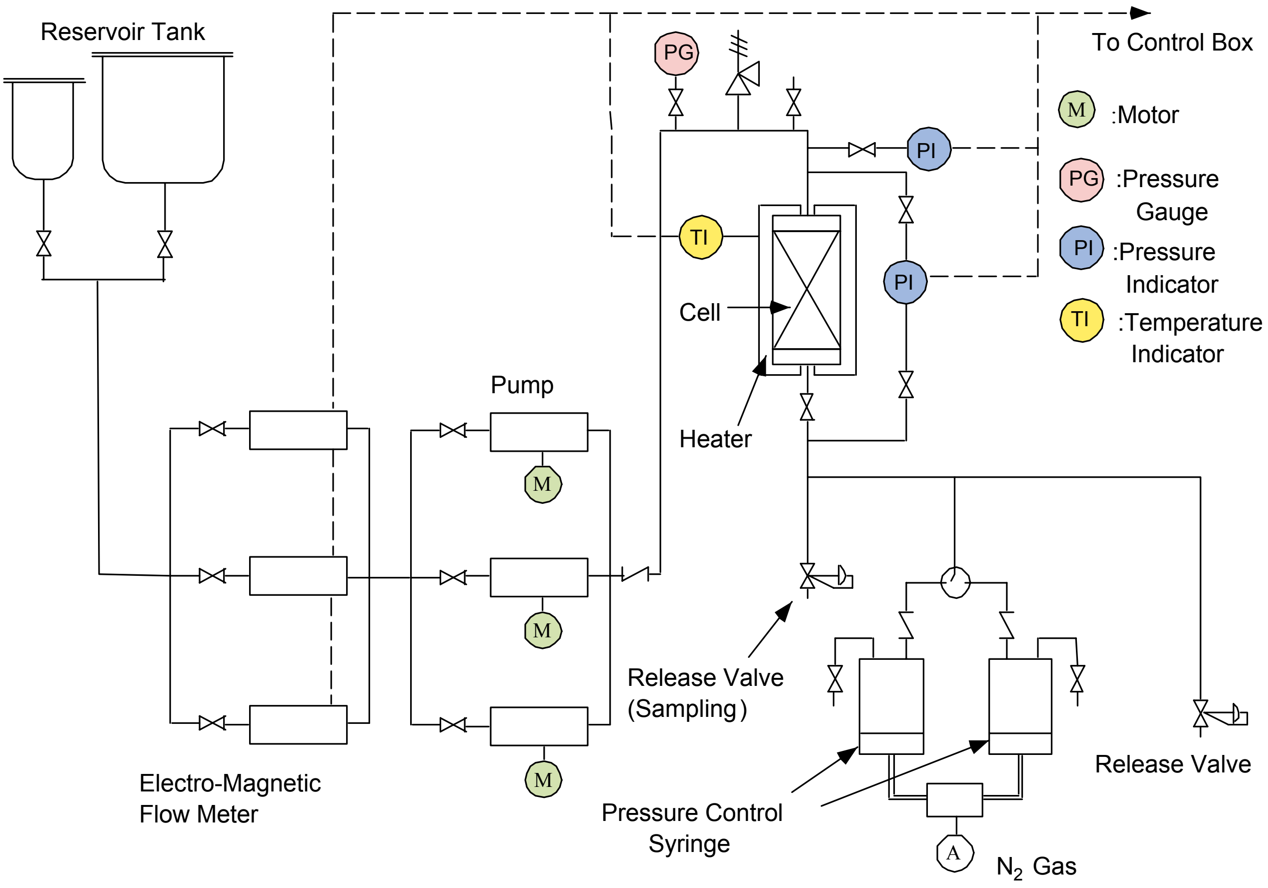

Fig. 3 Block diagram of the experimental apparatus

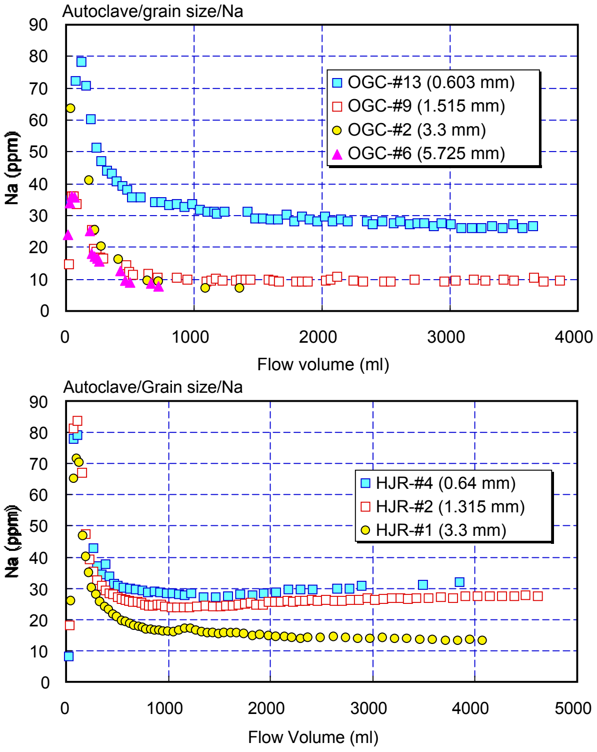

Fig. 4 Concentration of dissolved Na
versus rock sample size
top: series A bottom: series B

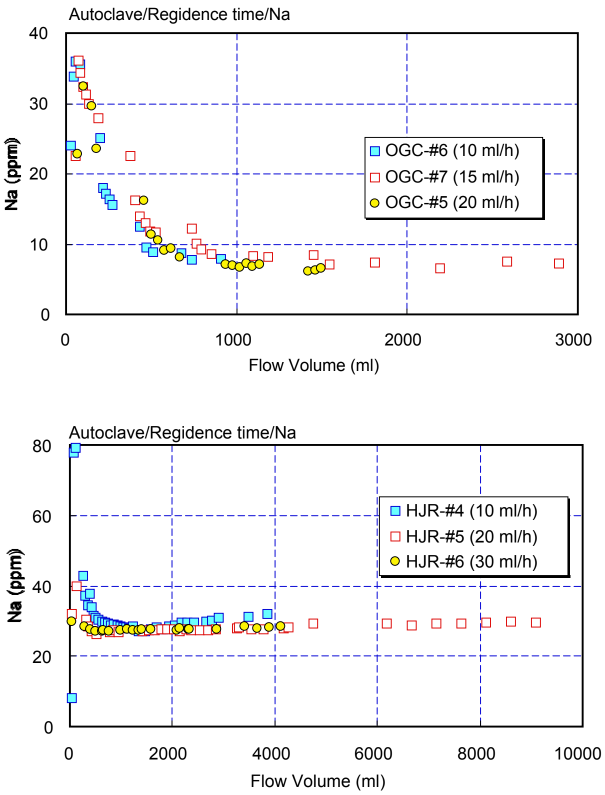

Fig. 5 Concentration of dissolved Na
versus flow rate
top: series C bottom: series D

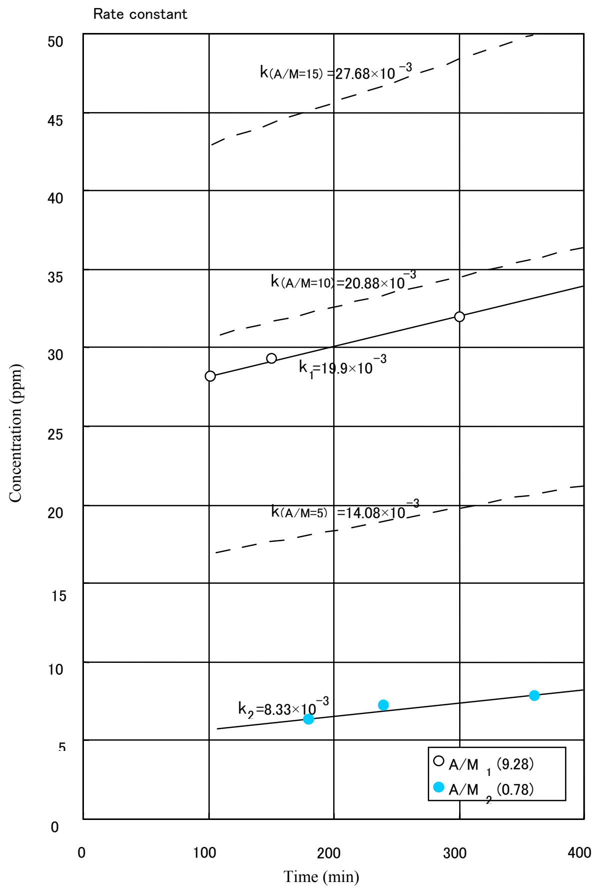

Fig.6 Sodium dissolution rate constant of the
reservoir rock deduced from laboratory experiments

Table 4 Estimated surface area of the Ogachi reservoir

Year	Result from tracer test: Modal volume ($x10^3$ l)	Result from tracer test: Residence time (min)	Dissolution value of Na (ppm)	A/M ratio (m^2/kg)	Surface area ($x10^3 m^2$)
1994	280	4080	218	23.08	6463
1995	135	1140	210	49.30	6656
1997	138	2520	200	30.25	4174