Water-Rock Interactions During a Three Month Circulation Test at the Hot Dry Rock Test Site in Hijiori, Japan

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ABSTRACT

A three month circulation test was conducted in 1991 at the Hijiori hot dry rock test site. We conducted six tracer tests during the circulation test. The injected water into a well SKG-2 and the produced fluid from three production wells, HDR-1, HDR-2, and HDR-3, were collected during the tracer tests. Major dissolved species were analyzed beside tracer reagents such as I, Br, and fluorescein. Chemistry analysis was used to evaluate rock water interactions in the fractured reservoir. Although the distance between the injection well and the three production wells are less than 60 m and the breakthrough time in each flow path is less than 7 hours, concentrations of dissolved species increased in produced fluid. Difference of produced fluid chemistry is mainly caused by the difference of the reservoir temperature.

1. INTRODUCTION

In 1991, a three month circulation test was conducted at the Hot Dry Rock (HDR) geothermal energy test site in Hijiori. During the test, many measurements and experiments were performed to diagnose the reservoir condition in the granitic basement rock at a depth of 1800 m. Pressure-Temperature-Spinner (PTS) survey was periodically conducted in the three production wells [Miyairi et al., 1992]. Tracer experiments conducted during the circulation test gave useful data to obtain the reservoir parameter such as volume in the inter-well region [Matsunaga et al., 1992].

Since fluid geochemistry is very important for predicting the behavior of fluid flow in the HDR geothermal-energy system [Pauwels et al., 1992], fluid geochemical behavior in experimental HDR reservoirs was observed in circulation tests at Fenton Hill [Grigsby et al., 1983, 1989; Robinson et al., 1987], Rosemanowes [Edmunds et al., 1985; McCartney, 1989], Soultz-sous-Forets [Pauwels et al., 1992], and Hijiori [Kiho and Ohsumi, 1992]. These circulation tests were conducted by using a single well (Soultz) and a doublet well system (Fenton Hill and Rosemanowes). Since a multi-well production system (one injection well SKG-2 and three production wells, HDR-1, HDR-2, and HDR-3) was used during the three-month circulation test at the Hijiori site, the circulation test gave a unique chance to obtain fluid samples which can indicate the fluid composition in different flow paths of the reservoir[McCartoney, 1987]. In this study, we give results of fluid geochemistry during a tracer test in the circulation test and discuss water-rock interactions in the reservoir.

2. THREE MONTH CIRCULATION TEST AT HIJIORI

The Hijiori HDR test site is located at the southern flank of the Hijiori caldera in northern Honshu. The caldera was formed during a recent volcanism of about 10,000 years ago. Figure 1 shows the location of a test site and stations for microseismic observation. It has been the site for development of HDR technology since 1985 [Matsunaga and Yamaguchi, 1992]. At the test site, three production wells, HDR-1, HDR-2 and HDR-3 have been drilled around the production well SKG -2, as shown in Figure 2.

The three-month circulation test was carried out from August 6 through November 3 in 1991. A total of about 135,000 m^3 of water was injected in SKG-2 and 94,300 m^3 of hot water was recovered from the production wells[Yamaguchi et al., 1992]. The injection flow rate was kept nearly constant at 1 m^3/min over a period of 3 months, except two high-rate injections at the early stage of the test. Following the first 23 days of circulation, single well production tests were conducted for 5 days each to evaluate the productivity of each production well.

The production temperatures at each wellhead were increased very rapidly and reached 160 and 180 °C at the beginning of the test as

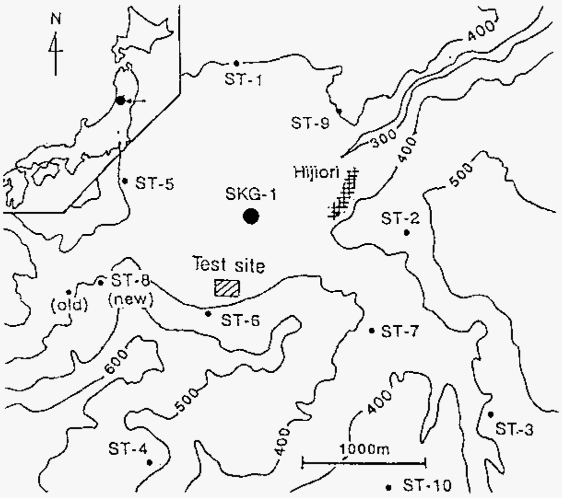

Figure 1. Hijiori HDR test site

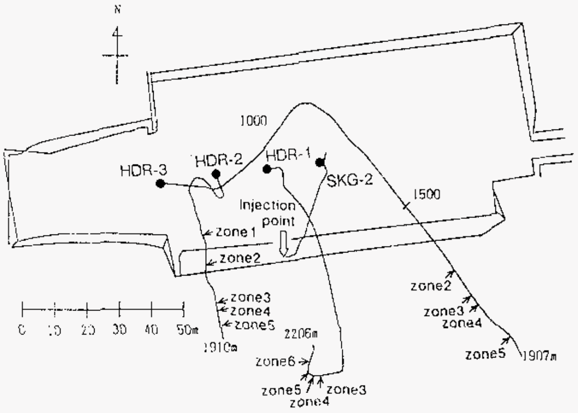

Figure 2. A plane view of trajectories of SKG-2, HDR-1, HDR-2, and HDR-3 wells.

shown in Figure 3. The recovery rate of injected water from the production wells reached almost 80 percent just after the filling up operation of the reservoir. Although the recovery from HDR-3 decreases to the same level as HDR-2 at the end of the test, the production from HDR-3 contributes greatly not only at the early stage but also throughout the circulation test. Fallowing the single well productions, a stable production was attained from the three wells from September 23 and was continued to the end of test. Since the production each from HDR-2 and HDR-3 was twice as high as that from HDR-1, fractures from SKG-2 to HDR-2 and HDR-3 were thought to be more permeable than those to HDR-1.

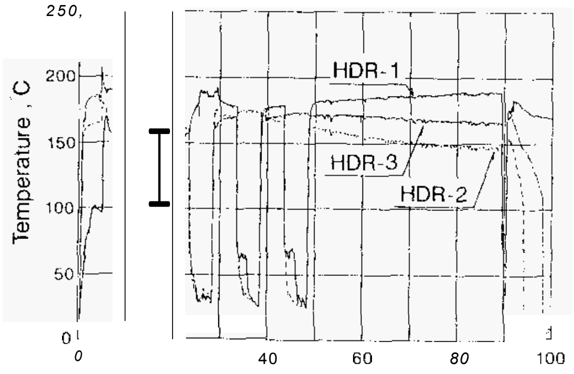

Figure 3. Temperature histories of produced fluid at each wellhead

During the circulation test, PTS logs were run every week in the three production wells and profiles of pressure, temperature, and spinner obtain were obtained along the wellbores (Miyairi et al., 1992). Sixteen feed zones; six in HDR-1, five both in HDR-2 and HDR-3, were confirmed from temperature profiles in Figure 4. Production flow rate of each feed zone could be calculated from spinner data, except the Zones in HDR-1 where no spinner data was obtained as a cemented liner set in the openhole section. As we can find from large temperature changes in Figure 4, zone 3 and 4 in HDK-2, and zone 3 in HDR-3 produced a large part of the fractional flaws in both wells. The amount of flow praduced from zone 3 at a depth of 1,754 m was about 70 % of the total flow in HDR-3. Those from zone 3 and zone 4 in WR-2 were around 30 % and 35 %, respectively. Flow rate change at about 45 days after the circulation started indicates that flow regime in the fracture was affected by the single well production in HDR-3.

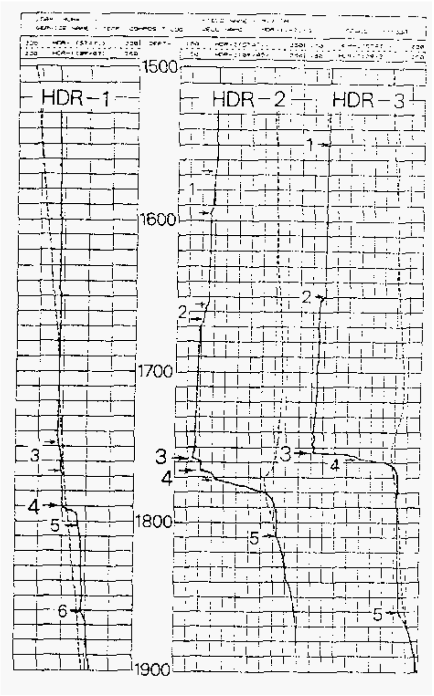

Figure 4. Temperature profiles of production wells

3. FLUID SAMPLING DURING TRACER EXPERIMENTS

Six tracer experiments were conducted during the circulation test [Matsunaga et al., 1992]. The first tracer experiment was conducted on August 19, just after the second high-rate injection, to confirm an initial flow condition in the reservoir. Three tests were performed during each single well production stage to obtain flow conditions between the paired well. After the single well production stage, stable production from the three wells was conducted in the later half of the circulation test. During that time, two tracer tests were conducted on October 2 and October 31 to characterize a flow regime in the stable condition and change of reservoir behavior with time.

In every tracer test, two kinds of inert tracer were used among potassium iodine, potassium bromide, sodium tungstate, and ammonium molybdate. Several kilograms of the tracer reagents were dissolved in water at a 1 m^3 tank and then tracer solution was injected in SKG-2 by switching a suction line to injection pumps as shown in Figure 5. Produced fluid was collected at each wellhead under the condition of high temperature and above bailing pressures, hence single phase fluid samples were obtained. Fluid samples were coaled down by water and then filtered through a 0.45 μm membrane. Electrical conductivity and pH were determined on site. Tracer and major dissolved species were analyzed in the chemistry laboratory at Tsukuba by ion chromatography (Cl, SO_4, Br, I, Na, K, Ca), titration with H_2SO_4 (HCO_3), and ICP (Si, Na, K, Ca, Mg, I).

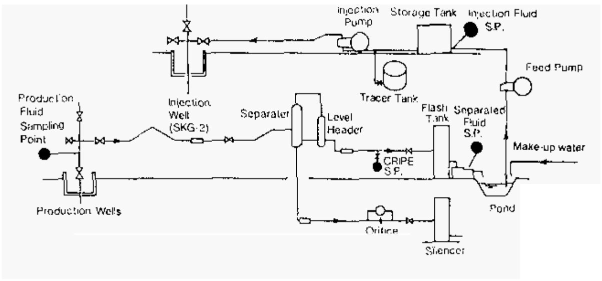

Figure 5. Schematic diagram of surface system for the circulation test. Solid circles show sampling points of fluid.

After the fifth tracer experiment, we recognized that the concentration of dissolved species in the injected fluid changed cyclically by make-up water supply. *So,* during the sixth tracer experiment, we sampled the injected fluid every *20* minute lor 4 hours and checked the change of concentration.

Figure *6* shows tracer breakthrough curves lor the three production wells observed at the 6th tracer experiment. These curves suggest that the connection from SKG-2 to the three production wells have different breakthrough time. By subtracting travel time of the tracer in both the injection and production wells, we may obtain tracer residence time in flow paths between well SKG-2 and the three production wells. The residence time is 6.7 hours for HDR-1, 2.6 hours for HDR-2, and 1.8 hours for HDR-3. From this result and also by the comparison of the response curves, we recognize that the fracture connections to HDR-2 and HDR-3 were more dominant than those to HDR-1.

4. GEOCHEMISTRY OF CIRCULATION FLUID

Figure 7 shows chlorine concentration curves of the injected and produced fluid. In the figure, relative time of 0 is adjusted to be time of tracer injected for the injected fluid and time of tracer peak arrival for the produced fluids. Therefore, we can compare the concentration of Same fluid that was sampled at both the inlet and outlet of the HDR reservoir. The Cl concentration of the injected fluid was changed

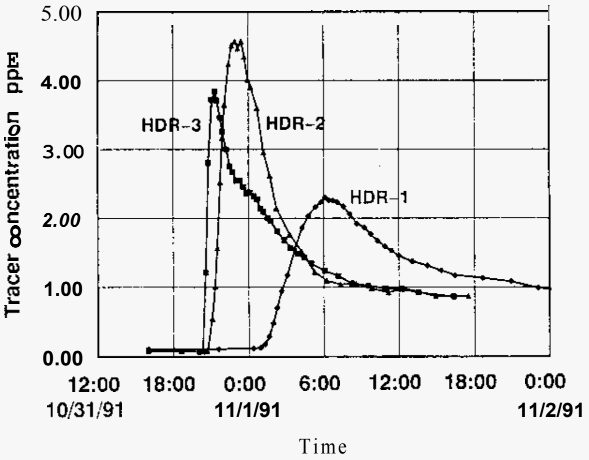

Figure *6*. Tracer breakthrough **curves** at each production wellhead.

cyclically. because of the periodical addition of the make-up water **at** a 450 m^3 storage pond. **On** the other hand, the Cl concentration of **each** production fluid increased and tended to be constant.

Other anions, SO$_4$ and HCO,, show generally the same behavior, although there is some difference such **as** the HDR-2 fluid has the highest SO, concentration and HDR-I has the highest concentration of HCO,.

Figure 8 shows Na concentration of the injected and produced fluid. **General** trends of the curves are **also** same as that of the Cl concentration **curves.** Although potassium concentration **of** each fluid is **about** one-tenth the order of Na, K concentration curves hare the same trend of those of **Na.** Calcium concentration curve is much different from those of Na and K, as shown in Figure Y. Ca concentration of HDR-1 fluid decreased ***to* about** half the concentration of the injected fluid. On the other hand, HDR-2 concentration increased ***to*** about twice the injected fluid. In the injected fluid, magnesium, which is a divalent cation **as** is Ca, is detected **at** a level of 2 mg/l in the injected fluid. However, no Mg is detected in fluids **from** HDR-1 and HDR-3 and only trace of Mg is recognized **in** HDR-2 fluid.

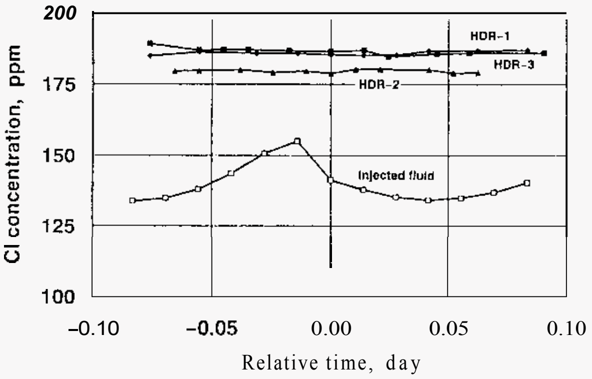

Figure 7. Cl concentrations of injected and produced fluids.

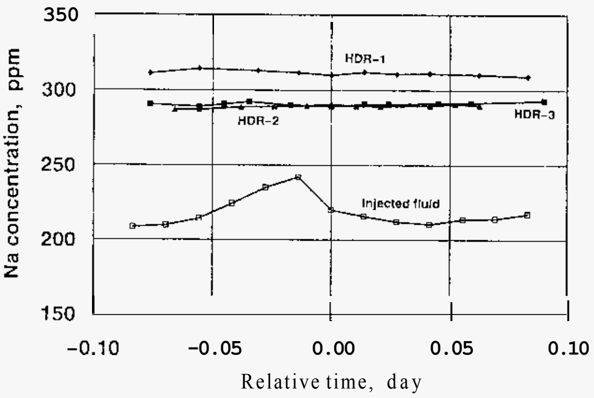

Figure 8. Na concentrations of injected and produced fluids.

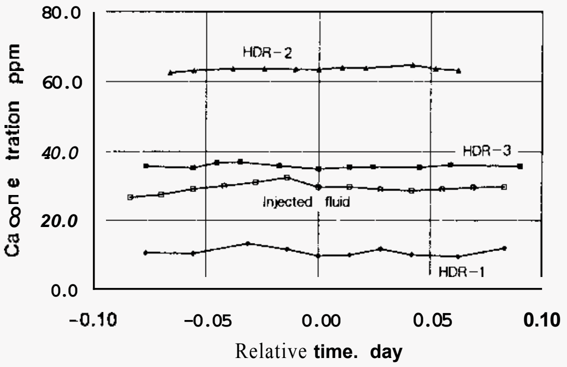

Figure 9. **Ca** concentrations of injected and produced fluids.

Silica concentration of bath injected and produced fluid is sham in Figure 10. Although an **average** Si concentration of 185 mg/l in the injected fluid was already higher than that expected from silica solubility at fluid temperature in the production wells, Si concentration increased remarkably in all produced fluids.

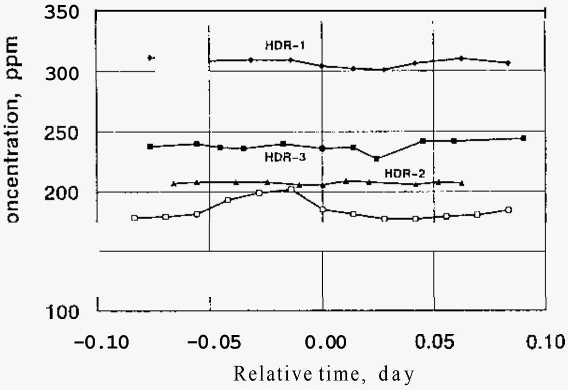

Figure 10. SiO$_2$ concentrations of injected and produced fluids.

5. SOURCES OF DISSOLVED SPECIES

As mentioned by many authors[Grigsby et **al.**, 1983; Edmunds et al., 1985; Robinson **et** al., 1987; Pauwels et **al.**, 1992; Kiho and Ohsumi, 1992], the chemical composition of the fluids sampled at the wellheads is controlled by chemical reactions between fluids and rocks and displacement and mining of formation fluid with injected fluid. **As** mentioned in the previous section, the concentrations of **all** dissolved species, **except** Ca, increased and tend to be **constant** in the produced fluid. Because it is indicated from laboratory dissolution experiments that Cl content in the Hijiori granodiorite is very low, and Cl behaves **as a** conservative species, the increase of Cl concentration in the produced fluid is only explained by mixing with indigenous fluid of high Cl concentration. However, **even** if miring with **a** single **source** of indigenous fluid **would** have occurred, there should be other reason to explain the constant Cl concentration in the produced fluid. **As** mentioned in section 2, Several feed **zones** were detected by the PTS logging in the production wells[Miyairi et al., 1992}. Therefore, the constant Cl concentration of the produced fluid from each well could be explained by mixing **of** fluids, which followed several paths and have different breakthrough times and concentrations.

The Na/Cl plots for fluid **samples are** show, in Figure 11. Plots of the injected fluid **are** on a mixing line between fresh make-up **water** and

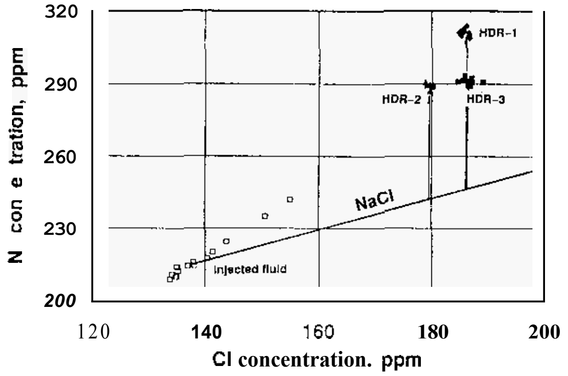

Figure 11. Na versus Cl far fluid samples during the sixth tracer test.

average concentration of the produced fluid from the three production wells. Kiho and Ohsumi[1992] described that the mixing was the major process causing the changes in the chemical composition of the produced fluid in the three-month circulation test at Hijiori. However, as shown in Figure 11, the plats of the produced fluid from HDR-1, HDR-2, and HDR-3 clustered in different areas and not on a simple mixing line. Therefore, water-rack interactions between the injected fluid and reservoir rocks should occur during a short residence time in the reservoir. Since the Na/Cl **molar** ratio of the produced fluid is about 1.0 at the beginning stage of the circulation test and both species consist the major part (over 90 mol %) of dissolved species, departure from the Na/Cl mining line from the average composition of the injected fluid, as shown in Figure 11, means that cumulative effect of the water-rock interaction which took place during the circulation test.

Since Cl concentration in the circulated fluid behaves as conservative species, normalized concentration of Cl in the produced fluid by the injected fluid, Cl_{prod}/Cl_{inj}, indicates a degree of mixed formation fluid. Therefore, the ratio of normalized concentration of dissolved species to that of Cl, $[C_{prod}/C_{inj}]/[Cl_{prod}/Cl_{inj}]$, might be **useful** to evaluate the effect of water-rock interactions. Figure 12 shows this ratio for major dissolved species in the produced fluids. Even though there are some **error** from analytical accuracy, Ca of the produced **fluid** of HDR-2 is remarkably higher than that of the others; SiO_2 of HDR-I fluid and SO, of HDR-2 are **also** slightly higher than those of the others. On the other hand, Ca in HDR-1 fluid is clearly decreased. In cores obtained from **HDR-1,** HDR-2, and HDR-3, calcite and anhydrite are frequently observed in parts of extensional fractures. Hence, calcite and anhydrite are thought to be main source of Ca and **SO,** in the produced fluids. Shigeno et al.[1993] conducted specification-solubility calculations by using geochemistry data of the circulation test. The result of their calculation indicated that anhydrite **was** in the undersaturated condition if fluid temperature was below 170°C **and** calcite **was** in the saturated condition at **all** temperature **range.** Measured fluid temperatures at the wellhead of HDR-1, HDR-2, and HDR-3 were 186, 147, and 167 °C, respectively[Miyairi et al., 1992]. These results **suggest** that increasing of Ca **and** SO, in HDR-2 fluid was **caused** by anhydrite dissolution and decreasing of **Ca** in HDR-I fluid occurred by anhydrite and/or calcite deposition.

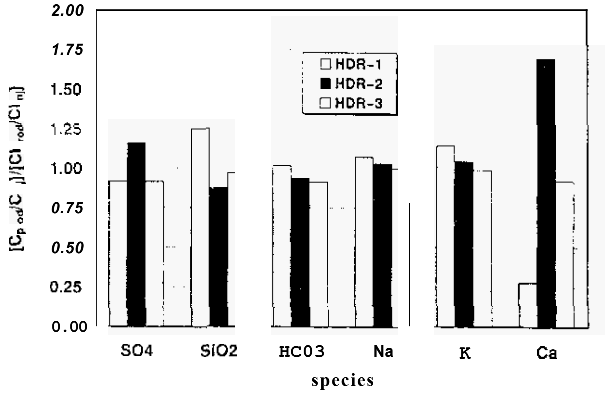

Figure 12. Normalized concentration of dissolved species to Cl concentration.

Quartz, Na-K, and Na-K-Ca geothermometers[Fournier, 1977; Fournier and Truesdell, 1973] were applied to estimate the reservoir temperatures. Temperatures of the three geothermometers and measured downhole temperatures are compared in Table 1.

Table 1. Geothermometer temperatures and measured temperatures at the end of the circulation **test**

	SKG-2	HDR-1	HDR-2	HDR-3
T_{qtz} °C	175	211	182	192
$T_{Na\text{-}K}$ °C	244	250	245	243
$T_{Na\text{-}K\text{-}Ca}$ °C	199	***220***	197	201
$T_{measured}$ °C	-	**186**	147	167

Results in Table 1 indicate all of the geothermometers predict higher temperatures than measured temperatures. Na-K geothermometer shows the highest temperatures around 245 °C. This temperature value is very **close** to original rock temperature of the reservoir region. Therefore, Na/K ratio in the circulate fluids seems to be kept in the original state and re-equilibrium reaction of these species in fluids might to be very slow. Quartz and Na-K-Ca geothermometers **show lower** temperature than the Na-K geothermometer and **those** temperatures seem to relate the measured temperatures. As discussed above, Ca and SiO_2 reacted in the reservoir, even though the circulation period **was** very short, and changed concentrations in the produced fluid. These chemical changes seem to **cause** the temperature changes of two geothermometers.

6. CONCLUSION

The analytical results of the injected and produced fluid sampled during the tracer experiment show that two processes, mining of injected water and formation fluid and water-rock interactions, occurred in the reservoir. Although the breakthrough time in each flow path is **less** than 7 hours, concentrations of dissolved species increased in the **produced** fluid by these processes. Difference.; in the produced fluid chemistry suggest the reservoir conditions, especially temperature, **in** each flaw path were differed from each other. Further study is required to reveal the process of water-rock interactions.

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