RESERVOIR EVALUATION OF THE HIJIORI HOT DRY ROCK GEOTHERMAL SYSTEM

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ABSTRACT

The natural fracture system at the Hijiori test site is described. The analysis of oriented cores and BHTV survey indicate fractures with E-W or ESE-WNW strike are predominant and major flow paths in the reservoir. The conductive fractures seem to be related with the ring fault of the Hijiori caldera. The flow regime in the deep reservoir is evaluated by the results of tracer experiments and PTS logs during circulation tests in 1995 and 1996. Severe interaction between the shallow and deep reservoirs was recognized during the tests. The PTS logs and tracer experiments reveal the connection from HDR-1 to HDR-2a is much better than that to HDR-3.

INTRODUCTION

After the success of a three-month circulation test of 1991 in the Hijiori hot dry rock (HDR) reservoir at a depth of 1800 m, R&D activity has been progressed to develop a deeper and hotter region (2,200 m depth and temperatures up to 270 °C). In 1995 and 1996, short term circulation tests were carried out in the deep reservoir with an injection well, HDR-1, and two production wells (HDR-2 and HDR-3). Pressure-Temperature-Spinner (PTS) surveys and tracer experiments were conducted to evaluate flow regime in the reservoir. Well tests with multi flow rates were also applied before and after the circulation tests to evaluate the injectivity of the reservoir. Those tests revealed the very complex flow regime and the severe interaction of the shallow and deep reservoirs (Hydo et al., 1996;Tenma et al., 1996).

Since the flow in the reservoir is controlled by the fracture system, the knowledge of the natural fracture system and also *in-situ* stress are very important to develop and evaluate an HDR reservoir (Willis-Richards et al., 1995; Dezayes, et al., 1995).

In this paper, the results of the natural fracture system analysis of the Hijiori test site are described. The flow regime in the deep reservoir is evaluated by the results of tracer experiments and other diagnostic methods conducted in the circulation tests.

FRACTURE SYSTEM IN HIJIORI

The HDR test site of NEDO is located near Hijiori hot spa in Yamagata prefecture. Geothermal activity in Hijiori is related with a recent volcanism which formed a small caldera of 2 km diameter around 10,000 years ago. The test site is located on the southern edge of the caldera, as shown in Figure 1.

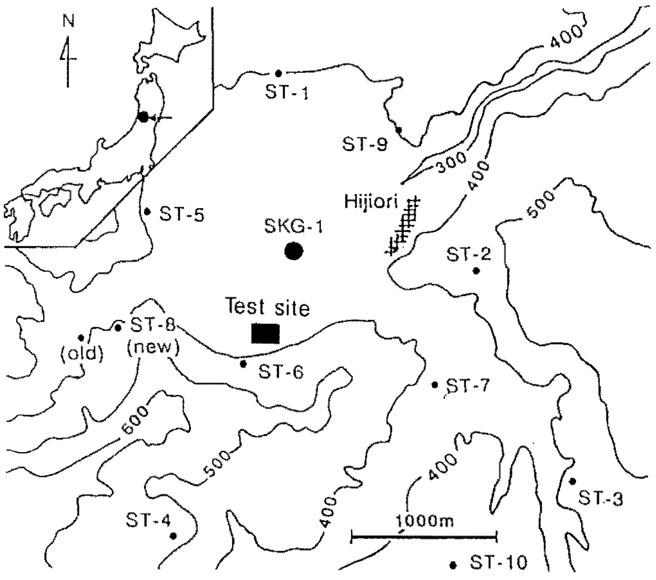

Figure 1. Location of the Hijiori test site

There are four wells, SKG-2, HDR-1, 2, and 3, at the site. Those wells penetrate into a Cretaceous granitic basement, which is a target rock, at around 1,500 m depth through Quaternary and Neogene volcanic rocks. SKG-2 was used as an injection well until 1991 and is now used for an observation well. Well HDR-1, which was the first well drilled by NEDO at Hijiori in 1987, had been used for a production well until 1991 but is now used for an injection well of a deep reservoir at 2,200 m depth. In 1991, Well HDR-2 had been drilled and used for a production well in the shallow system. In 1994, HDR-2 was sidetracked and deepened westwards to obtain a longer separation from HDR-1. HDR-3 was drilled in 1990 eastwards from a injection point of SKG-2 and deepened from 1,909 m to 2,300 m in 1993. Trajectories of those wells are shown in Figure 2.

During the drillings of HDR-1, HDR-2, and HDR-3, around 60 meters of cores were obtained by 28 spotted coring operations. Oriented coring was tried 21 times and 12 oriented cores were successfully obtained. Fracture analyses were conducted on the oriented cores by NIRE and NEDO.

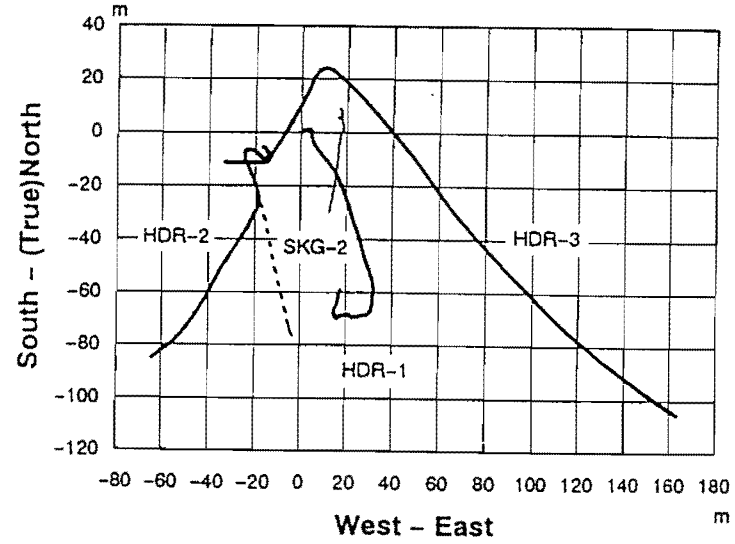

Figure 2. Trajectories of injection and production wells at the Hijiori test site.

A fracture set striking E-W or ESE-WNW with dip about 70°N is predominantly observed in the cores, as shown in Figure 3. This fracture set usually associates with hydrothermal alteration veins (quartz, anhydrite, calcite, epidote and chlorite) and is thought to be created by the extensional stress condition. Fractures with the same striking but dip S are also recognized on the cores from the deep reservoir (Figure 3). Other two fracture sets striking NNE-NE and NW, associated with chlorite and epidote veinlets, are also dominant. Since slikenside is often observed in the fractures, these conjugate fracture sets were thought to be formed under the shearing stress condition.

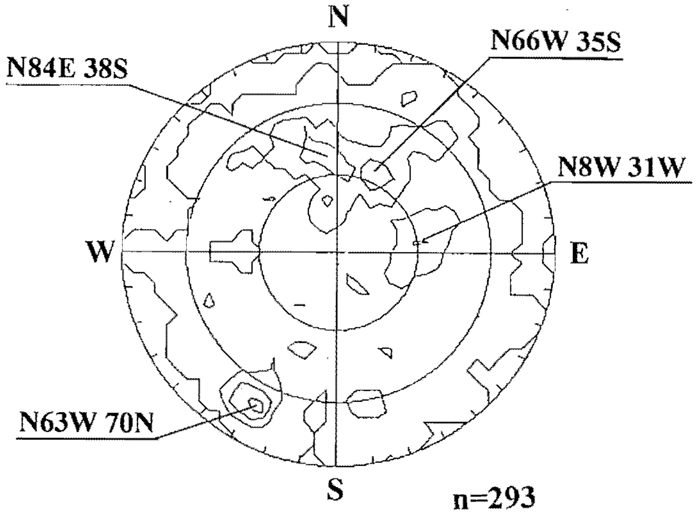

Figure 3. Contoured diagram (lower Schmidt projection) of natural fractures observed on oriented cores of HDR-3 deepened portion.

The extension and shear fracture sets were also detected by Borehole Televiewer (BHTV) survey in openhole portions of HDR-1, 2, and 3. In 1992, an injection portion of HDR-1 was observed by BHTV before and after a hydraulic stimulation of the deep reservoir. Although several fractures with N-S striking and dip W were newly created by the stimulation as shown in Figure 4 (Yamaguchi et al., 1996), the fractures striking E-W and dip N were mainly observed in the communication part of HDR-2 and HDR-3. During oriented coring at the depth of 2183 m in HDR-3, a hydraulic communication with HDR-1 was inferred by a rapid ascending of the water level in HDR-1. Two open fractures associated with quartz and adularia crystals and sericite alteration are observed on the oriented core recovered from that depth. Strike and dip of these fractures were N100°E and 74°N and N110°E and 78°N, respectively. Outflow zones detected by PTS surveys in the production wells also tend to spatially align on paralleled planes of the E-W trend and dip N, as shown in Figure 5 (NEDO, 1996), hence the E-W striking fractures are thought to be major flow paths in the reservoir.

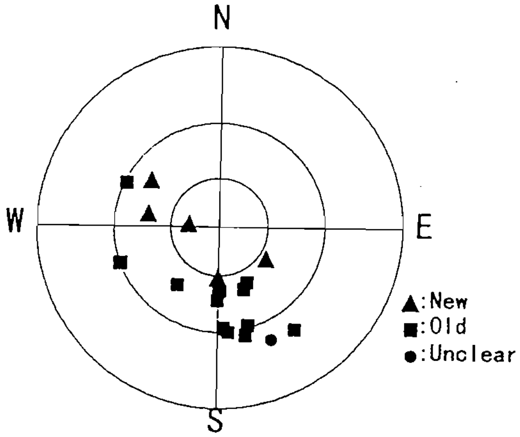

Figure 4. Orientation of fractures observed by BHTV before (old) and after (new) the hydraulic stimulation in HDR-1 (Yamaguchi et al., 1996).

This type of lineaments and fractures is not obvious in an outcrop of the Kotake granodiorite, which is the same granitic rock of the reservoir, at about 4 km south of the test site nor in a volcanic ash formation at the Hijiori caldera. The test site is located at the southern edge of the caldera, as mentioned previously, hence the conductive fractures of E-W trend seem to be closely related with the ring fault of the caldera.

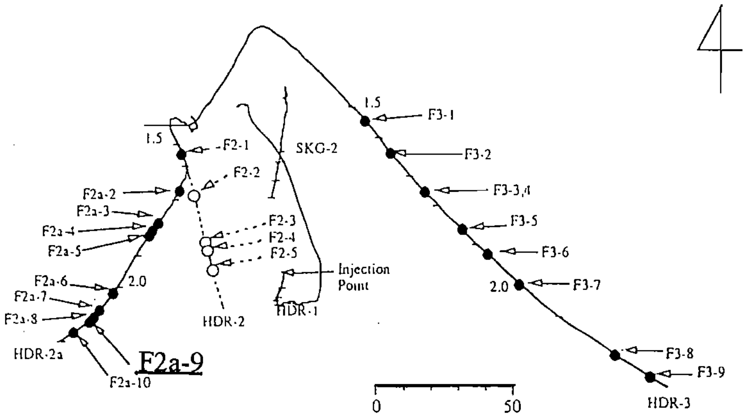

Figure 5. Outflow zones detected by the PTS log in HDR-2 and HDR-3 (NEDO, 1996)

DIAGNOSTIC METHODS APPLIED FOR CIRCULATION TESTS AT HIJIORI

After a hydraulic stimulation from an open-hole section of HDR-1 in 1992, HDR-3 was deepened in 1993 and HDR-2a was sidetracked in 1993 to achieve communication with HDR-1. The first circulation test was conducted for one month in 1995. The second circulation test was conducted for a month last summer. Results of these test were already reported by Sato et al. (1995) and Nagai et al.(1997), therefore several topics related with the reservoir evaluation are described here.

At the beginning and end of the circulation test, step-rate (multi-rate injection) test was conducted to obtain information of hydraulic parameters around HDR-1 (Kadowaki, 1996). Hydo et al. (1995) analyzed impedance components in the shallow reservoir using pressure and flow data obtained in the 1991 circulation test.

PTS log is the most powerful tool to distinguish fluid flow paths in a borehole. If PTS log is repeated during a circulation test, we can obtain temperature and flow changes at each flow zone. During the circulation test in 1995, PTS log was conducted 6 times each in HDR-2 and HDR-3. Miyairi and Sorimachi (1996) identified 10 effective fracture zones, which are already shown in Figure 5, by using these PTS logs.

Tracer experiment is a useful diagnostic method to identify flow in a reservoir, especially in a multi-reservoir and multi-production well system such as Hijiori. In the Hijiori test site, tracer experiments have been conducted with every circulation test at the shallow and deep reservoirs. Although tracer response curves are obtained as an overall response for a reservoir at the surface, we may distinguish each response of flow path by applying PTS logs as mentioned in Matsunaga et al.(1995a).

Fluid geochemistry is also a possible indicator of flow regime of an HDR reservoir. At Fenton Hill, sodium vs chlorine concentration plot indicates dilution process of an original high chlorine formation fluid by injected surface water (Grigsby et al., 1989). We observed the same phenomena at Hijiori in the circulation tests in the shallow and deep reservoir (Matsunaga et al., 1995b;1996). Since anhydrite is widely seen as alteration mineral at Hijiori and it exhibits inverse solubility with respect to increasing temperature, sulfate concentration of the production fluids is also a good indicator of the reservoir response for injected fluid.

EVALUATION OF FLOW REGIME IN THE DEEP RESERVOIR AT HIJIORI

At the beginning of the 1995 circulation test, interaction between HDR-2 and HDR-3 and also the deep and shallow reservoirs was recognized (Tenma et al., 1996). Although the injection well is cased through the shallow reservoir, a significant amount of production from the shallow reservoir was detected by PTS logs. This means there is flow somewhere between the deep and shallow reservoirs. However, the production from the shallow reservoir shows a negative correlation to the wellbore pressure at the depth, while the production from the deep reservoir correlate to the injection pressure at HDR-1 (Miyairi and Sorimachi, 1996). Therefore, the communication between the deep and shallow reservoirs seems indirect and not so dominant near the wellbores. Hyodo et al.(1996) applied their model for the analysis of impedance components in the deep reservoir, however it was difficult to measure due to extensive interaction between the deep and shallow reservoirs.

Figure 6 shows tracer response curves for the first experiment in 1995. These response curves suggest the deference in the fracture connections from HDR-1 to HDR-2 and HDR-3 (Matsunaga et al., 1996). It was estimated by PTS log analysis that roughly 75 % of fluid from HDR-1 to the deep reservoir part of HDR-2 flowed through a single fracture, F2a-9 (NEDO, 1996), hence a major part of injected tracer to HDR-2 flowed into this fracture in a short time and came out through the surface with a sharp response. On the other hand, paralleled and also slightly minor flows from HDR-1 to the deeper part of HDR-3 could have caused the small response in HDR-3.

As shown in Figure 7, the variation of Cl^- and SO_4^{2-} concentration in HDR-2 was closely related to the flow control at the surface. Decreasing Cl^- and increasing SO_4^{2-} levels suggests that relatively fresh surface water tends to flush out formation fluid which is high in Cl^- and low in SO_4^{2-} concentrations. In the 1996 circulation test, fresh river water was periodically injected at the same flow rate as the circulation rate for HDR-1 during tracer experiments. During tracer return, small decreasing of Cl^- and increasing of SO_4^{2-} were recognized only in the production from HDR-3. Since fluid geochemistry variation, as like the tracer response, is more remarkable in HDR-2, we can conclude that the

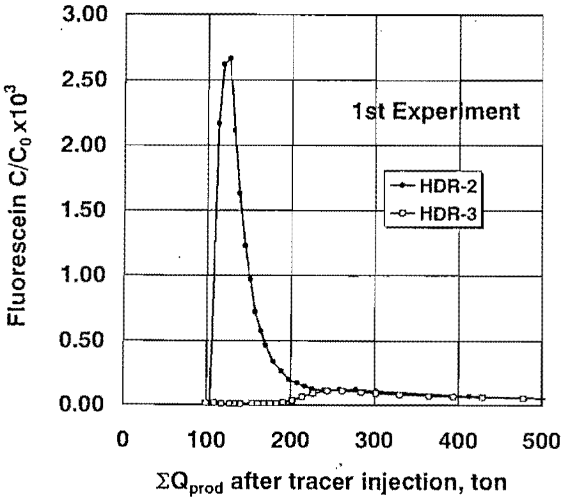

Figure 6. Tracer breakthrough curves of HDR-2 and HDR-3 at the first tracer experiment in 1995.

connection from HDR-1 to HDR-2 is more dominant than that to HDR-3.

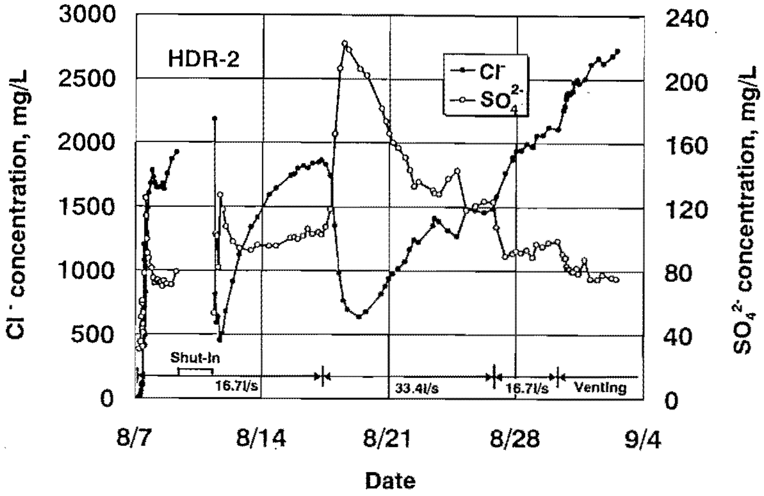

Figure 7. Cl^- and SO_4^{2-} concentration of HDR-2 production fluid during the 1995 circulation test in the deep reservoir.

If we compare tracer recovery with fluid recovery during a tracer experiment, we may estimate fractional flow from the shallow reservoir since tracer is contained in the flow from the deep reservoir. Once the flow fraction is obtained, we can estimate the tracer travel time in wellbore and also in the reservoir. As the response curves of HDR-2 were much clearer, it was easier to calculate recovery. Therefore a comparison was done for HDR-2 production. The result are shown in Table 1. Values obtained from the tracer recovery are almost comparable to those obtained from the PTS logs. Although the travel time in the reservoir increased during the circulation test, modal volume of the reservoir increased only in the second experiment from 9 m^3 of the first experiment to 15 m^3. This means that injection with a doubled flow rate (32 l/s) tended to inflate fracture volume near wellbore, however the effect did not continue for long since the modal volume was decreased to 7.2 m^3 at the third experiment.

Table 1. Results of tracer experiments in HDR-2

	1st exp.	2nd exp.	3rd exp.
Tracer recv.	14.3 %	11.1 %	9.0 %
Fluid recv.	30 % (5.0 l/s)	13.7 % (4.6 l/s)	30.3 % (5.1 l/s)
Fract. Q_{up}	0.52 (2.6 l/s)	0.19 (0.9 l/s)	0.7 (3.6 l/s)
Fract. Q_{low}	0.48 (2.4 l/s)	0.81 (3.7 l/s)	0.3 (1.5 l/s)
Residence time	1:03	1:07	1:20
Modal Vol.	9 m^3	15 m^3	7.2 m^3

CONCLUSIONS

Detailed analysis of oriented cores and also BHTV survey in boreholes reveals that the major fracture system contributed to the fluid circulation in Hijiori is the E-W or ESE-WNW fractures. These fractures seem to be correlated with the formation of the Hijiori caldera. Two fracture sets of NNE-NE and NW strike might be weak flow paths which connect major fractures.

During the 1995 and 1996 circulation tests, the severe interaction between the shallow and deep reservoirs were observed. Although the hydraulic analysis to obtain the impedance components in the deep reservoir was difficult, PTS logs and the tracer experiments reveal that the connection from HDR-1 to HDR-2a is much better than that to HDR-3.

Long term circulation test are needed to evaluate the performance of the Hijiori HDR reservoir.

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