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GEOCHEMICAL EVALUATION OF THE HIJIORI HDR RESERVOIR AT YAMAGATA, JAPAN

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ABSTRACT

A deep HDR reservoir in granitic basement rock at the Hijiori test site, Japan has been evaluated by using results of geochemical monitoring of circulation fluids and tracer experiments in the 1995 and 1996 circulation tests. Na-Cl and d^{18}O-Cl plots of the circulation fluids and river water clearly indicate the dilution process of the indigenous fluid by river water injected as the make-up water. Although dilution is a major process controlling the circulating fluid geochemistry, water-rock interaction processes, such as anhydrite dissolution, also occur in the reservoir. Changes in the chlorine and sulfate concentrations during the two-well production stage of HDR-2a and HDR-3 indicate that the connection from the injection well HDR-1 to HDR-2a is better than to HDR-3. Tracer experiments also suggest a difference in the fracture fluid between HDR-1 and the two production wells, HDR-2a and HDR-3.

1. INTRODUCTION

At the Hijiori HDR test site in Yamagata prefecture, research and development activity has progressed to the development of a deeper and hotter region (2,200 m depth and temperatures up to 270 ºC). This follows the success in 1991, of a three-month circulation test of an upper reservoir at a depth of 1,800 m. In 1995 and 1996, short-term circulation tests were carried out in the deep reservoir with wells HDR-1, HDR-2a and HDR-3.

During the circulation tests in 1995 and 1996, severe interaction of flow between the shallow and deep reservoirs was recognized (Tenma et al., 1996). Pressure-Temperature-Spinner (PTS) surveys were conducted to evaluate the flow regime in the reservoir (Miyairi and Sorimachi, 1996). Injection tests with multi flow rates were also conducted before and after the circulation tests to evaluate the injectivity of the reservoir. Those tests revealed the flow regime in the reservoir (Hyodo et al., 1996).

As mentioned by several authors (Robinson, et al., 1987; Althaus and Edmunds, 1987; Richards et al., 1992), geochemical investigations such as tracer experiments and geochemical monitoring of circulation may be useful in evaluating the flow in the reservoir. Tracer experiments were conducted to obtain reservoir parameters such as the volume in the inter-well region. Results of the tracer experiments during the 1995 and 1996 circulation tests have been briefly presented at the third and fourth HDR forums (Matsunaga et al., 1996; 1998). Here we evaluate the fluid geochemistry of samples which were collected during the tracer experiments, with a view to identifying the process which initiated the chemical differences between the injection and production fluids.

2 CIRCULATION TESTS IN 1995 AND 1996

2.2 Outline of the tests

The 1996 circulation test was carried out to improve the connection between HDR-1 and HDR-3 at the Hijiori HDR test site during a one-month period in the summer of 1996. The test was started on 10 August. As shown in Figure 1, the injection flow rate at HDR-1 was kept at about 16.7 kg·s^{-1} during the test. A main valve at the HDR-2a wellhead was closed on 11 August to enhance fluid flow between HDR-1 and HDR-3. Single well production from HDR-3 was continued for three weeks from August 12 to September 1. During this stage, the valve opening ratio at HDR-3 was controlled between 0.25 and 0.6 to evaluate the effect of valve opening on production. As a result of this operation, the production flow rate from HDR-3 increased from 3 to 7 kg·s^{-1}, as shown in Figure 1.

The HDR-2a wellhead valve was opened on 2 September, and two-well production was attained. Two-well production continued until the end of circulation on 9 September. About a 70% recovery rate of injection fluid was achieved during this stage (Tenma, et al., 1997).

PTS surveys were periodically conducted during the test to locate feed points and evaluate flow at each feed point in the wells. However, it was difficult to obtain a good result in HDR-3 because the flow in the borehole changed and occasionally stopped during PTS surveys. The production curve on 27 August in Figure 1 indicates such unstable production at well HDR-2a.

2.2 Geochemical monitoring during tracer experiments

The tracer experiments were conducted four times during the circulation test. First, three tracer experiments were conducted during the single-well production stage of HDR-3. The last experiment was conducted on 4 September during the two-well production stage. The purpose of the experiments was to confirm a flow change in the reservoir by opening HDR-2a.

During the experiments, except the second test, fresh water from the Nigamizu River was directly injected as a fresh- water flush (Edmunds et al., 1989). Produced fluid was collected at each wellhead under high-temperature and high-pressure conditions by an auto sampler that was designed at NIRE. Fluid samples were collected in 250 ml bottles at every scheduled time. Fluids were filtered through a 0.45 μm membrane and then kept in plastic bottles. Electrical conductivity and pH of the filtered samples were determined on site. Tracer and major dissolved species were analyzed in the chemistry laboratory at NIRE by ion chromatography (Cl^-, SO_4^{2-}, Na^+, K^+, Ca^{2+}), titration with H_2SO_4 (HCO_3^-), and ICP (Si, Na, K, Ca, Mg, I). Stable isotope ratios of ^{18}O, D, ^{34}S, ^{13}C and $^{87}Sr/^{86}Sr$ were obtained at the central laboratory of Mitsubishi Material Co.

2.3 Monitoring river water and spring fluids

The understanding of local hydrology inside the Hijiori caldera is of considerable benefit to the Hijiori project. Water pumped up from the Nigamizu River has been used for make-up water during circulation, hence geochemistry of the river water is important in evaluating geochemical processes in the reservoir. Several hot springs and natural carbonate springs are located inside and around the caldera. Geochemistry of those fluids might also be very important in understanding underground hydrology in the caldera and also to monitor any environmental effects of the Hijiori project on the local area, especially on hot springs.

Fluids have been collected four times a year at Nigamizu and Dozan Rivers since June 1997. Fluid samples have also been collected at Hijiori, Kogane, and Ishidaki hot springs within the caldera and at two carbonate springs along Nigamizu River. Major dissolved species and some stable isotope ratios have been analyzed by the same procedure mentioned above.

3 RESULTS

3.1 Geochemistry of the circulation fluid

Selected results of fluid analyses are reported in Table 1. Figure 2 shows temporal changes of chlorine (Cl^-) and sulfate (SO_4^{2-}) concentrations of the HDR-3 fluid at the beginning of the circulation test. Intermittent production similar to a geyser occurred at the start of the production. Although the concentration of dissolved species in the HDR-3 fluid fluctuated with the intermittent production, concentrations of most species tended to decrease. For example the Cl^- concentration decreased from 3000 $mg \cdot l^{-1}$ to 2000$mg \cdot l^{-1}$, as shown in Figure 2. After establishing stable production on the evening of 12 August, Cl^- and SO_4^{2-} concentrations of HDR-3 fluid also stabilized. A little decrease in both Cl^- and SO_4^{2-} concentrations, as indicated by an arrow in Figure 2, followed after the fresh-water flushing operation during the first tracer injection.

Figure 3 shows the changes of Cl^- and SO_4^{2-} concentrations at the reopening stage of HDR-2a. The Cl^- concentration of HDR-2a fluids suddenly decreased from 2750 to 430 $mg \cdot l^{-1}$ and then recovered gradually. On the other hand, the sulfate concentration increased to 218 $mg \cdot l^{-1}$ and then decreased.

The fresh-water injection was started at 11:30 on 4 September and continued for 20 hours. The fourth tracer experiment was conducted during this stage. The fresh-water flushing operation initiated a remarkable depression of Cl^- and projection of SO_4^{2-} in HDR-2A fluids, but not in HDR-3 fluids.

3.2 Mixing process in the Hijiori reservoir

Since Cl^- is one of the best indicators of mixing between original formation fluid and injected fresh water, the plot of Na-Cl concentration indicates the extent of the mixing process and of rock-water interactions in the reservoir (Grigsby et al, 1989; Pauwels, 1992). The Na-Cl plot of circulation fluids at the upper reservoir in a three-month circulation test in 1991 indicated that the mixing process was a major process controlling the fluid chemistry, despite water-rock interactions which also took place during the short residence time in the reservoir (Kiho and Ohsumi, 1992; Matsunaga et al., 1995). The same geochemical evolution of circulation fluids was recognized in the 1996 test.

A linear correlation is clearly identified in $\delta^{18}O$-δD and Cl-$\delta^{18}O$ diagrams for selected fluid samples obtained in the 1996 circulation tests and in water from the Nigamizu River, as shown in Figure 4 for the Cl-$\delta^{18}O$ correlation. On the other hand, plots of the Ishidaki, Hijiori, and Kogane hot springs are located in different points away from the mixing line. This result suggests that fluids of these three hot springs evolved in different processes from that of the Hijiori reservoir.

3.3 Estimation of flow in the Hijiori reservoir by using geochemical data

A remarkable change in fluid geochemistry was initiated by starting production from HDR-2a, as seen in Figure 3. We can estimate from this change in the fluid chemistry that the following process occurred in the Hijiori reservoir:

During the shut-in stage of HDR-2a, injection fluid from HDR-1 flowed into HDR-2a through fractures in the deep reservoir, flowed up the borehole, and then flowed into the shallow reservoir. Therefore, the open-hole fluid was displaced by injection water with a low Cl^- concentration. The Cl^- concentration of the injection water, around 500 $mg \cdot l^{-1}$, is almost the same as that of the first production fluid from the open-hole portion of HDR-2a. Hence, there may not have been any Cl^- uptake in the flow path between HDR-1 and HDR-2a during the shut-in stage of HDR-2a.

Once HDR-2a was open, fluid with a relatively higher Cl^- concentration in the shallow reservoir flowed into HDR-2a and merged with the fluid from HDR-1 flowing through the deep reservoir. The flow change associated with HDR-2a production is schematically drawn in Figure 5.

An explanation for the change in the SO_4^{2-} concentration is as follows: Since anhydrite is widely seen as an alteration mineral around the reservoir and since it exhibits inverse solubility with respect to increasing temperature, the SO_4^{2-} concentration of the production fluids is also a good indicator of the reservoir response to injection fluid temperature. During the shut-in stage of HDR-2a, SO_4^{2-} was dissolved from anhydrite because the open-hole fluid was slightly cooled by the injected fluid. When the valve was opened at the HDR-2a wellhead, heated fluid with high Cl^- and low SO_4^{2-} concentrations flowed back from the shallow reservoir into HDR-2a and went up with fluid from the deep reservoir. Since relatively low temperature river water was pumped into HDR-1 during the fresh-water flush, anhydrite dissolution was reactivated and the SO_4^{2-} concentration of the produced fluid increased.

The fresh-water flush appeared to be a kind of tracer experiment with negative Cl^- input. Hence, if we define the Cl^- budgets of the injection and production fluids during the fresh-water flush, we can estimate the ratio of fluid productivity from the deep and shallow reservoirs into HDR-2a. The Cl^- concentration of fresh river water was around 25 $mg \cdot l^{-1}$. As there was no Cl^- uptake in the deep reservoir as mentioned above, we may suppose that the Cl^- of the flow-back fluid from the upper reservoir followed the dashed line in Figure 4. Then, by comparing the mass balance of Cl^-, we can calculate that around 40% of the fluid in HDR-2a was produced from the deep reservoir. This number is slightly less but comparable with that, around 50%, of PTS surveys.

The geochemistry of HDR-3 fluids is slightly different from that of HDR-2a, in that the Cl^- concentration was higher and the SO_4^{2-} concentration was lower. These differences in the fluid chemistry and the concentration variations at the beginning of the two-well production test, and also during the fresh-water flushing stage, suggest that the connection from HDR-1 to HDR-2a is more dominant than that to HDR-3.

4 CONCLUSION

The analytical results of the injected and produced fluids sampled during the tracer experiments show that the water-rock interactions occurred in the reservoir. Differences in the produced fluid chemistry suggest that the reservoir conditions, especially temperature, in each flow path were differed from each other. The result also reveals the complexity of the flow regime, which was easily affected by flow controls at the wellheads and surveys in the wellbores, in the multi-well and multi-fracture system at Hijiori.

By comparison of the fluid geochemistry for the circulation fluids and surface fluids from natural hot springs, the circulation fluids had different evolution processes than those of the surface fluids. Further studies, in laboratory and in field, are desired to reveal in more detail the process of water-rock interactions in the reservoir.

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Table 1. Analytical data for selected samples during the 1996 circulation test, rivers, and hot springs. All analyses in mg·l^{-1} except electrical conductivity in mS·cm^{-1}

Sample	Time	Well	pH	EC	Cl	SO_4	HCO_3	Na	K	Ca	Mg	SiO_2
7	8/12 05:55	HDR-3	6.41	9.22	2922	45.1	843	1788	255	99.7	4.8	491
15	8/12 17:00	HDR-3	6.51	7.55	2296	50.9	753	1479	218	143	7.7	555
160	9/02 16:00	HDR-2a	6.17	8.90	2755	19.2	1893	1645	240	371	21.8	351
167	9/02 20:00	HDR-2a	6.92	2.24	551	184.6	222	435	66	24.0	0.8	378
173	9/03 02:03	HDR-3	5.96	5.35	1783	84.3	220	1112	159	-	-	539
174	9/03 04:00	HDR-2a	6.47	2.88	788	148.6	172	582	88	5.2	-	427
209	9/04 03:55	HDR-2a	6.24	3.57	974	157.2	208	695	106	4.1	-	440
232	9/04 13:55	HDR-2a	5.99	3.55	1001	156.9	216	720	110	4.7	-	436
251	9/05 01:35	HDR-2a	6.15	4.33	2185	72.1	172	1334	192	10.3	-	454
255	9/05 06:40	HDR-3	5.61	6.12	2018	67.5	195	1286	185	-	-	538
277	9/09 00:20	HDR-3	6.18	7.85	2682	54.3	171	1576	223	6.4	-	557
278	9/09 01:33	HDR-2a	5.63	6.57	2185	72.1	172	1334	192	7.1	-	491
Nigamizu	98/6/14	River	6.87	0.18	14.4	22.3	47.5	16.8	1.7	10.7	5.4	23.3
Dozan	98/6/13	River	7.46	0.07	6.8	6.2	20.2	7.6	1.3	2.2	1.4	28.8
Kogane	98/6/14	Hot Spr.	7.35	4.32	329	565	1318	807	55	64.4	41.5	233
Hijiori	98/6/13	Hot Spr.	6.36	4.52	922	200	765	727	60.7	53.5	19.5	231
Ishidaki	98/6/13	Hot Spr.	6.45	3.20	322	564	758	619	31.9	47.4	24.8	152

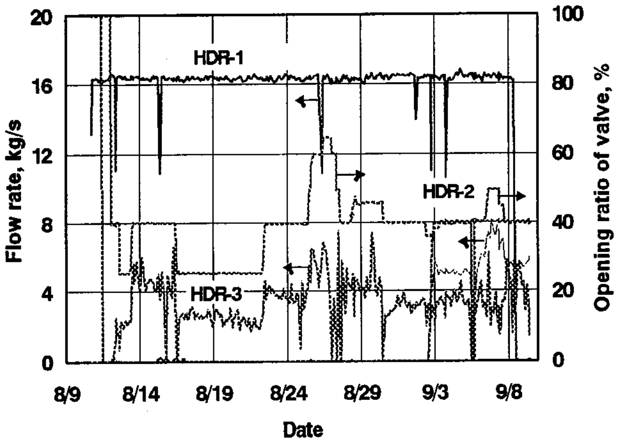

Figure 1. Relation between valve opening and production flow of HDR-2a and HDR-3 during the 1996 circulation test. Injection flow rate is almost kept constant.

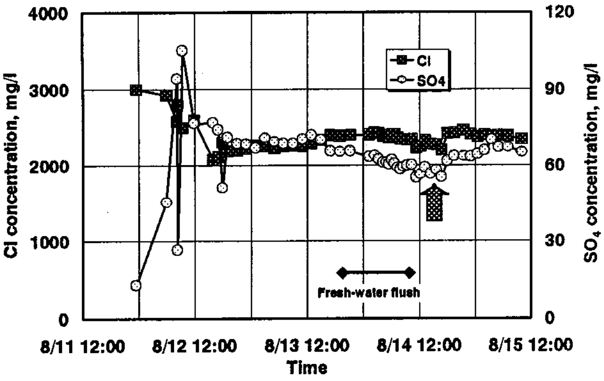

Figure 2. Cl$^-$ and SO$_4^{2-}$ concentration of circulation fluids at the beginning of the single well production HDR-3.

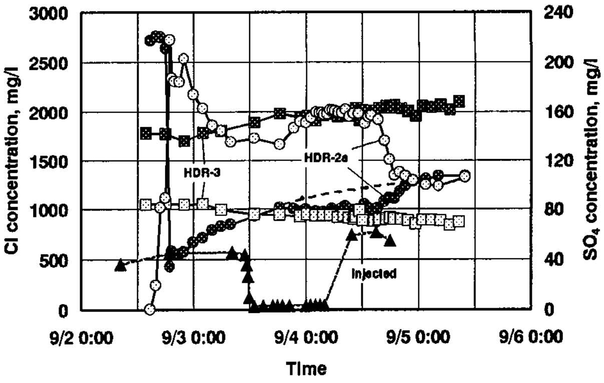

Figure 3. Cl$^-$ and SO$_4^{2-}$ concentration in injection and production fluids at the two well production stage in the 1996 circulation test. Red and blue marks: Cl$^-$, Yellow: SO$_4^{2-}$.

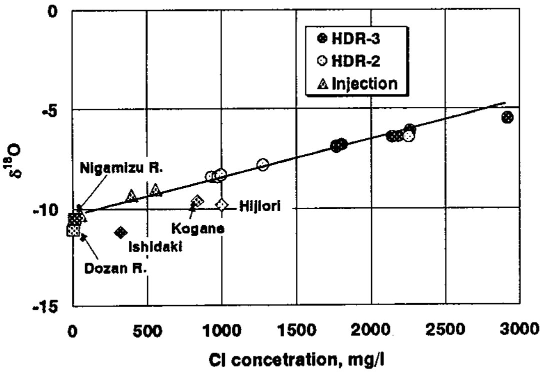

Figure.4. δ^{18}O-Cl correlation of circulation fluids and surface fluids in Hijiori area.

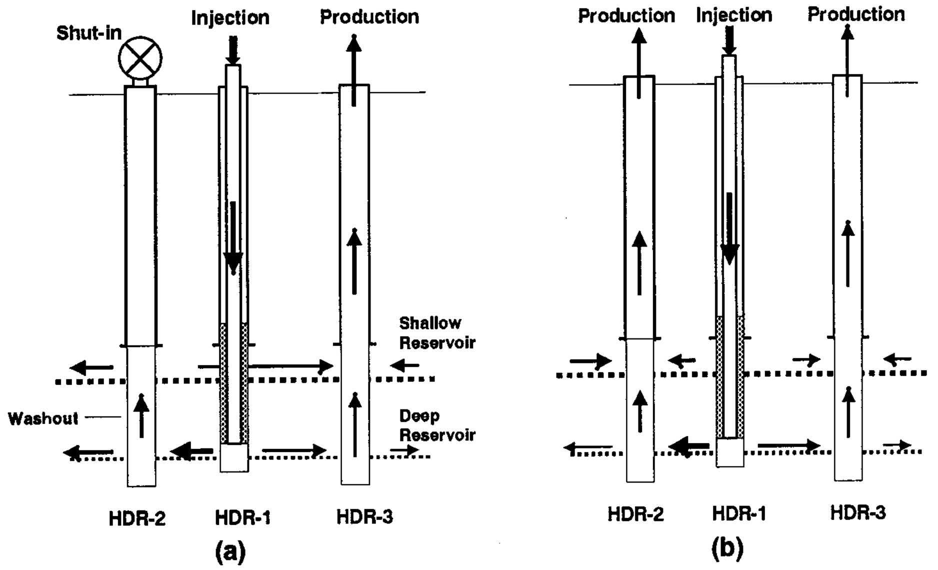

Figure 5. Schematic drawing of the fluid flow estimated by geochemistry of production fluid: (a) during the single well production, (b) after HDR-2 reopening (two-well production).