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Lessons learned from the Ogachi and Hijiori HDR/EGS Projects, Japan

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ABSTRACT

The Ogachi and Hijiori Hot Dry Rock (HDR) or Enhanced/Engineered Geothermal Systems (EGS) projects were conducted not in pure hot dry rock but in rock with many natural joints in Japan. Therefore, multiple reservoir and multiple well systems were planned to make water recovery higher during water circulation operations. Two reservoirs were created by hydraulic fracturing at different depths in the both projects. Water recovery during water circulation in the Ogachi system with one injection well and one production well increased up to 32%. The Hijiori project showed that water recovery during water circulation was improved more than 70% with one injection well and three production wells. Therefore, we can extract heat energy effectively from hot rock with many natural joints by a multiple production well system. These created reservoir characters and water flow in the reservoirs were strongly depended on geological conditions. In the Ogachi project two reservoirs created at different geological condition were evaluated by microearthquake hypocenter distribution to progress different directions. It was difficult of the production well to penetrate the best position of each reservoir. However, after many hydraulic stimulation operations in both the injection and production wells, hydraulic connection between the wells was improved. In the Hijiori project two reservoirs progressed in same direction in almost same geological condition at different depths. However, unbalanced water flow in the two reservoirs occurred and resulted in carbonate mineral scaling problems in the production wells during water circulation. No environmental problem such as induced earthquake observation and water chemical analysis of river and hot springs was occurred in both the HDR projects.

1. INTRODUCTION

The concept of Hot Dry Rock (HDR) geothermal energy originated at Los Alamos National Laboratory (LANL), USA in the early 1970s, to extract the heat contained in hot dry rock. LANL researchers created and tested man-made reservoirs at depths in the range of 2.8 to 3.5 km in crystalline rock formations underlying the Fenton Hill site in New Mexico, USA (Duchane, 1995, Brown, 2009, Kelkar et al., 2015). Some researchers including the author joined the Fenton Hill project though a collaboration between New Energy and Industrial Technology Development Organization (NEDO), Japan and LANL. The researchers learned basic technologies for the HDR development and contributed to the project. The researchers returned and led HDR projects in Japan.

HDR concept in Japan was different from the Fenton Hill project. The Fenton Hill hot dry rock was very old (pre-Cambrian) crystalline rock and the very deep, so rock was confined. In Japan we can access high temperature rock at relatively shallow depth where natural joints dominants. If the natural joints in hot rock are open, then we can easily produce steam for conventional geothermal power generation. But the joins were sealed by carbonate and/or silicate minerals, permeability of the rock will not be enough for water flowing, geothermal reservoir will not be developed. Hot Dry Rock (HDR) or Enhanced/Engineered Geothermal Systems (EGS) geothermal energy development technologies can be applied to extract heat energy from these low permeability rocks. When hydraulic stimulation operations are applied to the low permeability rocks, many fractures will be developed. In this case it is considered to be necessary for extracting heat effectively from these rocks to construct a multiple reservoirs and multiple wells systems.

Two HDR/EGS projects were conducted at Ogachi and Hijiori, northern Japan. The Ogachi project was conducted by the Central Research Institute of the Electric Power Industry (CRIEPI) at Ogachi in Akita prefecture from 1989 to 2002. Two reservoirs were created from an injection well, OGC-1, at different depths of 711 m to 719 m and 990 m to 1,000 m where temperatures were measured 170 degree C and 228 degree C, respectively. Two production wells, OGC-2 and OGC-3 were drilled based on the precise microearthquake hypocenter locations and succeeded to hydraulically connect to the reservoirs. River water was injected into OGC-1 and recovered as steam and hot water at a temperature of 165 degree C from OGC-2 with water recovery of a maximum of 32 % (Kaieda et al., 2005, Kaieda, 2012). Unfortunately, OGC-3 was not used for water circulation operations because the project finished just after OGC-3 was drilled and tested water flow connection to OGC-1.

The Hijiori project was conducted by NEDO at Hijiori in Yamagata prefecture from 1986 to 2003. In this project two reservoirs were created from two injection wells, SKG-2 and HDR-1 at different depths of 1,788 m to 1,802 m and 2,151 to 2,205 m where temperatures were measured 230 degree C and 270 degree C, respectively. Two production wells, HDR-2 and HDR-3 were drilled based on the microearthquake hypocenter locations and succeeded to hydraulically connect to the injection wells. Carbonate scaling problems occurred during water circulation operations by unbalanced water flow in the two reservoirs was solved by cleaning the production wells and adding scale prohibitor in injection water. River water was injected into the injection wells and recovered as steam and hot water from the production wells with water recovery of a maximum of 70.4 % (Tenma et al., 2001). A small of 50 kW binary power plant was operated during water circulation tests (NEDO, 2003).

2. CONCEPT OF MULTIPLE RESERVOIR AND MULTIPLE WELL

In Japan there are more than 100 active volcanoes. We can access high temperature rocks at relatively shallow depth near volcanoes. These rocks may have many natural joints and not be confined as the rock in the Fenton Hill project in USA. It is considered to be difficult to obtain high water recovery during circulation operations in joint rocks with a pair of one injection well and one production. The concept of the multiple reservoir and multiple well is shown in Figure 1. The reservoirs are created from injection wells at different depths to enlarge heat extraction area. Production wells are drilled to penetrate these reservoirs. Four production wells locate around one injection well in an ideal case. Each reservoir is hydraulically connected with one injection well and four production wells at least. Therefore, water injected into an injection well is recovered from four production wells. If 25% or more of water injected into the injection well is recovered from one production well, then the total recovery from four production wells will be about 100%.

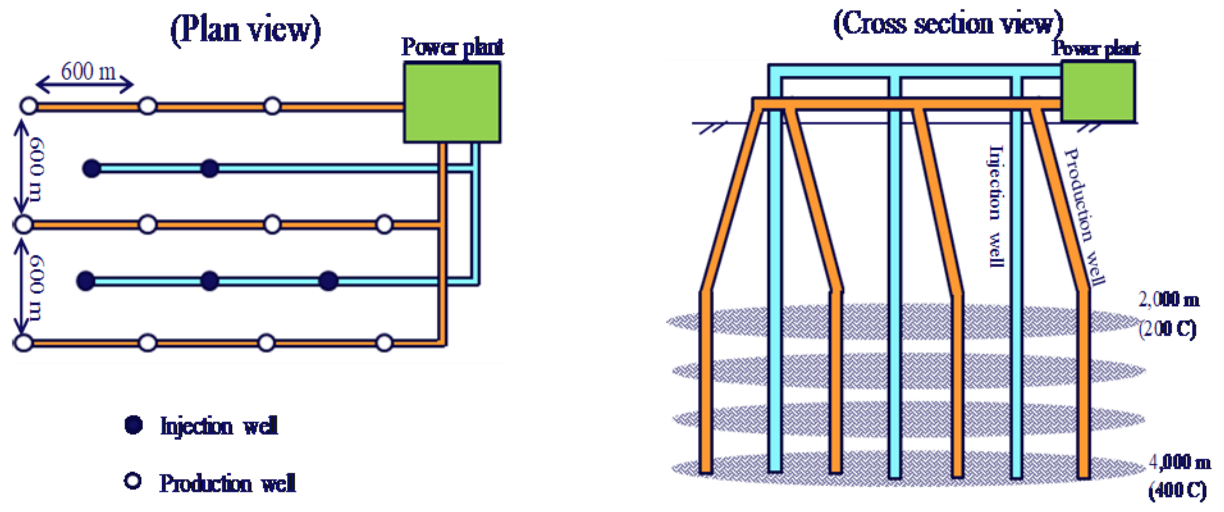

Figure 1: The concept of the multiple reservoir and multiple well HDR system. Left: Plan view. Right: Cross section view.

2. REVIEW OF THE OGACHI PROJECT

2.1 Underground structure

The Ogachi site is located in the caldera of northern Japan. The geology of the Ogachi site consists of the Cretaceous granodiorite covered with Tertialy lapilli tuff to a depth of 300m from the ground surface. The underground structure was estimated by geophysical explorations of the CSAMT, TDEM, gravity and seismic reflection methods. From the comprehensive analysis of these exploration results a three-dimensional structure model of the granodiorite was constructed as shown in Figure 2. In this model, the top of the granodiorite is relatively flat within about 500 m of the test site, and a large fault was estimated to locate at 500 m to the south-west of the test site (Suzuki and Kaieda, 2000). In 1990 an injection well, OGC-1 was completed with casings to a depth of 990 m and the interval of 990 to 1,000 m with a diameter of 76 mm left uncased (Kaieda et al., 1993). The bottom hole temperature was measured 228 degree C. Many natural joints are developed in the granodiorite, with an average spacing of about 8 cm and predominant direction in the north-north-east as observed from geological investigations of oriented cores. Th granodiorite has a comparably low natural permeability, because some of joints are sealed by carbonate minerals.

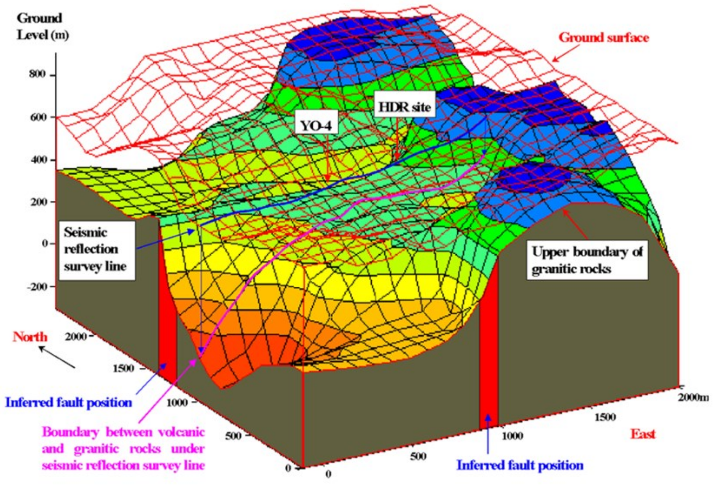

Figure 2: The three-dimensional underground structure at the Ogachi site constructed by the results of CSAMT, TDEM, gravity and seismic reflection surveys.

2.2 Reservoir creation and stimulation

A first (lower) reservoir was created from the open-hole interval between 990 m to 1,000 m of OGC-1 by hydraulic full-hole pressurization in 1991. A total of 10,140 tons of water was injected for 7 days with an injection pressure at a maximum of 20 MPa and a flow rate of an average of 40 tons per hour. From the microearthquake hypocenter distribution the created reservoir was estimated to progress nearly north-north-east direction with length of 1,000 m from OGC-1 (Kaieda et al., 2002b).

For a second (upper) reservoir creation the casing of OGC-1 was milled from 711 m to 719 m to create a window below which sand plug was set to prevent water flowing into the lower reservoir. A total of 5,440 tons of water was injected for 6 days with an injection pressure at a maximum of 22 MPa and a flow rate of an average of 30 tons per hour. The upper reservoir was estimated to progress nearly east-south-east direction with length of 400 m to the east OGC-1 by the microearthquake hypocenter distribution. The upper and lower reservoirs extended different directions at only 300 m different depths (Kaieda et al., 2000a). This difference was considered because of natural joints characteristic differences at the depths (Ito and Okabe, 2001). After the second reservoir creation sand was removed from OGC-1 (Kaieda et al., 2005).

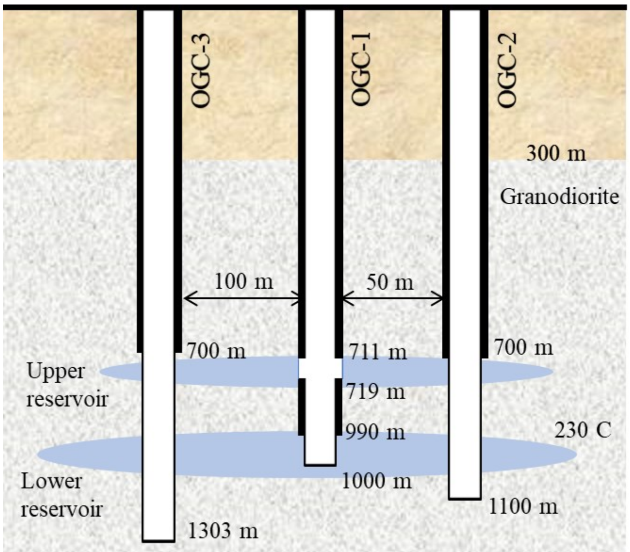

Figure 2: The concept of the Ogachi HDR project.

2.3 Reservoirs evaluation

Microearthquake or acoustic emission (AE) events were monitored to evaluate the created reservoir location and volume by a 10-station network of three-component geophones installed in 30- to 50-m deep boreholes and by a single-component geophone set at a depth of 480 m in a 946 m deep observation well. The velocity structure around the site was determined as a three-flat layers model by the seismic survey results. However underground structure was estimated very complicated, so some detonation shots were conducted at the bottom of OGC-1. From these detonation shots station collection values which compensated heterogeneity of the velocity structure were obtained for each station. Using these station collection values, the detonation shot point was calculated to the point of 13.0 m north, 22.6 m west and 6.7 m deep. Therefore, the microearthquake location accuracy at Ogachi was estimated about 10 m to 20 m around the shot point. From the hypocenter distribution the lower reservoir was estimated to extend about 200 m thick and about 500 m wide, propagating 1,000 m in the NNE direction and the upper reservoir was 200 m thick and about 400 m wide, propagating ESE direction as shown in Figure 3. The two reservoirs extended different directions at only 300 m different depths (Kaieda et al., 2000).

Tracer tests were conducted during the circulation tests in 1994, 1995 and 1997. Two peaks in the tracer concentration curve were observed in the 1994 test, but only one peak was detected in the 1995 test. The tracer concentration peak value increased from the 1994 test to the 1995 test, but the modal volume of the reservoir decreased from 1994 to 1995. This may be caused by occurrence of shot cut in the reservoir. Value of width at 1/2 height which is assumed to represent dispersion of the reservoir decreased from the 1994 test to the 1995 test, but the value increased in 1997 (Kiho, 2000). This increase is considered to be caused by the plugging the fracture with the sand particles which was used in the upper reservoir circulation test in 1997.

In the Ogachi project the optical fiber thermometer survey was shown very useful to detect water flow between the injection and production wells. Temperature in the production wells were monitored every meter and every minute continuously. From the temperature change in the production well during the water circulation operations water connection locations were clearly detected (Suenaga et al., 2001) and also fractures were observed by the Borehole Tele-viewer survey at the water flow connection positions (Ito and Okabe, 2001).

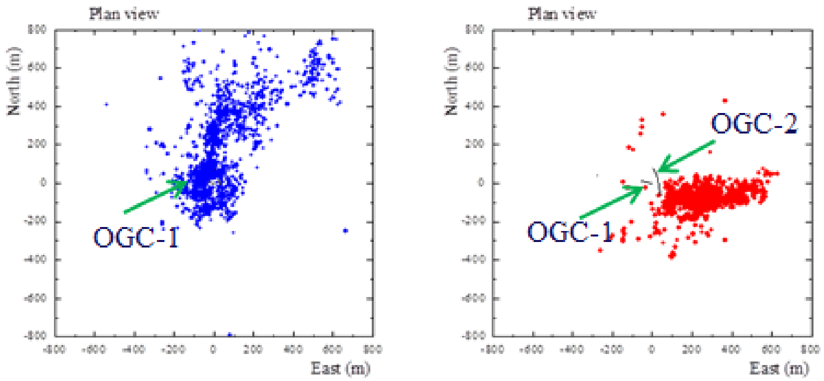

Figure 3: Microearthquake epicenter locations during the lower (left) and the upper (right) reservoir creation at Ogachi.

2.4 Water circulation and reservoir simulation

A production well, OGC-2, was planned to penetrate both the upper and lower reservoirs based on the microearthquake hypocenter distributions. However, OGC-2 could not drill into the best points of each reservoir, because these reservoirs progressed different directions. At the beginning of the water circulation tests, the water recovery of injected water into OGC-1 from OGC-2 was so small of a few % that both the wells of OGC-1 and OGC-2 were stimulated by hydraulic fracturing to improve hydraulic connection. After some hydraulic stimulation operations in OGC-1 and OGC-2, water recovery gradually increased up to a maximum of 32 % (Kaieda et al., 2002).

A computer code to simulate thermo-hydraulic behavior, GEOTH3D, was developed. The GEOTH3D code computes a 3-D distribution of Darcy velocity, pressure and temperature, including the interaction between flow and temperature, but not the effects of rock stress and deformation on apertures. A feature of the GEOTH3D is that a 3D permeability distribution model was constructed by seismic energy distribution determined by microearthquake hypocenter and magnitude. Using the GEOTH3D some water circulation tests were evaluated, and water recovery was estimated to increase to 44.5 % when two production well system would be operated (Suenaga et al., 2000).

2.5 Environmental monitoring

There is spa resort about 2 km south of the Ogachi site and residents used underground water for drink. Therefore, chemical analysis of underground and surface water was conducted at five sampling points before and after field experiments every year. Two points were for drinking water analysis at water spring point and a resident’s house. Other three points were located in the river for water quality analysis. No environmental impact was observed in the Ogachi project.

Seismic monitoring was conducted continuously using AE observation system around 2 km within the site. A traffic light system was applied during water injection as follows. If an event with magnitude larger than 2 occur, then continue injection but monitor well head pressure and seismicity very carefully. If an event with magnitude lager than 2.5 occur, then stop pumping and vent injected water immediately. Only one large event with magnitude of 2.4 occurred in 1991 near OGC-1 at night. Some residents felt quake but no complain was made.

3. Review of Hijiori project

3.1 Underground structure

The Hijiori HDR site is located at southern edge in the Hijiori caldera which was formed about 10,000 years ago in Yamagata prefecture northern Japan. From the logging results of the pre-existing geothermal survey well, SKG-2, some large natural joints in granodiorite dipping steeply to the north with strike of nearly east-west are observed. The geology of the Hijiori site consists of the granodiorite covered with tuff to a depth of 1,500m from the ground surface.

3.2 Reservoirs creation

A pre-existing well, SKG-2, was recompleted casings as an injection well with an open-hole section from 1,788 m to 1,802 m. SKG-2 was stimulated by full-hole pressurization with injecting a total of 1,080 tons of water for 11 hours with a maximum flow rate of 6.2 ton/min and a maximum well-head pressure of 16 MPa. The created reservoir was evaluated by the microearthquake hypocenter distributions to progress nearly east-west direction within 200 m from SKG-2 and from 1,600 m to 2,000 m in depth. Based on the hypocenter distributions, three production wells of HDR-1, HDR-2 and HDR-3 were drilled to penetrate the reservoir to a depth of 1,805 m, 1,909.9 m and 1,907.0 m, respectively (NEDO, 2003).

After some water circulation tests among four wells, HDR-1 was re-drilled to a depth of 2,205 m and was cased to a depth of 2,151 m, in 1992. For a second (lower) reservoir creation a PBR (Polished Bore Receptacle/ Cemented-in-liner) was set at 1,367.18 m depth. HDR-1 was stimulated by injecting a total of 2,115 tons of water for 12 hours with a maximum flow rate of 4.3 tons/min and a maximum well-head pressure of 25.5 MPa. The created reservoir was evaluated by the micro-earthquake hypocenter distributions to progress nearly east-west direction within 400 m from SKG-2 and from 2,000 m to 2,400 m in depth. Based on the hypocenter distribution, HDR-2 and HDR-3 were re-drilled to penetrate the deep reservoir to a depth of 2,303 m and 2,300.9 m, respectively (NEDO, 2003).

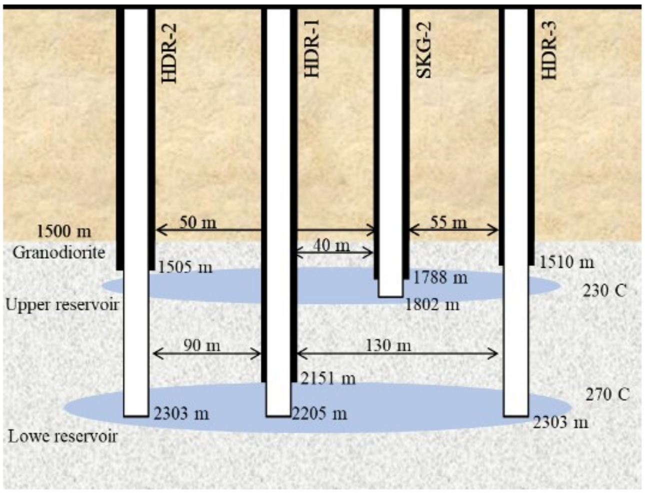

Figure 4: The concept of the Hijiori HDR project.

2.3 Reservoirs evaluation

A shallow borehole seismic network was constructed consisting of ten stations (ST-1 to ST-10) deployed in a circle at a radius of 1.5 to 2 km around the Hijiori HDR site. The seismometers were cemented in place at the bottom of 50 to 150 m deep wells to reduce noise levels. Three-component velocity seismometers were used (Sasaki, 1998).

The velocity structure around the site was determined as an eight-flat layers model by the seismic survey results. Some detonation shots were conducted at the bottom ofSKG-2 and at depth of around 1,890 m of HDR-2. From these detonation shots station collection values which compensated heterogeneity of the velocity structure were obtained for each station. Using these station collection values, hypocenter determination accuracies were estimated.

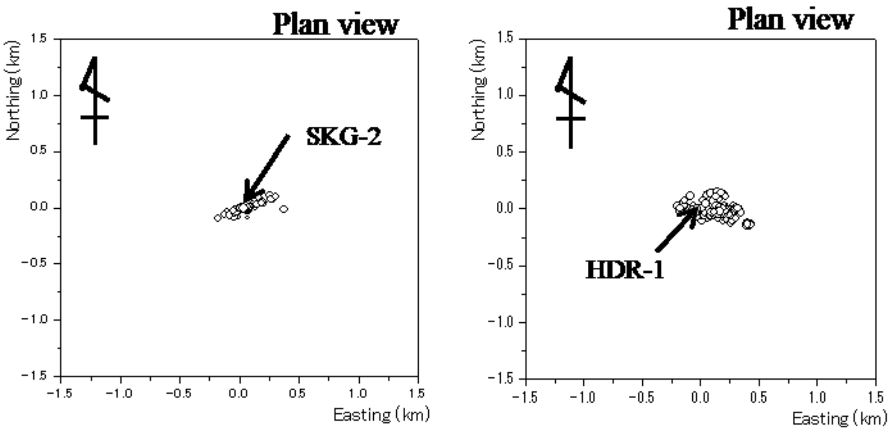

Figure 5: Microearthquake epicenter locations during the upper (left) and the lower (right) reservoir creation at Hijiori.

3.2 water circulation tests

In a 90-day circulation test through the upper reservoir in 1991, a total of 134,510 tons of water was injected into SKG-2 at an average flow rate of 1 ton/min and an average well-head pressure of 3 MPa. The circulated water (hot water and steam) was recovered from HDR-1, HDR-2 and HDR-3. The water recovery of each production wells of HDR-1, HDR-2 and HDR-3 were 11.2 %, 26.9 % and 32.2 %, respectively. The total water recovery from the three wells was 70.4 % (NEDO, 2003).

In a 25-day circulation test through the lower reservoir in 1995, a total of 51,500 tons of water was injected into HDR-1 at an average flow rate of 1 ton/min and an average well-head pressure of 8.5 MPa. The circulated water (hot water and steam) was recovered from HDR-2 and HDR-3. The water recovery from HDR-2 and HDR-3 were 25.6 % and 13.4 %, respectively. The total water recovery from the three wells was 39 % (NEDO, 2003).

From November 27, 2000 to August 31, 2002 a log-term (550 days) circulation test (LTCT) was conducted. At the beginning of this test water was injected into only the lower reservoir through HDR-1 and hot water and steam were produced from HDR-2 and HDR-3 for 333 days. During the lower reservoir circulation anhydrite ($CaSO_4$) scaling problem was occurred at a shallower depth than the upper reservoir. The anhydrite scale was washed out from HDR-2 and HDR-3 by the coiled tubing system and after that scale inhibitor was added into the injection water to prevent scaling. After these preparation operations, water was injected into both the reservoirs through HDR-1 and SKG-2, and hot water and steam were produced from HDR-2 and HDR-3 for 217 days as the dual reservoir circulation. A total of 85,329 tons of water was injected into SKG-2 and a total of 96,210 tons of water was injected into HDR-1. The amount of recovered water from HDR-2 and HDR-3 was 69,347 tons and 27,534 tons, respectively. The total water recovery of produced steam and hot water to the injected water was 53.4 % (NEDO, 2003, Matsunaga et al., 2005).

2.5 Environmental monitoring

There is spa resort about 500 m north-west and north-east of the Hijiori site. Chemical analysis of hot spring and river water was conducted every month. Water samples from two rivers of Nigamizu and Dozan were analyzed of temperature, turbidity, total solids, electric conductivity, pH, Na, K, Ca, Mg, Cl, SO_4 and HCO_3. Water samples from 6 hot springs were analyzed of temperature, flow rate, turbidity, total solids, electric conductivity, pH, Na, K, Ca, Mg, Cl, SO_4, HCO_3 and SiO_2. No environmental impact was observed in the Hijiori project.

Seismic monitoring was conducted continuously using microearthquake observation system around 2 km within the site. A traffic light system was applied during water injection as same as the Ogachi project. The maximum magnitude of observed events was 2.4 around the Hijiori site.

4. LESSONS LEARNED FROM THE OGACHI AND HIJIORI PROJECTS

4.1 Underground structure

The Ogachi site is located in the granodiorite in the middle in a caldera as shown in Figure 6. There are many small natural joints exist in the granodiorite. The Hijiori site is located in the granodiorite at the edge of a caldera. There are some large natural joints in the granodiorite. At the Ogachi site, the underground structure was estimated by geophysical explorations of the CSAMT, TDEM, gravity and seismic reflection methods. From the CSAMT and TDEM methods, a three-dimensional resistivity structure model was constructed. Using a road crossing east-west near the site, the seismic reflection and gravity survey were conducted. Comparing these results with the resistivity results in this cross section, the resistivity of the granite was estimated 100 ohm-m. From these comprehensive analysis of these exploration results a three-dimensional structure model of the granodiorite was constructed.

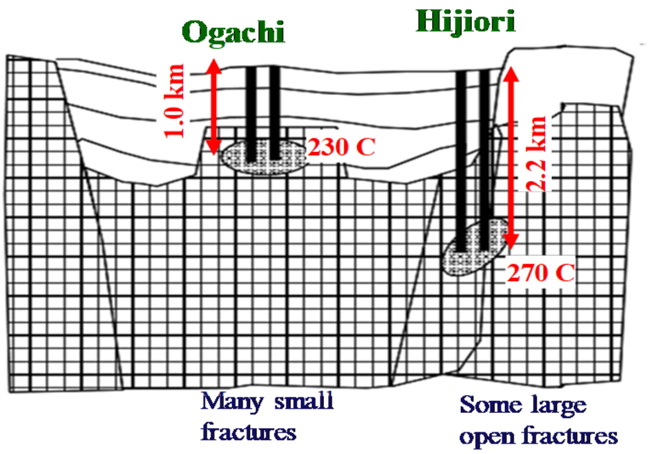

Figure 6: Conceptual geological model of the Ogachi and Hijiori sites.

3.2 water circulation tests

4.2 Multiple reservoir creation

In both the projects at the Ogachi and Hijiori sites two reservoirs were created successfully at different depths. At the Ogachi site, a first (lower) reservoir was created from the bottom open-hole interval with full hole pressurizing by injecting water into an injection well of OGC-1. For the second (upper) reservoir creation, an interval from 711 to 719 m of the casing in OGC-1 was milled as a window and a sand plug was set below the window. A second (upper) reservoir was created with full hole pressurization by injecting water into the window of OGC-1. After the upper reservoir creation, the sand plug was removed from OGC-1. Then water can flow into both upper and lower reservoirs. This multiple reservoir creation method was shown to be applicable in field, but some problems occurred at casing milled section during well logging and well operations.

At the Hijiori site, the upper reservoir was created from SKG-2 with full hole pressurization by injecting water into the bottom open-hole part. The lower reservoir was created by using PBR. These methods were also shown applicable to create artificial reservoirs in field. But only one reservoir was created from one well.

4.3 Reservoir evaluation

At the both HDR experiment sites, during the reservoir creation and water circulation operations microearthquake events were monitored by a network of 10 or 11 stations where three-component geophones were installed in shallow of some tens to 150-m deep boreholes. The velocity structure around the site was determined as a some flat-layers model by the seismic survey results. However underground structure was estimated very complicated at the both sites, so some detonation shots were conducted at around bottom of the injection wells. From these detonation shots station correction values which compensated heterogeneity of the velocity structure were obtained for each station and hypocenter locations were determination very accurately by using these station correction values.

Production wells were drilled to penetrate the created reservoirs according to the microearthquake hypocenter locations and succeeded to achieve water flow connection to the injection well.

Tracer test and the fiber optical thermometer survey were shown to be very useful to water flow monitoring in the reservoir and detect water flow locations between the injection and production wells.

4.4 Hydraulic characteristics of the reservoir

Hydraulic characteristics of the reservoirs were changed by hydraulic stimulation and water circulation operations. Usually these operations are useful to improve permeability of fractures in the reservoirs. However, these operations don't work equally to fractures in the multiple reservoirs. Sometimes only specific fractures were stimulated, and short cut of the flow paths occurred in the reservoirs. These phenomena were detected by the Pressure Temperature and Spinner (PTS) logging and evaluated by the tracer tests. It is hard to stimulate fractures equally and to make specific fractures open or close without open-hole packers. The open-hole packers are not applicable at a high temperature of more than 200 degree C at the moment.

In the Ogachi project, it was found that sand particles used for preventing water flow during the 1997 upper reservoir circulation test partially plugged the short cut flow path. Sand particles have been used for propping the fracture open in the sedimental formation to keep high permeability so far, but sand particles may be effective to plug the flow path in volcanic formation. More basic study on size and density of particle is needed to use sand particles for plugging fractures.

The size and location of these created reservoirs were estimated by microearthquake observation. In the Ogachi project the two reservoirs were estimated to progress in different directions. The lower reservoir progressed north-north-east direction and the upper did only eastward. The lower reservoir was created in the pre-existing joints dominant area and the created reservoir progressed along with the pre-existing fracture system. However, the upper reservoir was created in a small number of pre-existing joint area and the created reservoir progressed eastward which is consistent with the horizontal maximum stress direction. The production well of OGC-2 was intended to penetrate both the reservoirs, but OGC-2 penetrated the edge of the upper reservoir. These results show that pre-exiting fracture system strongly affected on reservoir creation. On the other hand, in the Hijiori project the created two reservoirs were estimated to progress nearly same direction of east-west along pre-existing large joins at different depths. Therefore, the production wells could penetrate both two reservoirs relatively easy. It is desired to create multiple reservoirs in same or similar geological conditions.

The reservoirs extended not only during reservoir creation stage but also during the water circulation tests. If the reservoir extends, the water recoveries during the circulation tests will decrease. Some of the injected water flowed outward and microearthquake hypocenter locations distribute beyond the edge of the reservoirs during the reservoir extension. During the long-term circulation tests in the Ogachi and Hijiori projects microearthquake hypocenters were distributed wider beyond the two reservoir areas.

4.3 Chemical characteristics in the reservoir

During the water circulation in the LTCT at Hijiori, scaling of anhydrite ($CaSO_4$) occurred at a shallower depth than the upper reservoir in the production wells. Temperature of the lower reservoir decreased faster than the upper by the water circulation tests. When the temperature of the lower reservoir water decreased lower than the upper reservoir, scaling was occurred in the production wells. There are a lot of anhydrite veins in the granodiorite. The injected low temperature water dissolved anhydrite during flowing in the reservoir. The anhydrite dissolved water flowed into the production wells in the lower reservoir and flowed up in the production well. When the water met hotter water from the upper reservoir in the production well, the solubility of anhydrite in water became over saturated to precipitate. Scale inhibiter was added to the injection water and water injection flow rate into the upper and lower reservoirs was controlled to prevent scale occurring (NEDO, 2003, Matsunaga et al., 2005).

Scaling was also occurred in the Ogachi project at the beginning of the 1993 circulation. A thin calcite scale was found in the well-head of OGC-2, but this phenomenon occurred only at the beginning of the project. No more scaling occurred in the Ogachi project. This is considered that the water flow area of the Ogachi circulation system is smaller than that of Hijiori, so the dissolved carbonate mineral volume was small.

4.4 Multiple well system

Based on the microearthquake hypocenter distributions production wells were successfully drilled to penetrate the artificially created reservoirs in the Ogachi and Hijiori sites. In the beginning of the water circulation tests water recovery of amount of steam and hot water from production wells to injected water amount was very small in the both projects. However hydraulic stimulation of the injection wells and production wells were very effective to improve the recovery. In the Ogachi project a maximum recovery was obtained around 32 % from one production well in the 1995 one-month circulation test (Kaieda et al., 2000) and in the Hijiori project a maximum recovery of 70.4 % was obtained by producing from three production wells in the 1991 90-day circulation test (NEDO, 2003, Tenma et al, 2001). Therefore, the multiple-well system was shown effective to increase water recovery. However water recovery during these water circulation tests was very small comparing to the other projects, for example, 87.5 % in the long-term flow test (LTFT) #1 and 92.7 % in the LTFT #2 of the Fenton Hill project in USA (Duchane, 1995) and pumped hot water from the production wells fully re-injected into the injection wells almost 100 % recovery in the Soultz project in France (Genter et al., 2013). It is desired to apply down-hole pumps in order to improve water recovery during water circulation tests in Japan. However down-hole pumps which can work at a high temperature of more than 200 degree C have been still under development.

Numerical simulation of the fully three-dimensional thermo-hydraulic computation was conducted to study how the water flow in the reservoir and how to improve the water recovery rate (Suenaga et. al., 2000). The results showed that the water recovery will increase to 44.5 % if another production well will be added to the water circulation system. The recovery will be expected to increase more than 80 %, if we use four production wells. If a down-hole pump can be applied in OGC-2 during the water circulation, the water recovery may be improved drastically.

5. Conclusions

Hot Dry Rock geothermal energy development projects were conducted at Ogachi in Akita prefecture and at Hijiori in Yamagata prefecture, Japan by NEDO and CRIEPI, respectively. In these projects two reservoirs were created at different depths from one 1,000 m deep well at Ogachi and from two of 1,800 m and 2,200 m deep wells at Hijiori. Production wells were drilled to penetrate these reservoirs based on the microearthquake hypocenter distribution. At Hijiori two production wells succeeded to penetrate both the reservoirs. But the production well grazed the upper reservoir at Ogachi, because the created reservoirs progressed different directions depended on geological heterogeneity. Therefore, the multiple reservoir system should be created in a same or similar geological condition.

It was difficult to control water flow in the multiple reservoirs and multiple wells system at the moment. Short cut in the flow paths occurred and the temperature of the short cut area decreased rapidly. At Hijiori, temperature of the lower reservoir decreased faster than the upper, so the anhydrite scaling problem occurred. Developing open-hole packers and sand plugging is desired to control water flow and prevent scaling occurring in the multiple reservoirs.

There are many natural joints in granodiorite at Ogachi and Hijiori, but original permeability of the granodiorite was small because some joints were sealed by carbonate minerals. During the reservoir creation and the water circulation fractures in the reservoir extended outward beyond the originally created reservoir boundary, therefore water recovery during the water circulation through the reservoirs was small of 10 to 30 % from one production well. However, a maximum recover of injected water from three production wells at Hijiori reached 70.4 %. The multiple-production well system was effective to increase water recovery.

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