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Review of the Ogachi HDR Project in Japan

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ABSTRACT

There are many geothermal areas in Japan. These areas are located tectonically active regions. In these areas we can access hot rock at relatively shallow depth, but there are many natural joints in the rock. Original Hot Dry Rock (HDR) geothermal energy system designed by Los Alamos National Laboratory (LANL) considered extracting heat from deep and low permeability rock. Therefore, we thought that we needed some new technologies for constructing the HDR system in Japan.

We designed an HDR heat extraction model of multiple reservoirs and multiple production wells. For realizing the HDR model, we had conducted field experiments at Ogachi from 1989 to 2002. In these experiments, we developed new technologies, for example, a multiple reservoir creation method without open-hole packers, an electrical reservoir evaluation method, a numerical simulation code for predicting heat extraction, a temperature monitoring method by using a fiber optic thermometer, and so on.

Using these technologies, we succeeded to produce hot water and steam at a temperature of 165 degree C in some water circulation tests between two 1,000 m class wells through artificially created two reservoirs. Unfortunately, we could not apply the multiple production wells system because of financial problems. The water recovery rate in the water circulation tests was relatively small of 25 to 32 % comparing with that of other HDR programs such as LANL. However, we simulated that the water recovery would increase 44 % if we had another production well. If we had four production wells and use down-hole pump, we expected to be able to get the recovery more than 80 %.

We considered that the basic technologies for constructing HDR system in Japanese thermal and geological condition had been developed. Now we are applying some of these technologies to the Australian HDR program in Cooper Basin for improving the technologies and contributing the program.

1. INTRODUCTION

Researchers of Los Alamos National Laboratory originated Hot Dry Rock (HDR) geothermal heat extraction concept in early 1970s. LANL has conducted the first HDR development program since 1974, succeeded to extract heat of 3.9 MWt by HDR system by 1993 (Duchane, 1995). In Europe, some small HDR experiments had been conducted since 1970s and these experiments gathered to a large HDR development program at Soultz-sous-Foret in France in 1987 (Baria et al, 2000).

We, researchers of the Central Research Institute of the Electric Power Industry, have started geothermal research program in 1981 because of Japanese electric companies interested in geothermal energy development after the oil crisis. Our research started to study for prospecting conventional geothermal reservoir at beginning, but later we found that we had large HDR potential in Japan and there were many research subjects for technology development for constructing HDR system in Japan. Therefore our research moved to technology developments for constructing HDR system. Some researchers have joined the LANL HDR project through New Energy Development Organization (NEDO) and learned basic technologies for HDR development from 1982 to 1987.

Most of geothermal areas in Japan are located in tectonically active region. Geological conditions in these areas are very different from that of the original HDR system designed by LANL researchers. The rock for HDR in the original concept was considered that it was located at deep as 4 km to 5 km, at high temperature of 200 to 300 degree C and with low permeability. But in Japan the geothermal gradient is so high that we can access hot rock at a high temperature enough for producing steam at relatively shallow depth, but natural fracture system may dominate in the rock and the permeability may be relatively high. Therefore we thought we had to develop some new technologies for constructing HDR system in Japan.

In this paper we describe our research history and technologies developed in the Ogachi project.

2. HISTORY OF PROJECT

At first we considered how to extract heat from hot rock at relatively shallow depth and with many natural joints. Figure 1 shows a basic model of HDR system with multiple reservoirs and multiple production wells (Hori, 1991). The upper map view shows that four production wells (single circle) are arranged around one injection well (double circle). The lower elevation view shows that multiple reservoirs at different depths were created from the injection well and hydraulically connected to the production wells. The drilling cost for four production wells may be high, but if the depths of these wells were shallow, the drilling cost would be low enough for economical construction of HDR system.

If we succeed to construct the basic model, it may be easy to create another system adjacent to the original system. We considered extending this basic model as shown in Figure 2 to create large heat extraction system. In this large scale model, the combination of one injection well and four production wells system in each block is same as a basic model, but some production wells are used as a production well for the neighboring system.

Our HDR project at field has started in 1986 at the Akinomiya test site as a preparation stage (Phase 1) with using 400 m class wells (Kaieda et al., 1990). In this phase we developed basic concepts for a new hydraulic fracturing method for creating multiple reservoir without open-hole packers (Kaieda et al., 1993). LANL research results showed that open-hole packers were not applicable in the condition of high temperature and hard rock. We also developed an electrical measurement method for evaluating water-stored area in the reservoir (Kaieda et al., 2000), because LANL results showed that the fracture location were estimated by induced microearthquakes, acoustic emission (AE), hypocenter locations but the injected water were not guaranteed to store in the estimated fractures. We thought

that the electrical method was effective to estimate the water-stored area. If the reservoir was created at deep as LANL program, it may be difficult to apply the electrical method, but we thought we could create the reservoir at shallow depths enough to apply the electrical methods.

After this preparation stage, we had conducted nearly real size experiments for confirming these technologies practical at Ogachi.

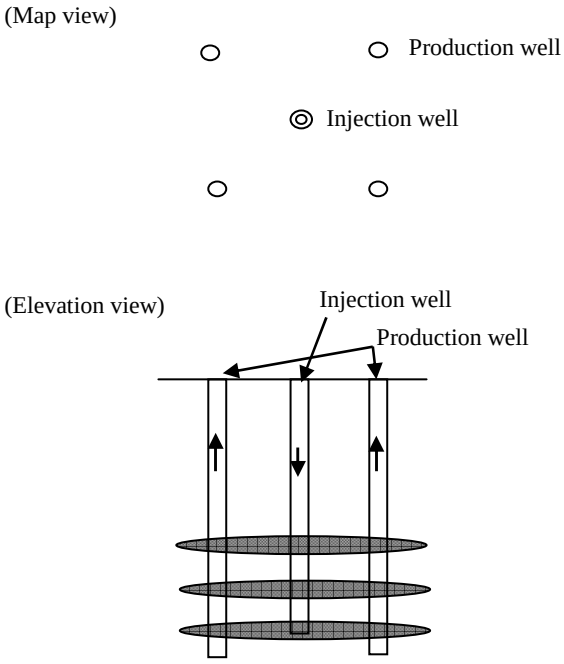

Figure 1: Concept model for multiple production well system.

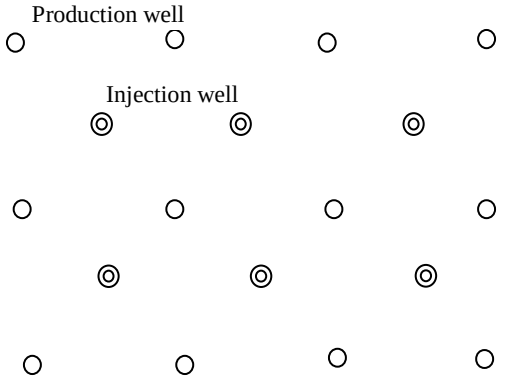

Figure 2: Plane view of the large scale HDR system.

2.1 Phase 1 (preliminary test)

The purposes of this phase were to develop underground structure evaluation methods, artificial reservoirs creation methods, reservoir evaluation methods, and numerical simulation methods for predicting water flow in the reservoir. We developed the CSAMT method that can survey the resistivity structure deep to 2,000 m, the new hydraulic fracturing method that can produce multiple reservoirs at different depths in a well, an electrical method that can estimate fracture progression direction and a numerical simulation method that can predict water flow in the reservoir and future heat production rate (Kaieda et al., 1990).

In 1986 an injection well was drilled into lapilli tuff to a depth of 400 m. The bottom hole temperature was measured 60 degree C. Three artificial reservoirs were created at different three depths of 400 m, 374 m and 362 m by a newly developed hydraulic fracturing method which was described later in section 3.2. According to AE hypocenter location and apparent electrical resistivity anomaly that was described in section 3.3, artificially created reservoir extension was estimated. Then a production well was drilled to penetrate the reservoirs at around 40 m apart from the injection well in 1988.

Water was injected into the injection well and some of the injected water was recovered from the production well in 1989. Therefore we thought that our technologies for reservoir creation and evaluation were appreciable for real size experiments.

2.2 Phase 2 (reservoir creation)

According to the success of phase 1, we have started a large-scale program with using 1,000 m deep wells in which bottom hole temperature would be more than 200 degree C (Kitano et al., 2000). In 1989 a test site was selected for the project at Ogachi southern in Akita Prefecture, Japan (see Figure 3). The site is 2 km northeast from the Akinomiya site.

The purposes of this phase were to create two large reservoirs at different depths by using multiple fracture creation method and to extract heat from these reservoirs. The concept of this experiment is shown in Figure 4.

In 1990 an injection well (OGC-1) was drilled into granodiorite to a depth of 1,000 m where the rock temperature was measured at 228 degree C. OGC-1 was cased except for a 10 m open-hole section at the bottom. In 1991, a total of 10,140 tons of river water was injected into OGC-1 at an average flow rate of 41 tons per hour and at an average wellhead pressure of 19 MPa, creating a fractured area about 200 m thick and about 500 m wide, propagating 1,000 m in the NNE direction, as estimated from the envelope of the AE hypocenter distribution. This fractured area composed a lower reservoir.

After the lower reservoir created, the casing pipe was milled from 711 m to 719 m to produce an open-hole section called a window. Then, the open-hole section at the bottom was filled with sand. In 1992, the upper reservoir was created at the window section by injecting a total of 5,440 tons of water with an average flow rate of 30 ton per hour and at an average wellhead pressure of 22 MPa. The upper fracture was estimated to extend 200 m thick and about 400 m wide, propagating ESE direction, as estimated from the envelope of the AE hypocenter distribution.

According to the reservoir evaluation described in section 2.3, a production well (OGC-2) was drilled to penetrate the two reservoirs. The well was cased from the ground surface to a depth of 700 m and the bottom hole section from 700 m to 1,100 m was left uncased (open-hole). The distance from OGC-1 is 50 m at 700 m depth and 80 m at 1,000m depth.

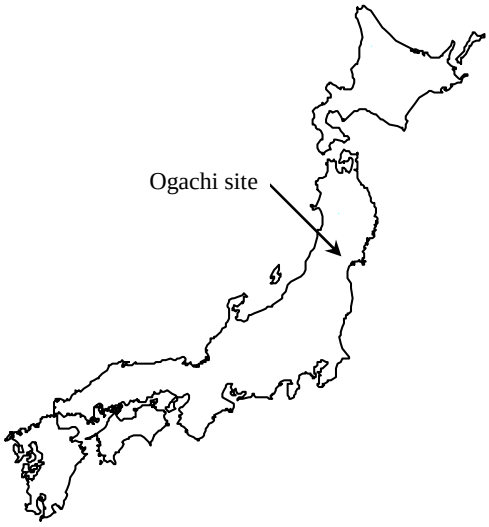

Figure 3: Location of the Ogachi HDR test site.

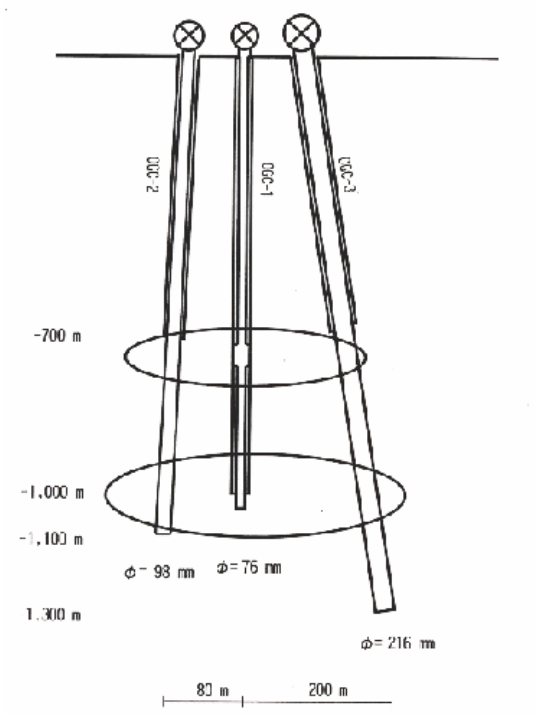

Figure 4: Concept of the Ogachi HDR experiment.

2.3 Phase 3 (reservoir evaluation)

In 1993 a first water circulation test was conducted. Water form a river near the Ogachi site was injected into OGC-1 at a flow rate of 24 tons to 72 tons per hour and at a wellhead pressure of 19 MPa for 22 days. Water level in OGC-2 that is usually 135 m below the ground surface increased gradually. After 2 days water injection into OGC-1, water was overflowed form OGC-2. After 17 days produced water temperature increased 100 degree C at the ground surface. Flow rate of the recovered water from OGC-2 gradually increased and reached 2.1 ton per hour, that is 3% of injected water at the end of this circulation test.

The water recovery rate was so small in the first circulation test that we applied hydraulic stimulation to OGC-2 in 1994. In this stimulation, water was injected into OGC-2 at a flow rate of 45 tons per hour and at a wellhead pressure of 13 MPa. A total of 2,204 tons of water was injected. After this stimulation, 5 months circulation test was conducted as a second circulation test. Water was injected at a flow rate of 42 tons per hour and at an average wellhead pressure of 15 MPa. A total of 140,224 tons of water was injected. Produced water recovery rate increased to 10 % of injected water in this test.

In 1995, we applied hydraulic stimulation in OGC-2 again by injecting a total of 3,400 tons of water at a flow rate of 135 tons per hour and at a wellhead pressure of 18 MPa. OGC-1 was re-drilled from 1,000 m to 1,027 m to extend the water injection region and stimulated by injecting a total of 3,400 tons of water at a flow rate of 105 tons per hour and at a wellhead pressure of 18 MPa. After these stimulations, we conducted a third circulation test to confirm the above re-drilling and stimulation effects. We injected water into OGC-1 at a flow rate of 33 tons per hour and at an average wellhead pressure of 7 MPa. A total of 24,241 tons of water was injected. Water recovery rate in this test increased to 25 % (maximum of 32 %). In this circulation, the injection pressure decreased about a half of that of second circulation, and the water recovery from OGC-2 increased more than twice as much as that in 1994.

From the stimulation results we thought that the stimulation in production well was very effective for water recovery improvement.

In 1997, we tested which reservoir, upper or lower, is effective for water recovery. The bottom open-hole section in OGC-1 was plugged with sand. Then water was injected into OGC-1 at a flow rate of 7.2 tons per hour and at a wellhead pressure of 18 MPa. But no water was produced form OGC-2. Therefore we thought that the upper reservoir dose not contribute for water circulation so much. After removing sand from bottom open-hole section, we conducted a forth circulation test for 10 days. Water was injected into OGC-1 at an average flow rate of 30 tons per hour and at an average wellhead pressure of 13 MPa. Hot water with steam at a temperature of 160 degree C was produced from OGC-2. The produced water recovery rate to injected water was about 20%.

2.4 Phase 4 (detail analysis of reservoir)

The water recovery rate from OGC-2 increased gradually after some circulation tests, but the rate was very small of 20 to 32 % comparing with other HDR programs. We studied in the reservoir characters more detail.

Before analyzing the reservoir in detail, we conducted geophysical measurement around the test site to construct the more precise under ground structure. We conducted the CSAMT method around the test site in 1996, gravity survey in 1997, and seismic reflection survey in 1998. Compiling these results, we constructed a three-dimensional underground model described in section 3.1. In this model, the basement rock is relatively flat within 500 m of the test site, and two faults were estimated to locate at 500 m and 900 m to the west of the test site.

Using this model, we revised the velocity model for locating AE hypocenter and re-calculated all of the observed AE locations. Then we applied the collapsing method for AE hypocenter distribution to search significant structure in the reservoir (Kaieda et al., 2000).

In 1999, a third well (OGC-3) was drilled to confirm the relationship between the significant structures in the AE

hypocenter distribution and water flow paths in the reservoirs.

Water flow tests and well bore survey were conducted from 2000 to 2002. The fiber optic thermometer was shown to be very useful for measuring and monitoring temperature distribution in the well. From these measurements, we confirmed that the significant structure in the AE distribution is related to the water flow paths.

Because of financial problem, our project at Ogachi was stooped in 2002. We started a new project to keep our technologies and apply to another site. We have joined the Australian HDR program since 2002.

3. DEVELOPED TECHNOLOGIES

Here we describe major technologies developed and shown to be practical in the Ogachi project.

3.1 Site Selection

For the purposes of prospecting the underground structure for sitting HDR systems, we developed the Controlled Sourced Audio-frequency Magnet-telluric (CSAMT) method which can apply to estimate the under ground electric resistivity structure to a depth around 2 km and the Time Domain Electro-Magnetic (TDEM) method which can estimate the under ground electric resistivity structure to a depth around 5 km.

For constructing a three-dimensional underground structure, we conducted the CSAMT method to construct a three-dimensional electric resistivity structure with 63 points in two dimensionally distributed around the test site in 1996, gravity survey along the road closing E-W direction near the test site in 1997, and the seismic reflection survey along the same road as the gravity measurement in 1998. From these results, we constructed a three-dimensional underground model shown in Figure 5. In this model, the basement rock is relatively flat within 500 m of the test site, and two faults were estimated to locate at 500 m and 900 m to the west of the test site (Suzuki and Kaieda, 2000).

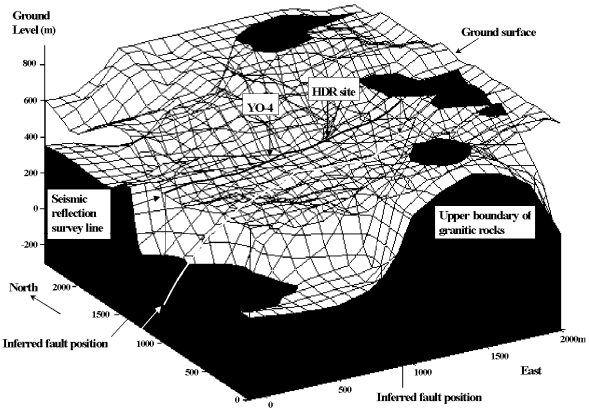

Figure 5: A three-dimensional model of the under ground structure below the Ogachi test site within 1 km.

3.2 Reservoir Creation

We developed a new hydraulic fracturing method that can create multiple reservoirs at different depths from a well. The procedure of this method is shown in Figure 6 and described as below.

(1) drill an injection well and case the well except for an open-hole section at the bottom, inject water into the well and pressurize inside the well, continue water injection for fracture progression from the bottom open-hole section into rock, and stop injecting water when the fracture progressed enough as a reservoir then vent injected water. (2) mill the casing pipe some meters at adequate depth for the upper reservoir. (3) insert sand for plugging the bottom open-hole section, inject water into the well again and pressurize inside the well, continue water injection for second fracture progression from the upper open-hole section into rock. (4) remove sand from the injection well, drill production well, inject water into the injection well, and recover the water form the production well through the reservoirs.

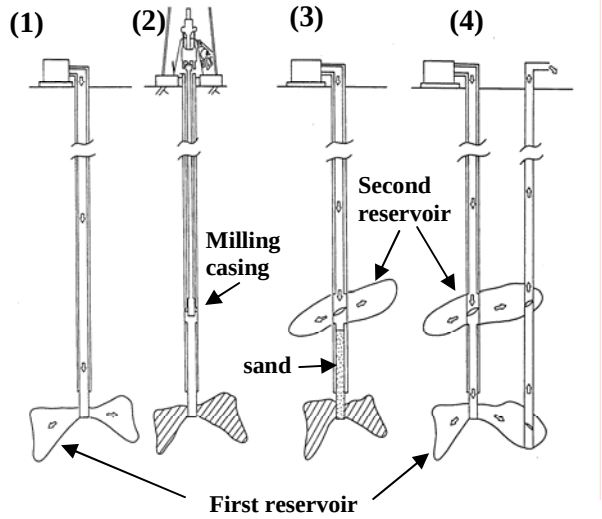

Figure 6: A multiple reservoir creation method.

We applied this method at Akinomiya and Ogachi sites. Three stage reservoirs at depths of 412 m, 384 m and 372 m, and two stage reservoirs at depths of 1,000 m and 719 m were successfully created at Akinomiya and Ogachi, respectively. Therefore, the method is appreciable for practical use.

3.3 Reservoir Evaluation

We applied AE measurement for estimating location and size of the reservoirs following the LANL AE measurement system. We successfully evaluated the reservoir distribution as shown Figure 7. From this distribution we evaluated that the lower reservoir extended about 200 m thick and about 500 m wide, propagating 1,000 m in the NNE direction and the upper reservoir did 200 m thick and about 400 m wide, propagating ESE direction. The two reservoirs extended different directions at only 300 m different depths (Kaieda et al., 2000). We considered this difference because of natural joints characteristic differences at the depths (Ito and Okabe, 2001).

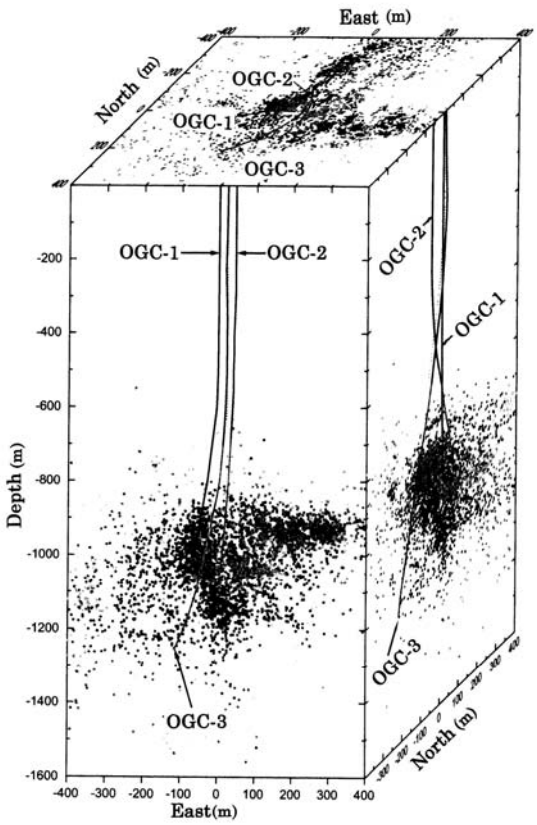

Figure 7: AE hypocenter distribution observed in all of the Ogachi HDR experiments.

However few AE events were observed in the reservoir creation at Akinomiya. Then we applied electric method for reservoir evaluation. In this method, the casing pipe in the injection well was used as an electric current electrode. More than 200 electric potential electrodes were distributed around the injection well to measure electric potential cased by the electric current. Apparent resistively was calculated with electric current charged to the casing pipe and electric potential around the injection well. Reservoir distribution was evaluated with anomaly distribution of apparent resistivity change before and after water injection into the reservoir (Kaieda et al., 2000).

We applied this method to reservoir creation at Akinomiya and Ogachi tests. The results of the electrical method were consistent with the reservoir evaluation results obtained by AE method in the Ogachi test. This means that the fractures estimated their location and distribution by AE store the injected water in the hydraulic fracturing.

We conducted some tracer tests during water circulation tests. The results showed that there were two peaks in the tracer (Na Fluorescent, KI) concentration curve with time at earlier circulation test but one of the peaks became not clear and only one peak was detected in the later test. This may mean the flow paths in the reservoirs changed from two dominant paths to one (Kiho et al., 1999).

3.4 Heat Extraction

Using the injection well and production well, surface water from a river was injected in to OGC-1 and hot water with vapor was recovered from OGC-2. In some water circulation tests showed water recovery rate of produced form OGC-2 increased gradually, but it was small as around 20 to 32 % comparing with other sites tests.

In order to predict the water flow in the reservoir and the future heat extraction we developed a numerical simulation code (GEOTH3D) and constructed a three-dimensional permeability model of the reservoirs (Suenaga et al., 2000). The model was constructed by an assumption that an element block in which large AE (seismic) energy emitted was consistent with a high permeability block. A three-dimensional model was shown in Figure 8.

Appling the GOETH3D cord to the permeability model and using parameters of the water circulation test in 1995, we predicted water flow in the reservoir. If we add another production well, the water recovery rate would increase to 44 % (Suenaga et al., 2000). If we have four production wells, the water recovery rate would increase more than 80 %.

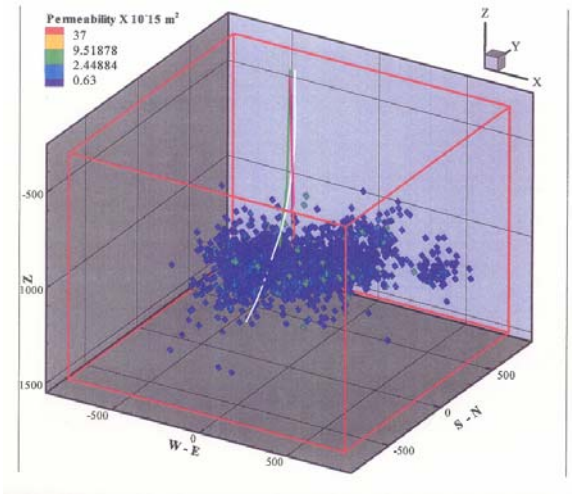

Figure 8: A three-dimensional permeability model.

3.5 Detail Analysis of Reservoir

It is most important for determining the production well trajectory to estimate where water flow is located in three-dimension. We applied the collapsing method to the AE hypocenter distribution for extract significant structures in the reservoir (Kaieda et al., 2000). The results were shown in Figure 9. In this figure, we can see some linear structures. A third well, OGC-3 was drilled to penetrate one of the significant structures.

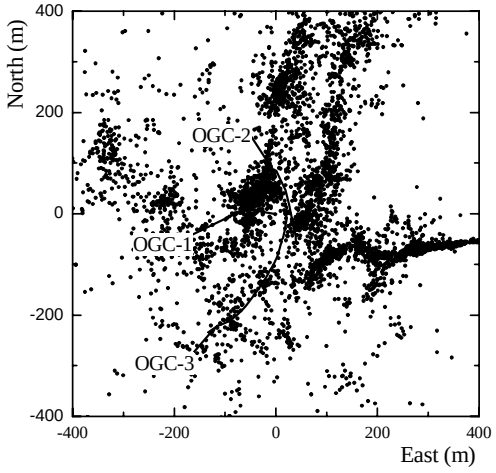

Figure 9: Collapsed AE hypocenter distribution for searching significant structure in the reservoirs.

Temperature measurement in OGC-3 was conducted during water injection into OGC-1 by using the optical fiber thermometer (Suenaga and Kaieda, 2001). Figure 10 shows an example of this measurement. In this measurement, water was injected into OGC-3 at first to cool down the well. After stopping the water injection, water was injected into OGC-1. The temperature distribution in OGC-3 was monitored by the optical-fiber thermometer (from Start to End in Figure 10) during water injection into OGC-1. Temperature changes at almost one-hour interval were plotted in the figure. Temperature in OGC-3 gradually recovered after stopping the water injection into OGC-3, but temperature recovery at some depths was faster than other depths. This may mean hot water flowed into OGC-3 from OGC-1 at the temperature anomaly depths.

We applied geophysical logging in OGC-3 to survey water flow paths. The formation micro-imager (FMI) and the ultra-sonic borehole imager (UBI) methods of Schlumberger were conducted (Ito and Okabe, 2001). From these measurements, we found clear feature of fractures on the OGC-3 wall at depths of the temperature anomaly detected by the optical fiber thermometer. Figure 11 shows an example of the features of the detected fractures in OGC-3.

Therefore, we concluded that the AE hypocenter location consistent with fractures and significant structures determined in AE hypocenter distribution also consistent with the water flow paths.

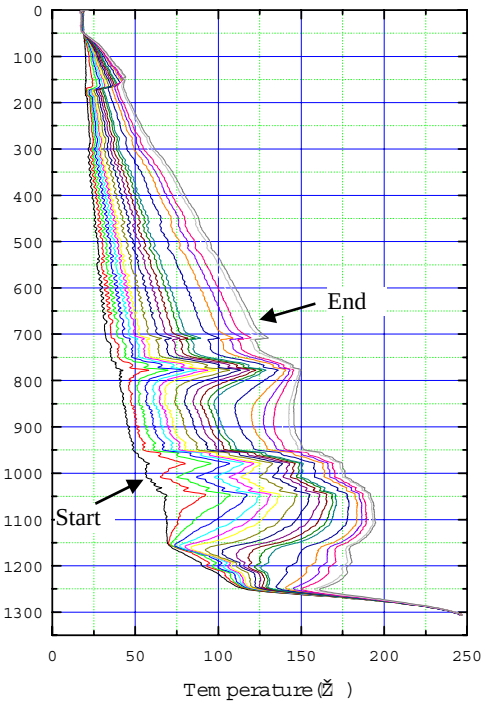

Figure 10: Temperature distribution in OGC-3 at nearly every one-hour during the water injection into OGC-1.

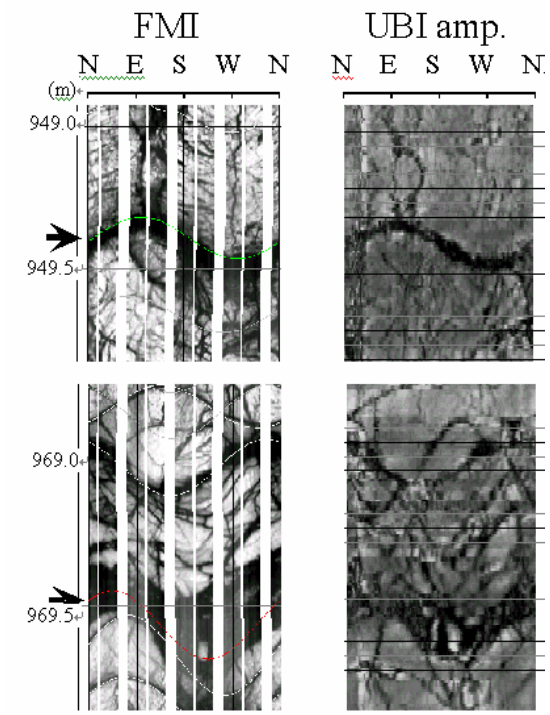

Figure 11: Pictures of fractures detected on OGC-3 wall by FMI and UBI at depths where the temperature anomaly observed by optical fiber thermometer survey in OGC-3.

Figure 12 shows a comparison of the AE hypocenter density, temperature and permeability distribution along OGC-3. This figure shows that the permeability model may be reasonable.

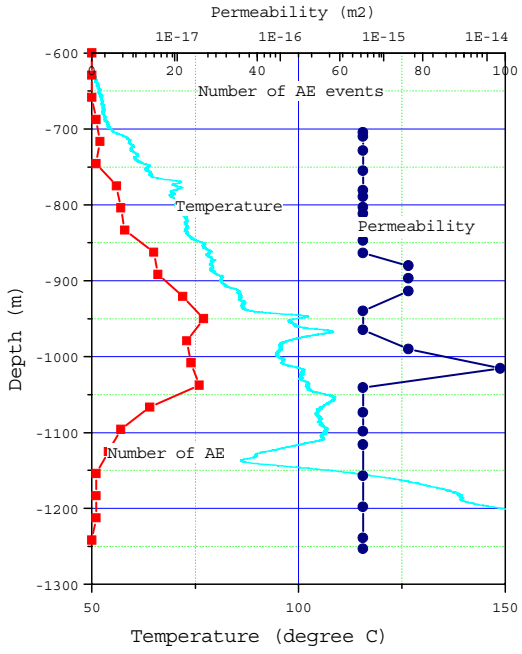

Figure 12: Comparison of number of AE hypocenter locations, temperature, permeability along OGC-3.

In-site rock stress was measured by laboratory tests using the Acoustic Emission (AE) method and the Differential Strain Curve Analysis (DSCA) method, together with core disking phenomenon and shut-in pressure. According these results, the direction of the maximum stress is estimated roughly NE-SW (Shin et al., 2000). However, analysis of drilling-induced tensile fractures (DTF) and borehole breakouts detected in OGC-3 showed that the maximum horizontal stress was nearly E-W (Ito and Okabe, 2001). From these results, we considered that the maximum stress around the Ogachi site was E-W which was consistent with wide area stress condition in northern Japan, but the stress in a small area such as core sample was recovered was not consistent with it. The estimated stress from the core samples may be affected by natural fracture system.

Ito (2003) considered that the upper reservoir progression was strongly affected by natural fracture system.

3.6 Technology Application

In 2002, a new HDR development program started at Cooper Basin in South Australia by Geodynamics limited (Chopra, 2003). We have joined the program and apply the developed technologies in our Ogachi project for contributing to the Australian HDR development program and improving our technologies.

We conducted CSAMT and TDEM method around the Cooper Basin test site. The resistivity structure in the site was estimated down to 5 km.

We set four AE measurement stations at 5 km away from the Cooper Basin test site to monitor induced AE activity. The results of measurement during the reservoir creation showed that more than 10,000 events were observed and located. These results contributed to the decision of a production well trajectory Therefore, the AE measurement was shown to be useful to evaluate the reservoir (Soma et al., 2004).

4. CONCLUSIONS

Through the Ogachi HDR program we developed many basic technologies for constructing HDR system considering Japanese thermal and geological conditions. Most of the developed technologies were shown to applicable for real HDR development scale. Unfortunately, we could not show the water recovery rate increase depending on number of production wells. But we estimated it by the numerical simulation that the recovery rate would increase more than 40 to 50 % if we have another production well and use a down hole-pump. Then we think the recovery rate will more than 80 % if we have four production wells as we considered as a basic model.

Now we have applied the developed technologies to the Australian HDR program for contributing to the program and improving the technologies.

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