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# Progress of the EGS project for water injection in the superheated region at the Okuaizu geothermal field in Japan

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**ABSTRACT**

An R&D project funded by Japan Oil, Gas and Metals National Corporation (hereafter referred to JOGMEC) on technology development for geothermal reservoir evaluation and management is under way. The purpose of the project is to propose guidelines for a technical manual, based on numerical simulation and model verification, for better understanding of artificial water recharge effects to geothermal reservoirs and/or hot spring aquifers.

Relevant examples include steam shortages resulting from the imbalance between the steam production rates and the natural water recharge; corrosion of surface facilities by superheated steam; and production of highly acidic fluid generated by superheating within the geothermal reservoir. These problems are widespread, and occur not only in existing geothermal power plants, but also in new geothermal developments and in newly developing areas. Our aim is to develop new and general countermeasures to such problems, which are both technically effective and cost effective. We will then collate these comprehensive measures into a new set of guidelines to ensure a stable supply of geothermal energy. Artificial water recharge is one of the EGS (Enhanced Geothermal Systems) technologies which has been successfully applied and shown to increase steam supply in the Geysers and Larderello geothermal fields. We will develop and verify an artificial water recharge technology through R&D set in the Okuaizu geothermal field in Fukushima prefecture, with an installed capacity of 65MW which has been running since 1995 and the capacity was changed to 30MW in 2017. The utilization factor of this power plant has reduced to 27.7% in 2014, mainly due to the depletion of steam, the superheating effect, acidification and a decline of productivity and injectivity. The R&D project consists of project planning, design & management, survey and modeling, design and construction of a test facility, drilling of a recharge well, well testing and logging, a recharge test, numerical reservoir simulation, monitoring, and the preparation of a technical operation manual.

There are very few examples of reservoir simulation of superheated reservoirs in the world. The location of the recharge well in the field was decided by the comprehensive analysis of simulations, risk evaluations from past field injection tests and tracer analysis. Drilling of the recharge well and, recharge testing started in the beginning of June 2015. Approximately 170,000t of river water was injected through to the end of December until a cyclic phenomenon at an adjacent well (Well-8) caused by the recharge operation was observed. Despite this cyclic behavior, an increase of steam flow at Well-8 of 3-5t/h and a reduction of non condensable gas (NCG) concentrations were benefits of the recharge operation. Effects at Well-5 and 6 located in the same fault of the recharge well were also observed suggesting it is possible to maintain and/or increase of steam production and control NCG by suitable recharge operation. The cyclic behavior at Well-8 can be assumed by injection at shallow depths by the flow behind the casing of the recharge well. The well was successfully repaired to stop the flow by using a metal packer and is ready to start a long term injection test.

## 1. INTRODUCTION

Research on artificial water recharge projects is important since several geothermal power plants sometimes require artificial recharge to support power production. One of the geothermal power plants with problems such as reservoir superheating and acidification is the Okuaizu geothermal field in Fukushima prefecture. The utilization factor of the facilities (actual power output/permitted capacity × power generation hours × 100%) has fallen below half of that at the start. Commercial operation of the Yanaizu-Nishiyama power plant started in 1995 by Okuaizu Geothermal Co., Ltd (geothermal developer and steam supplier) and Tohoku Electric Power Co., Inc. (power generation), but the amount of steam has decreased every year along with superheating problems. Fluid acidification phenomenon followed by superheating occurred requiring the discontinuation of production in some of the wells. Therefore, it is important to establish technology for water recharge and its know-how by using the Okuaizu geothermal field as EGS R&D project in Japan.

This type of projects has been seen overseas, municipal effluent water from Clear Lake and Santa Rosa has been injected in wells in the Geysers geothermal field from 1997 improving levels of power generation as well as reducing concentrations of non-

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condensable gas (Sanyal and Enedy, 2011). In the Larderello geothermal field in Italy, artificial water recharge was carried out from the 1970's after the steam production rate went down and the reservoir was superheated. As a result of the injection, steam production increased and non-condensable gas concentration also reduced (Capetti, 1995). However, it is believed that these artificial water recharge projects were not based on detailed simulation, an operation manual and/or a detailed plan. The geothermal structure in Japan is smaller and rather complicated compared with these overseas examples and technology development is required to pay attention to environmental factors such as hot spring monitoring, pressure/temperature maintenance in a borehole and reservoir sustainability.

Until now, a comprehensive R&D project including evaluation of a recharge well location in a superheated reservoir by extensive simulation, drilling the recharge well, injection testing and evaluation of the injection test results has not yet been carried out. Although this project started in 2013 as a five year project, it was extended by two more years to cope with the flow behind the casing of the recharge well. The purpose is to develop a guideline for an artificial water recharge technology and to develop a technical manual through a verification test and numerical simulation of the effect of artificial water recharge on the geothermal reservoir and hot spring aquifer.

This paper reports on brief history of the project and present progress including explanation and evaluation of monitoring data while recharge operation in 2015 and 2018 as well as the well workover in the Okuaizu superheated geothermal reservoir.

## 2. PROJECT OVERVIEW

### 2.1. Okuaizu Geothermal Field in Fukushima

The Okuaizu geothermal field is located in northeastern Japan (Figure 1). Exploration of the Okuaizu geothermal field commenced with a reconnaissance survey by Mitsui Mining and Smelting Co., Ltd. (MMS) in 1974. Subsequently, the first-phase geological, geophysical and geochemical surveys were conducted by the New Energy Development Organization (NEDO) from 1976 to 1977. After a geophysical and geochemical survey by MMS in 1981, second phase geological, geochemical and geophysical surveys by NEDO were conducted from 1982 to 1983 (NEDO, 1985). In 1983, Okuaizu Geothermal Co., Ltd (OAG) was established to carry out further exploration and assessment, and to undertake development. From 1984 to 1985, OAG carried out geological, geophysical and geochemical surveys, and drilled five cored wells and four other wells. Production tests of 18 to 119 days for each production wells were also conducted. From 1986 to 1989, 13 more wells were drilled, with 30 to 109 day production tests conducted for each production well (Nitta et al., 1987). A total of 509 t/h of dry steam at about 165 °C from nine wells was confirmed during a three month simultaneous production test, from December, 1989, to February, 1990 (Nitta et al., 1990). Three additional production wells were drilled after that initial reservoir evaluation and the commercial operation started with the capacity of 65MW in 1995 and the capacity was changed to 30MW in 2017. The utilization factor of this power plant has reduced to 27.7% in 2014, mainly because of depletion of steam, the superheating effect, acidification and decline of productivity and injectivity. The areas in the Chinoikezawa footwall fault and Chinoikezawa southeast fault have been gradually superheated from the decrease of the pressure and production some of the wells in the Chinoikezawa southeast fault was suspended due acidification caused by the superheating effect (Figure 1).

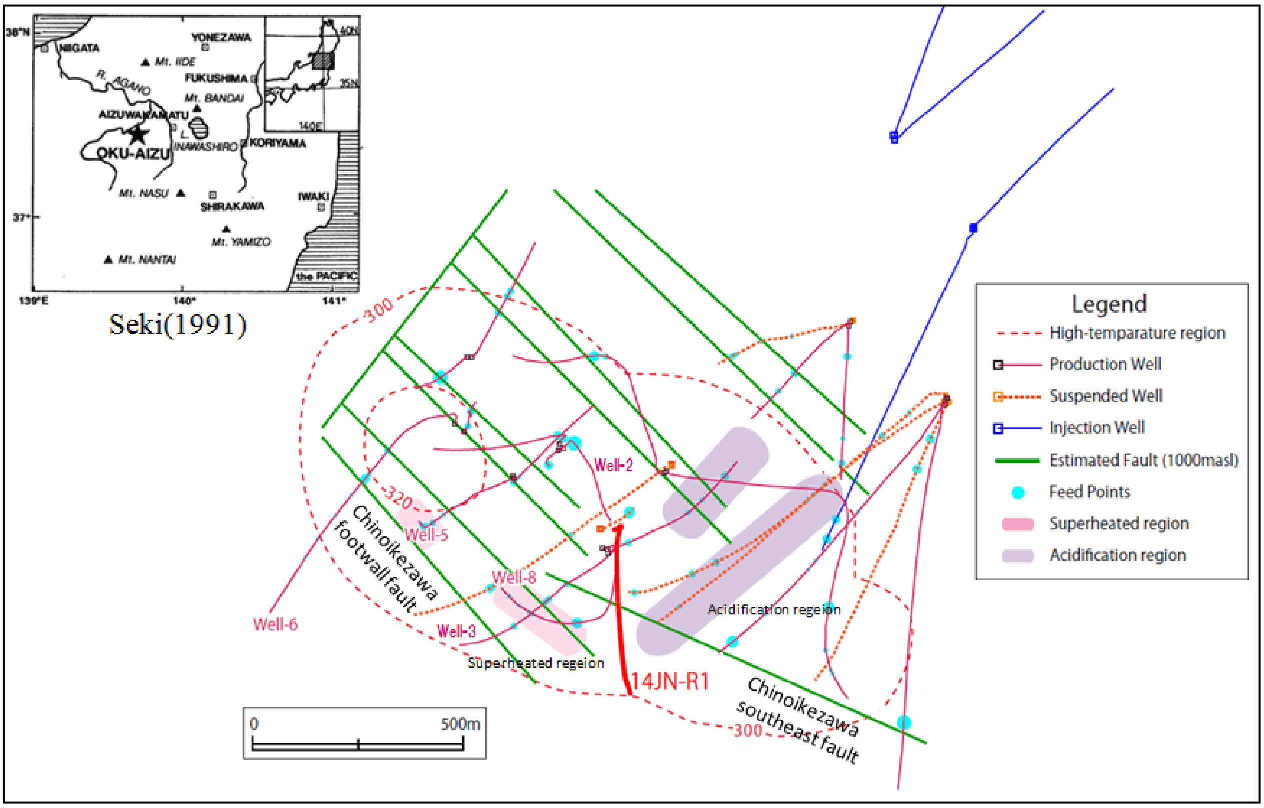


**Figure 1: Location map and details of the Okuaizu geothermal field**

### 2.2. Outline of the project

This project initially had a duration of five years starting from 2013, and was later extended an additional two years to repair the well and conduct a long-term recharge test. The purpose of the project is to optimize and/or stabilize production rate by improving the accuracy of prediction of the reservoir behavior through a verification test and numerical simulation of artificial water recharge in order to clarify the impact on the geothermal reservoir and hot spring aquifers. A guideline for an artificial water recharge technology and a technical manual will be produced at the end of the project.

The R&D project consists of project planning, design & management, survey and modeling, design and construction of a test facility, drilling of a recharge well, well test and logging, operation of a recharge test, numerical reservoir simulation, monitoring, and preparation of a technical operation manual.

The project is separated in two stages, Phase I and Phase II. Phase I ran from 2013 to 2015 and its object was to locate the recharge well and start the injection experiment. Phase II runs from 2016 to 2019 with an aim to maintain injection, calibrate the simulation model, and create a guideline to wrap up the project (Okabe et al., 2015).

## 3. PROGRESS OF THE PROJECT

### 3.1. Determination of the recharge well location

The recharge well location was determined by a comprehensive evaluation of an extensive numerical simulation, a tracer test, and past field injection tests (Okabe et al., 2015). The recharge simulation was conducted using the reservoir simulator TOUGH2 (Pruess et al.,1999) using a MINC (Multiple Interacting Continua) model. The tracer test suggested the existence of fast fracture flows that could result in a short circuit, and that injection water from the shallow depths may have a severe influence on production wells locally. According to the past field injection tests, severe interference such as stopped production has occurred when production feed points are at the same level as injection feeds or shallower. The results suggest that the fractures that cause a local short circuit exist in a shallow region of the reservoir. Thus a shallow recharge location was avoided and a deep part was selected as a drilling target. The chosen target depths were 1,975m and 2,075m located on an extension of the Chinoikezawa footwall fault.

### 3.2. Drilling and logging results

The recharge well was drilled based on the comprehensive study above. As expected before drilling, total lost circulation (L/C) at 1,926m and a drilling break at 2,034m were encountered, and on Dec. 12, 2015 the well was completed at 2,100.26m with a 7” slotted liner and a 5.5” injection pipe to protect the 9-5/8” casing (Figure 2).

Temperature, Resistivity, Sonic and Borehole Televiewing (BHTV), and PTS logging were conducted. The static temperature at 1,350m is 296°C. Most of the fractures detected from the BHTV have a steep northward dip. Four L/C depths (1,930m, 1,980m, 2,040m, and 2,080m) were detected from injection PTS logging. The main L/C depth was 2,040m, and 76% of the injection fluid was lost at that depth. However, the main L/C depth changed from 2,040m to 1,890m as detected by the step rate test at the beginning of June. Characteristics of L/C fractures detected from injection PTS logging are a NW-SE strike steeply dipping toward the north, which is consistent with the characteristics of the Chinoikezawa footwall fault. Drilling-induced fractures which indicate the present stress state were observed, showing an approximate E-W direction in the 12-1/4” casing and an N-S direction at around 1,950m. Permeability evaluated from a falloff test was 0.5 darcy-m with a skin factor of -4.2.

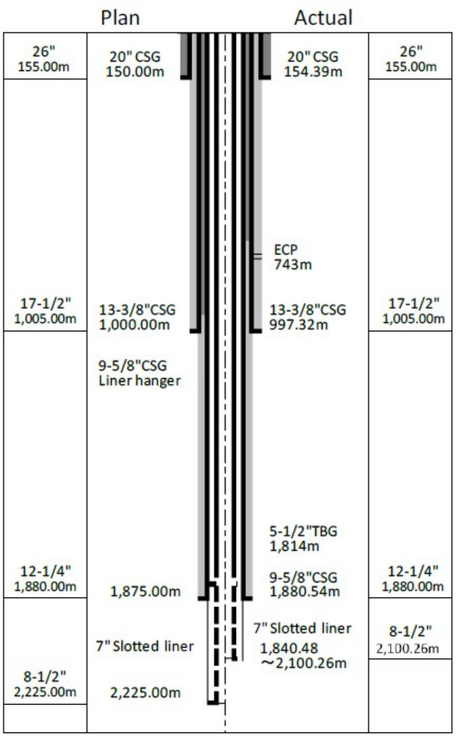



**Figure 2: Casing program and a picture of the wellhead**

### 3.3. Outline of the recharge operation

(1) Recharge operation in 2015

Before starting the recharge operation, a high temperature, high pressure monitoring system was installed in the well at 1,895m and an AE/Micro seismicity array including borehole stations was prepared. Regular two phase and gas tracer tests, geochemical sampling, and PTS+fluid sampler logging close to the recharge well were organized. In addition, steam, brine, wellhead pressure, etc. were monitored by the DCS (distributed control system) from OAG.

Recharge operations started in the beginning of June 2015 with short term step rate tests to confirm the capacity of the well (Figure 3). Although the original plan was to change injection rate by 3 steps (50, 70, 100 t/h) before the power plant preventive maintenance check-up scheduled for September 1 (1st recharge test), only two step rate tests were conducted before the check-up, because of a decline of superheat in Well-5 and river water pumping limitations during the summer.

After the check-up, recharge re-started from November 27 with short term step rate tests after which recharge continued at a rate of 70t/h (2nd recharge test). Due to decreases of superheated amount and steam rate and cyclic effect of the steam with the production of brine that was observed in late December, the recharge operation was stopped on Dec. 26.

The reservoir pressure and temperature before recharge were 9.2 MPa and 313°C respectively (Okabe et al., 2016). Injection pressures increased and temperatures decreased once injection started. Injection pressures after the power plant preventive maintenance checkup decreased by about 1.5 MPa and temperature increased by about 10°C despite using the same injection rate (70t/h). Accrording to the fall off analysis of the data, the permeablity was inproved by a factor of about 3 times that at the start of the 1st recharge test.

When production was restarted from Nov. 13 an initial steam decline was observed, but the steam rate was almost steady from Dec. 5 to Dec. 23 in Well-8 (Figure 4). The degree of superheating decreased from 22.4 to 18.0°C on Dec 23-24, and steam flows decreased from 19.6t/h to 16.8t/h on Dec 24-25. Note that the injection rate was reduced from 70t/h to 50t/h on Dec 25. The degree of superheating decreased to 0.8°C on Dec 26, and the recharge operation was stopped on the same day. The well was separated from the power plant because of the cyclic effect between Dec 28 and Jan 14. The well was connected to the power plant again on Jan 14. After the checkup, the steam rates for Well-5 and Well-6 have almost steady, with small increases of a few tons per hour.

Figure 5 shows a tracer (PDMCH:Perfluorodimethyl Cyclohexane) test result. The tracer was detected at wells mainly to the east and north of the recharge well (circles painted by pink in Figure 5).

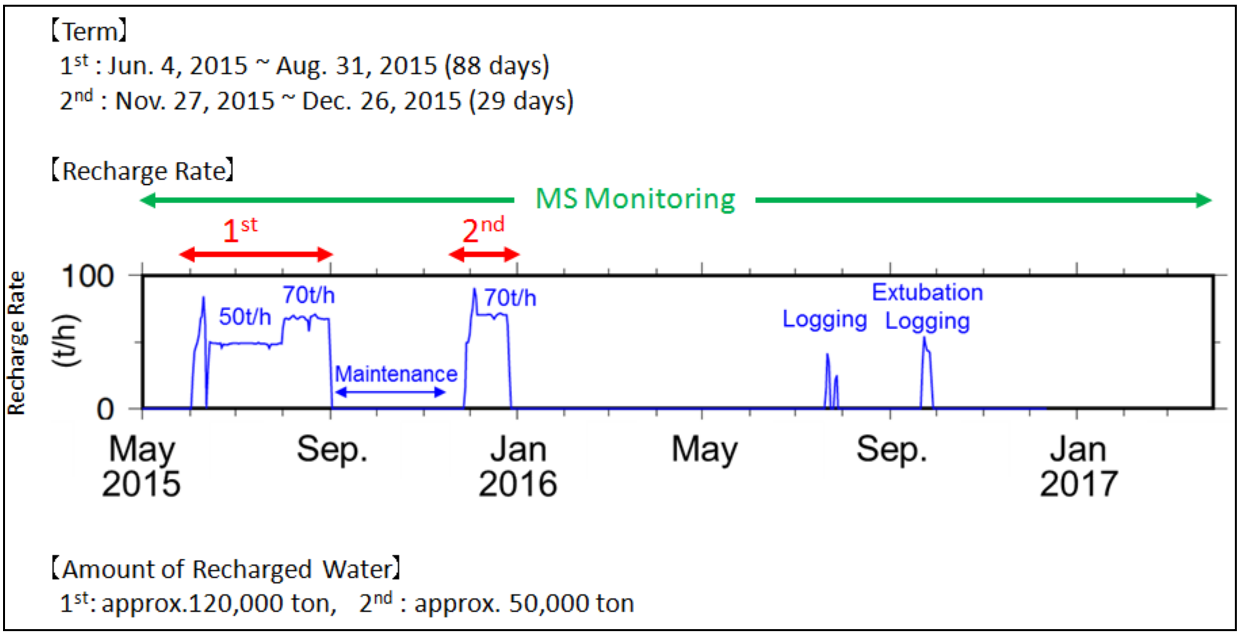


**Figure 3: Recharge history and downhole pressure and temperature data in the recharge well at 1,895m**

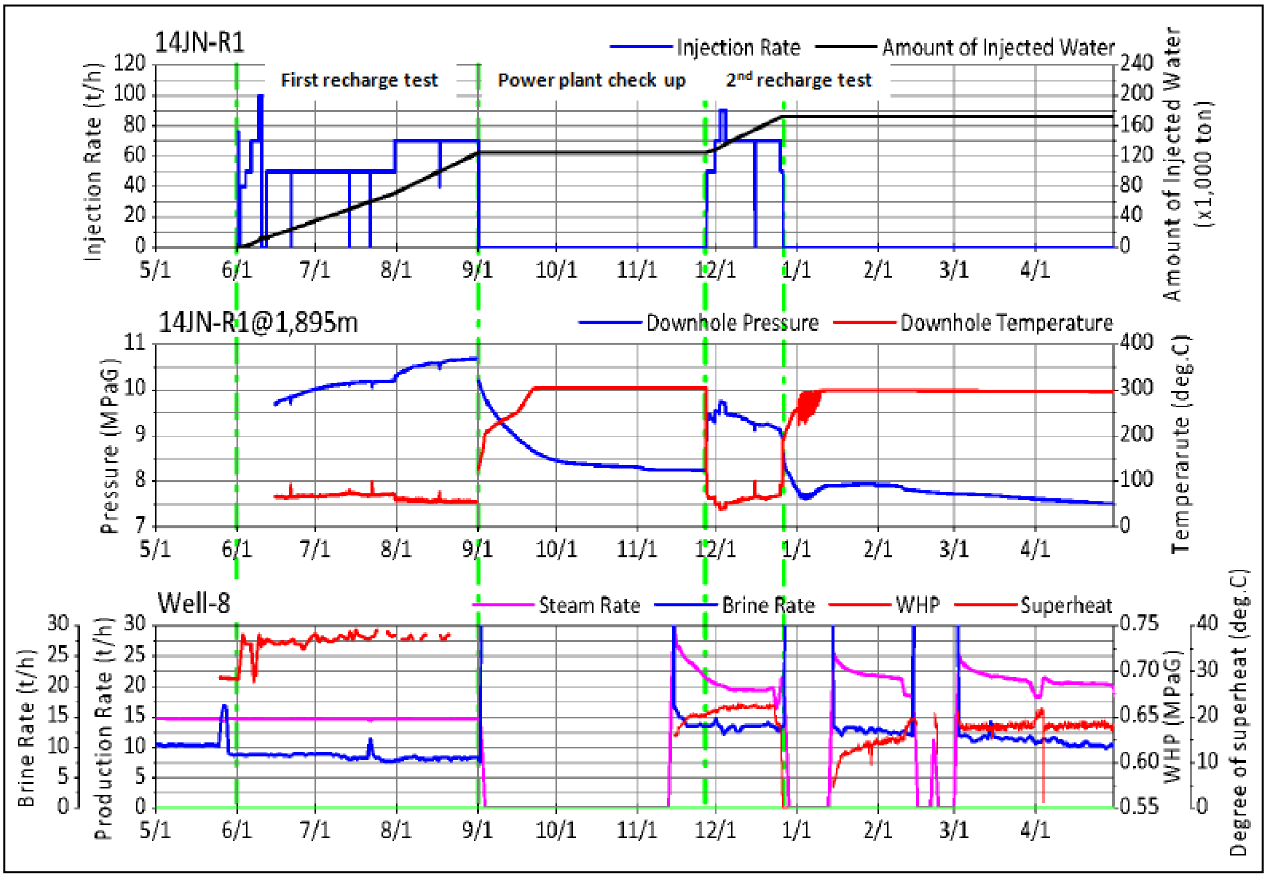


**Figure 4: History of production at Well-8, Well-5, and Well-6**

Tracer test results (Figure 5) and geochemical analysis (Figure 6) show that the recharge water is observed in the production well near the recharge well. The isotope ratio moves to meteoric water (blue arrow in Figure 6). This suggests that the production fluid includes river water injected as well.

During the second recharge test, a remarkable increase in production (about 6 t/h) was observed at Well 8 next to the recharge well, showing the effect of recharge. In addition, the decrease of NCG (Non Condensable Gas) concentration in the steam was also observed, and contribution to the improvement of the power generation efficiency was expected. On the other hand, the decrease in superheating degree and periodic fluctuation that are considered to be interference due to recharge water injection were observed in Well 8 and recharge was stopped. The factor that triggered the interference is the failure of the casing cement of the recharge well due to thermal shock (quenching) associated with the recharge water injection, which causes the recharge water to flow up to the shallow depth behind the casing through the casing shoe. It was thought that interference was initiated by migration of the recharge water to Well 8 through highly permeable fractures (mainly 1,617 m and 1,671 m).

Three borehole microseismic stations were newly prepared in order to study the fluid flow by the recharge (Okabe et al., 2016). As a result, the detection rate of AE / micro earthquakes is improved by a factor of about 3 to 4 times and the determination accuracy of the hypocenter position is greatly improved by using the borehole seismic stations, enabling detailed grasp of recharge water flow. Micro earthquakes occur in a very limited area in the Okuaizu geothermal field, which is considered to form the main reservoir (Figure 7).

The physical properties of the formation, the fluid migration, the shape of the cap lock, estimation of the permeability boundary, etc. were reviewed by organizing the existing information and the new information obtained in this research about the geothermal structure model and interpreting it. New fault and connections shown in Figure 8 were estimated based on the review. Although Region 2 had low resistivity and was considered cap rock from MT survey, it was found that it is not cap rock, because of the micro seismic activity (Figure 7). The geothermal structure model was updated by combining these studies. As a result of reviewing and updating the geothermal model including the cap-rock shape, temperature matching of the natural state simulation result was greatly improved (Figure 9).

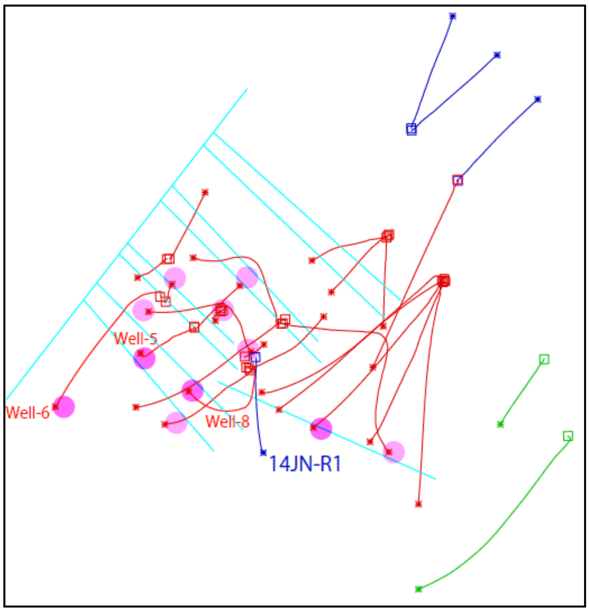


**Figure 5: Tracer test result (PDMCH:Perfluorodimethyl Cyclohexane), pink painted circles show wells where the tracer was detected**

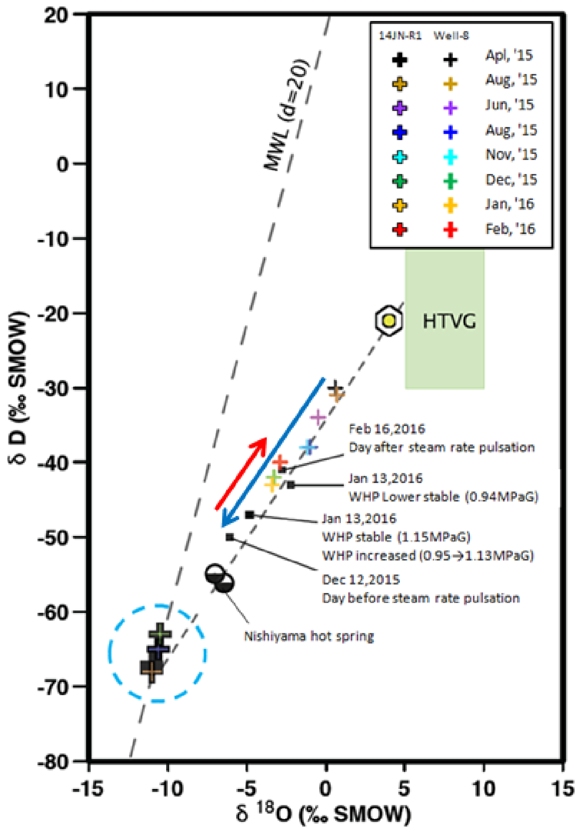


**Figure 6: Isotope analysis at Well-8**

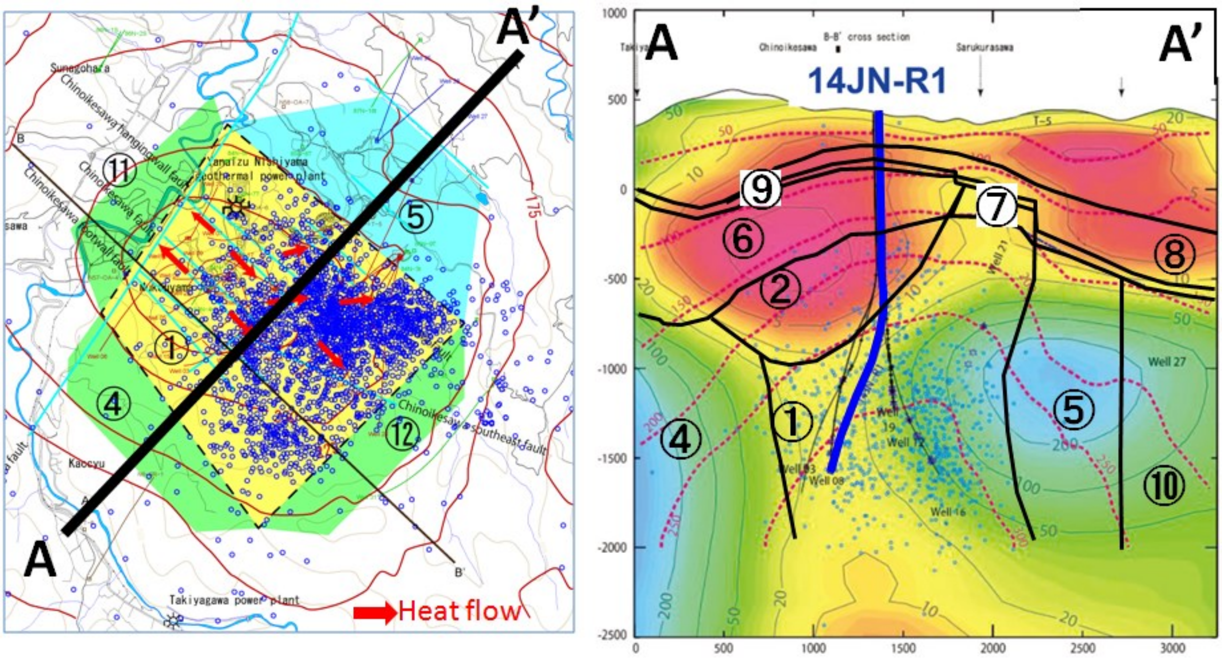


**Figure 7: Microseismic activity, Plan view (Left) and microseismic activity with MT analysis result, Cross section (Right)**

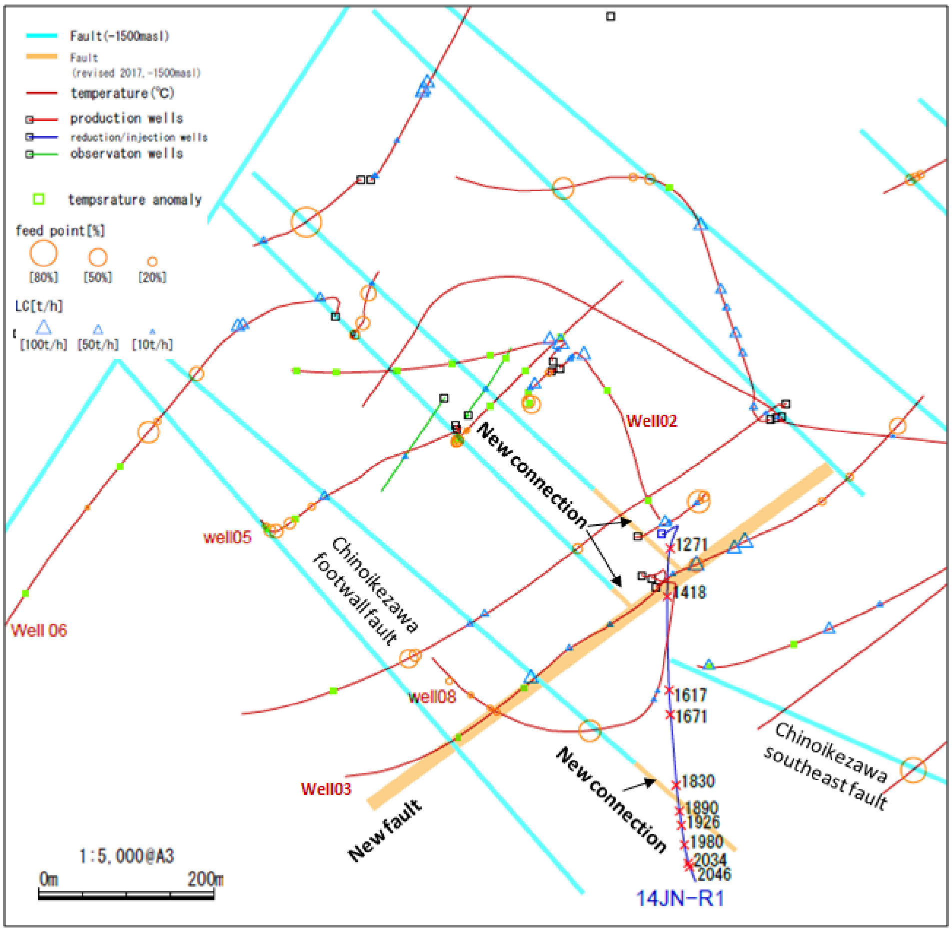


**Figure 8: Estimated faults based on the data acquired**

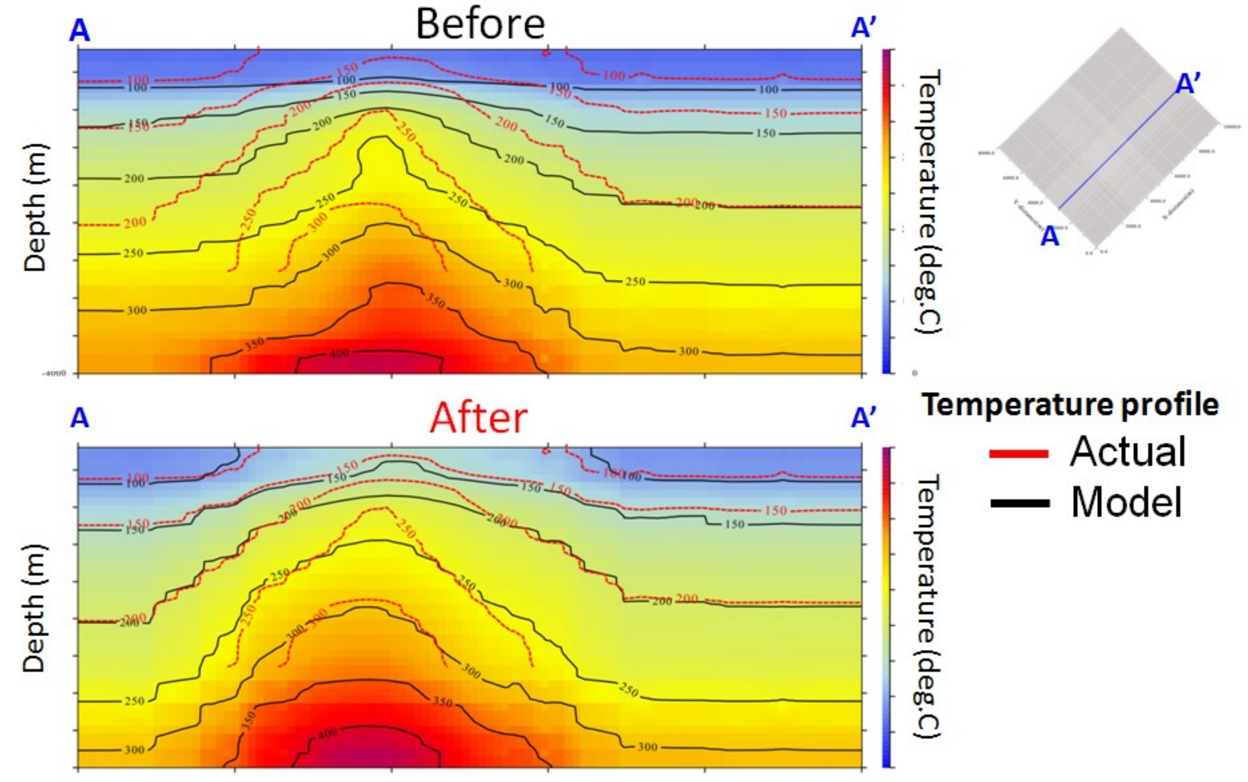


**Figure 9: Comparison of simulation matching based on review of the geothermal model**

(2) Recharge operation in 2018

Recharge operation in 2018 was conducted while repairing the well. The recharge fluid goes into the formation through a milled section between 1,439 and 1,454m of the 9-5/8" casing (see Figure 11 in 4. ). The original well is completely cemented with no flow. The purpose of the test is to check the present recharge situation for the long term recharge operation. Recharge was conducted at a rate of about 5t/h and continued for 30 days, from Nov. 22 to Dec. 21.

Recharge fluid was considered to go into the fractures at 1,617m, 1,671m, and 1,830m, in view of the drilling situation, pressure data during recharge, PTS logging data, and the tracer test result (see Table 1 and Figure 10 shown in 4. ). Total lost circulation at 1,271m which occurred during the drilling of the original well was not observed in the 2018 recharge operation. In the static logging result after injection logging, a rapid temperature recovery was observed in 2015, but not at this time. Also, according to the gas phase tracer test results, the concentration of Well 3 is much higher than that of Well 2 and Well 5 in comparison with the past tracer test results. This is considered to be due to the water path at this time changing from the last time. From the above, it is considered that the water injected this time did not move to the shallow part above the milled section, but it moved to the depths of 1,617 m, 1,671 m, and 1,830 m (see Figure 11 shown in 4. ).

On the other hand, focusing on the recharge effect, steam increase was observed at Well 3 and Well 6. In Well 3, the steam increase is evaluated by the tracer test and isotope analysis. Since Well 8 had been known to cause interference, production was stopped during the recharge test. It was restarted after completion of the recharge test, and an increase in the steam rate and a decrease in the degree of superheated amount were observed, which is considered to be an effect of recharge as well. It is necessary to review the steam increase rate of each well, since the drilling is carried out with total lost circulation condition before conducting the recharge test.

Table 1 shows a comparison of the 2015 and 2018 recharge tests. As stated above, the values in the table marked ※ should be reviewed, because of the contribution for the drilling-related lost circulation.

**Table 1: Comparison of the recharge tests**

| Item | 2015 recharge test | 2018 recharge test |
|---|---|---|
| Recharge rate | 50～70 t/h | 5 t/h |
| Total recharge rate | 170,000ton | 2,900ton |
| Recharge period | 4 months | 1 month |
| Main regcharge depth | 1st : 1271m, 1417m<br>2nd : 1271m, 1417m, 1617m, 1671m, 1830m | 1617m, 1671m, 1830m |
| Steam increase | Well8: 13.2→18.9 (t/h)<br>(5.7t/h, 43% increase) | Well3: 4.5→6.2 (t/h)<br>(1.7t/h, 38% increase)※<br>Well6: 13.3→14.7 (t/h)<br>(1.4t/h, 11% increase)※ |
| Recovery rate<br>(Steam increase/recharge rate) | 9.5% | 62.0%※ |
| Acidification after the recharge test | Well5: pH decrease,CL increase | Well5:pH no change,CL decrease |
| NCG | Well8: 8.9→7.0 (wt%) | No change |
| Superheated degree | Well5: No change<br>Well8: Large decrease | Well5: No change |

## 4. RECHARGE WELL WORKOVER

### 4.1. Well situation before the workover

The cyclic behavior at Well 8 can be assumed by injection interference at shallow depths by the flow behind the casing of the recharge well. Temperature logging during injection shows sharp temperature increase at 1,880m, and static logging shows quick temperature recovery at the depths of 1,271m, 1,617m, and 1,830m, where those depths show temperature change in the injection log as well. Both the flow out at the casing shoe observed from the spinner log and poor cementing situation from the cement bond log support the flow behind the casing as well.

### 4.2. Recharge well workover

A Welltec metal packer was used to stop the lost circulation through the casing shoe and ensure deep recharge. Diameter of the metal packer used is 8.2" and the length of the seal section is about 2m. When using the metal packer, since the dog leg should be kept within 8°, a dummy run simulating the metal packer was conducted up to 1500m before the actual use to ensure that the packer can go down to the required depth. BHTV logging was carried out to confirm the borehole stability and the diameter. After setting the metal packer to a depth of 1938-1940 m, the cement was injected. The entire 7” liner was pressurized with an HT-400 cementing pump. The pressure was gradually increased to 1000 psi (6.89 MPa), then the pressure was applied in steps of 200 psi (1.38 MPa) to 3,150 psi (21.7 MPa). The pressure was held for 1 minute in each step and for 5 minutes in the final stage (3,150 psi).

Although the maximum pressure applied by the packer is 5,000 psi (34.5 MPa), the pressure was decreased to 4,500 psi (31.0 MPa) in view of the failure of the borehole wall caused by the packer. In addition, if 3,150 psi is pressurized at the wellhead, the differential pressure at the packer depth will be about 4,500 psi due to the water level in the well. The pressure was maintained for about 1 minute in each step and for 5 minutes in the final step. After that, pressure testing of the well and RCBL (Radial Cement Bond Log) logging were carried out to evaluate the packer and cementing. The RCBL logging results confirmed that the Amplitude was large, because the packer part was filled with water and it was small above and below the packer, showing that the cement was effective (Figure 12). This was the first deployment of a metal packer in a geothermal well in Japan.

After setting the metal packer and completely blocking the 7" casing shoe, it was drilled to 2,200 m by a 5-7/8" bit to capture deep lost circulation zones originally planned as injection points (Figure 11). According to the PTS logging results, lost circulation zones were confirmed at 2,023 m and 2,120 m (Figure 13).

The well was successfully repaired by using a metal packer and is ready to start a long term injection test.

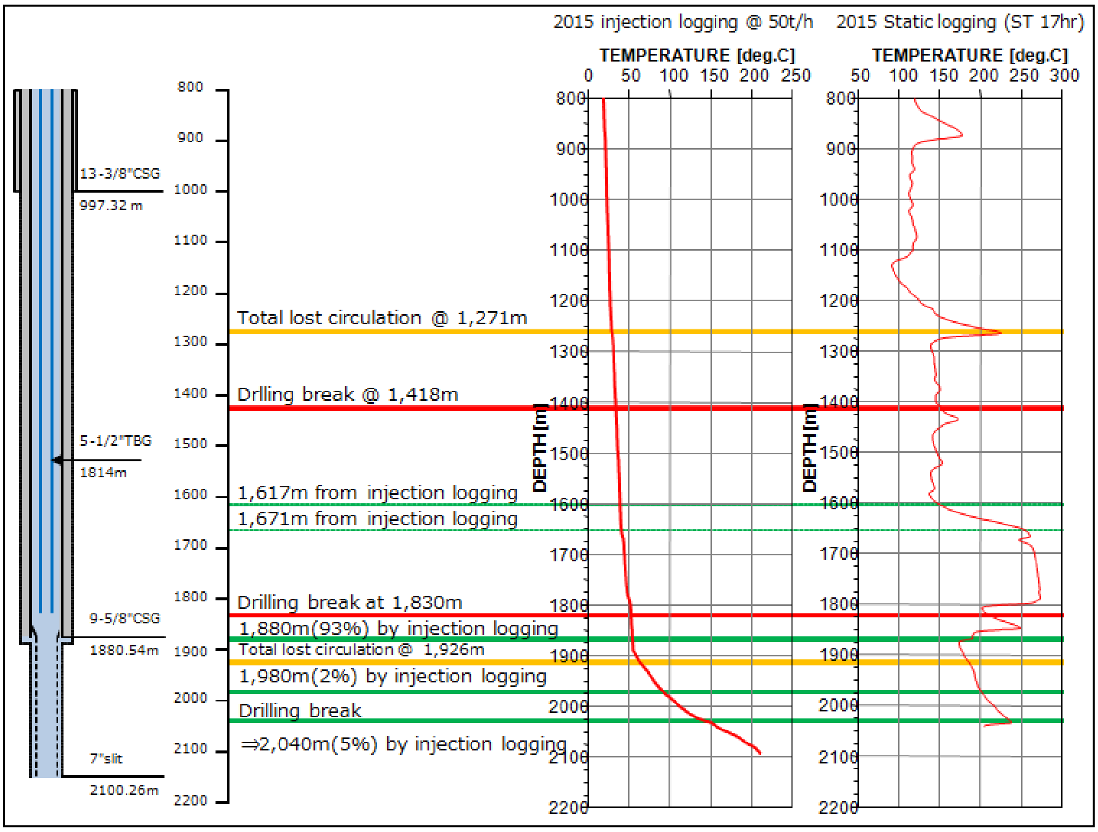


Figure 10: Well situation before the workover

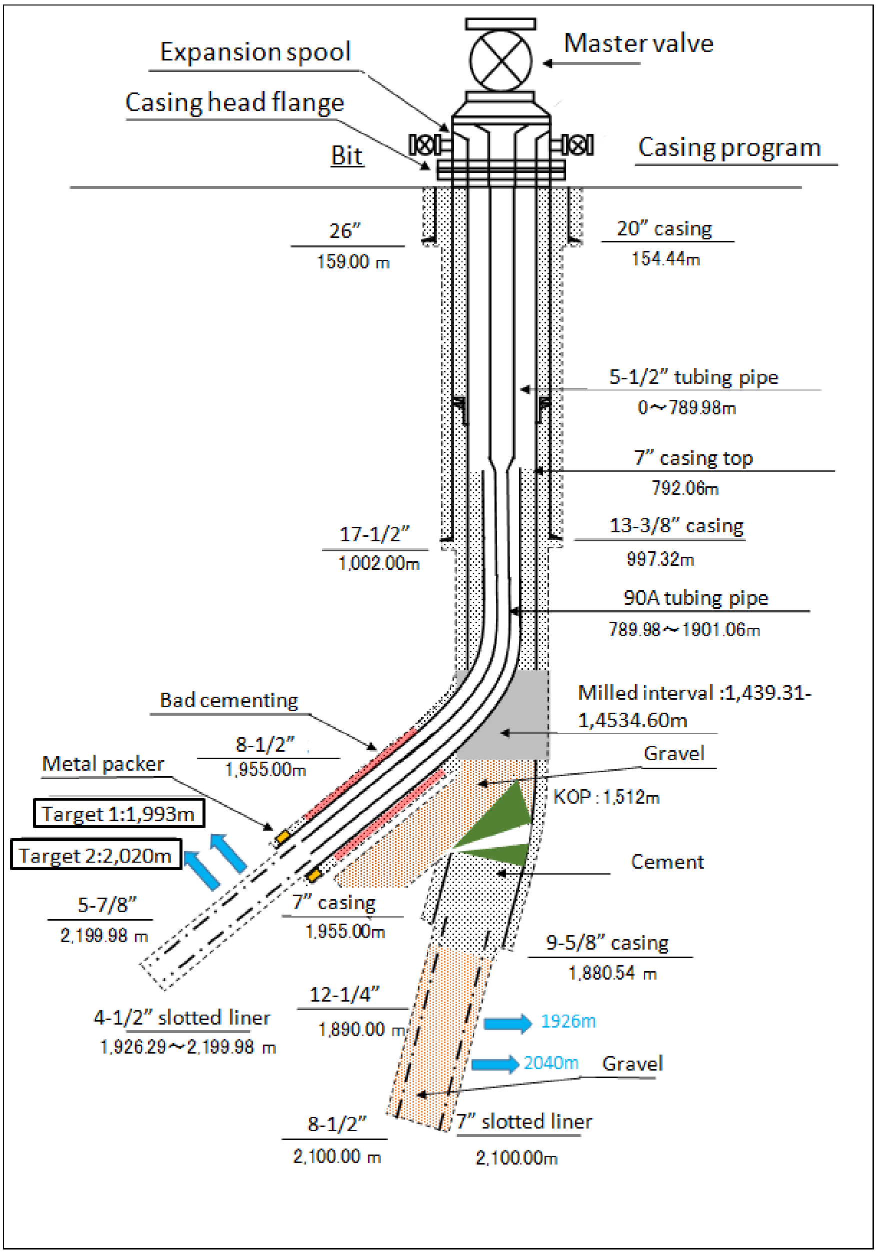


**Figure 11: Final casing program of the sidetracked recharge well**

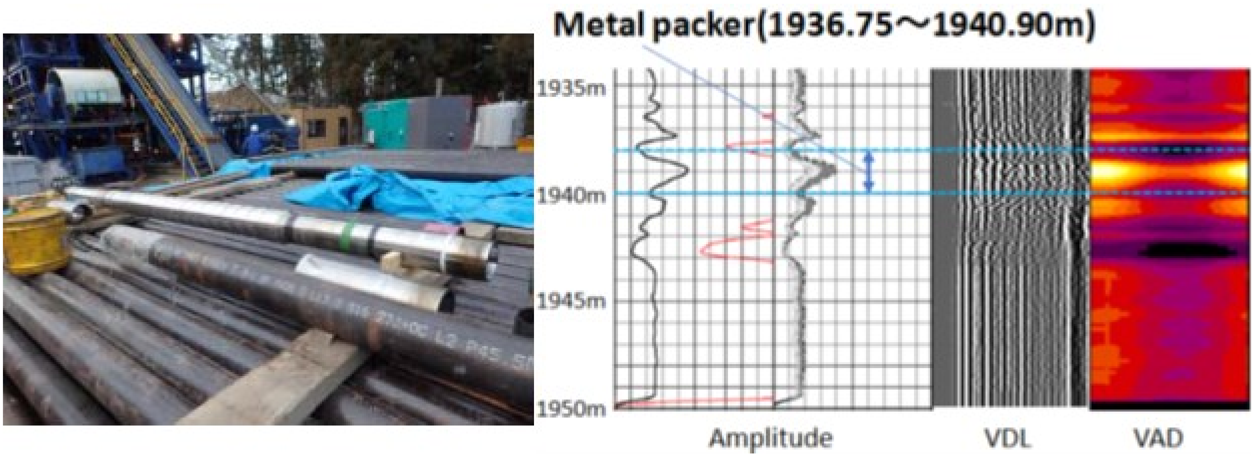


**Figure 12: Metal packer (Left) and RCBL result (Right)**

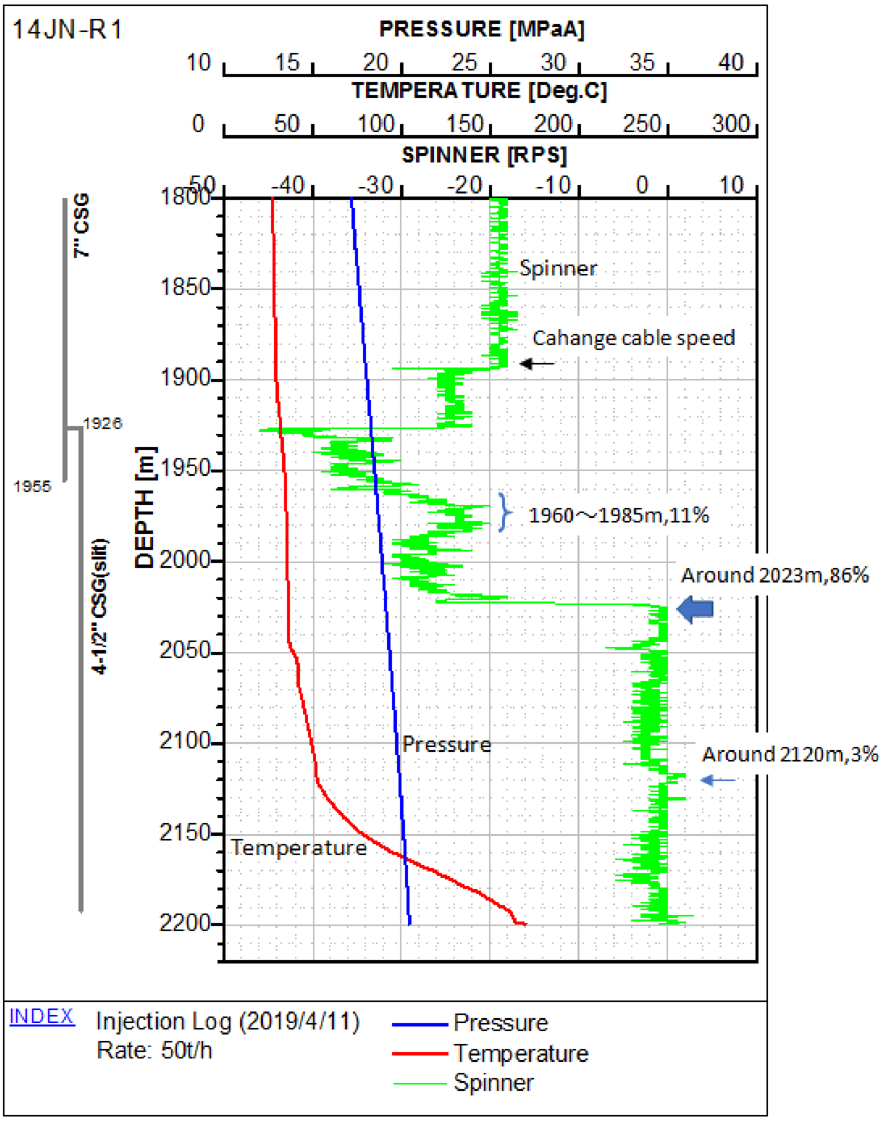


**Figure 13: Injection PTS logging**

## 5. CONCLUSION

This paper presents progress of the EGS project for water injection in the superheated region at the Okuaizu geothermal field in Japan.

The project has been proceeded by improving geothermal structure, simulation accuracy, and well repair using state-of-the-art technologies such as 3D MT analysis, superheat simulation, PTS + fluid sampler, high temperature downhole pressure and temperature monitoring system, high temperature borehole seismic tool, metal packer, etc. in order to understand the Okuaizu geothermal field in detail. As a result, in the recharge test conducted in 2015, although positive effects such as steam increase, superheat decrease, and NCG decrease were observed mainly at Well 8, interference was observed and the well production status became unstable. Judging that this is due to the outflow of recharge water from the shallow area including the 9-5/8” casing shoe at 1,880 m of the original well, we newly formulated a plan to stop the fluid outflow from the shoe to the shallow area by using a metal packer. Based on the plan, a metal packer was applied to the 7"casing shoe in the side track well. After drilling was completed, injection PTS logging was conducted to confirm the lost circulation depth.

The following is a summary of the achievements so far:

i) In the 2015 recharge test, water was injected through fractures shallower than the 1,880 m casing shoe, such as at 1,271 m, 1,417 m, 1,617 m, 1,671 m, and 1,830 m. Although there were positive effects such as steam increase, increase in superheat degree, and NCG decrease at Well 8, interference was observed at the well and the production became unstable.

ii) The physical properties of the formation, the fluid migration, the shape of the cap lock, estimation of the permeability boundary, etc. were understood in detail through the 2015 recharge test. Based on the new information, the geothermal structure model was updated, leading to great improvement in the natural state simulation result.

iii) In the 2018 recharge test, water was injected through the 1,617 m, 1,671 m, and 1,830 m fractures. Due to the small flow rate and change of the flow path, negative effect by the recharge was not observed in the nearby well. An increase in the amount of steam due to the recharge was observed, but it is thought that it will be necessary to review the quantitative evaluation in the future because it is possible to include the effect by the water loss during the drilling.

iv) In order to stop the flow behind the casing through the 1,880 m shoe, a plan to use a metal packer during cementing was implemented. This made it possible to reliably stop the flow from the shoe. The effectiveness of the method was confirmed by the pressure test and RCB logging. This is the first time to use a metal packer in a geothermal field in Japan.

v) After drilling the final stage (5-7/8"), injection PTS logging was carried out, and the main lost circulation depth was observed at 2,023 m and a fracture originally planned for deep recharge was secured.

The recharge operation for the deeper depth re-started from July 2, 2019 after PTS logging and setting a pressure and temperature monitoring tool.

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