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Current Status of Technology Development for Geothermal Reservoir Evaluation and Management

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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 power plants 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 our artificial water recharge technology through R&D set in the Okuaizu geothermal field in Fukushima prefecture, whose installed capacity is 65MW and has been running since 1995. The utilization factor of this power plant has reduced today to 43.6%, mainly because of depletion of steam, the superheating effect, acidification and decline of productivity and/or injectivity. The R&D project consists of project planning, design & management, survey and modeling, design and construction of test facility, drilling of a recharge well, well test and logging, operation of recharge test, numerical reservoir simulation, monitoring, and preparation of a technical operation manual.

In order to locate a recharge well, extensive reservoir simulations at superheated conditions by using TOUGH2 with the MINC model, are underway. Recharge simulation shows shallow depth injection is more effective than deep injection, because it recovers heat from subsurface rock mass where geothermal fluid has been almost depleted, and acts similarly to a Hot Dry Rock system. In contrast, deep injection tends to block fluid flow supplied from the deeper two phase zone, and depends on the injection rate. The risk to production from cold sweep will be evaluated by tracer analysis and past field injection tests, separately. The location of the recharge well will be decided by the comprehensive analysis of the simulations and the risk evaluation.

1. INTRODUCTION

The concept of EGS(Enhanced Geothermal Systems) includes artificial reservoir creation and energy extraction (hereafter referred to as Type A), extension of fractured zones and increasing productivity/injectivity by hydraulic fracturing (hereafter referred to as Type B), and artificial water recharge (hereafter referred to as Type C). The Desert Peak and Bradys projects in the United States focuses on research on the extension of the fractured zone and increasing productivity/injectivity by stimulation of a low permeability well (Type B). An example of a Type A project is in Australia, where artificial reservoir creation and energy extraction by hydraulic fracturing is in use, but has encountered economic problems, as well as producing an unusual overpressured zone at greater depth. In Europe, the technique aiming to use deep geothermal water (Type B), and recover heat by reservoir creation by hydraulic fracturing in low to moderate temperature rock mass, has been employed. A Type B example occurs in Germany, FIT (feed-in tariff).

A Hot Dry Rock project (Type-A) was carried out in Hijiori, Ogachi and east Hachimantai, Japan, yielding various results and knowledge, but these projects finished before showing the economical prospect for commercial power generation (e.g. Matsunaga et al., 1995; Kaieda et al., 1995). On the other hand, research on Type C projects is important since several geothermal power plants require the artificial water recharge to support the power output. One of the geothermal power plants which have problems such as reservoir superheating and acidification by the reservoir superheating is the Okuaizu geothermal area in Fukushima prefecture. 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 Type C EGS R&D project in Japan.

Type C examples have been seen overseas, municipal effluent water from Clear lake and Santa Rosa has been injected in wells in the Geysers geothermal area from 1997 improving levels of power generation as well as reducing concentrations of non-condensable gas (Sanyal and Enedy, 2011). In the Larderello geothermal field in Italy, artificial water recharge was carried out from 1970's after the steam production rate went down and the reservoir was superheated. As a result of the injection, steam production rate increased and non-condensable gas concentration also reduced (Capetti, 1995). However, it is thought that these artificial water recharge designs 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 overseas and technology development is required to pay attention to environmental preservation such as hot spring monitoring, pressure/temperature maintenance in a borehole and reservoir sustainability is also required.

Up to now, a comprehensive R&D project including evaluation of a recharge well 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. This five year project started in 2013 and 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 for the artificial water recharge effect on the geothermal reservoir and/or hot spring aquifer.

This paper reports on an extensive simulation including a model of the Okuaizu superheated geothermal reservoir in order to identify optimal recharge well targets.

2. PROJECT OVERVIEW

2.1 Okuaizu Geothermal Field in Fukushima

The Okuaizu geothermal field is located in northeastern Japan (Fig.1). Exploration of the Okuaizu geothermal field commenced with a reconnaissance survey by Mitsui Mining and Smelting Co., Ltd. (MMSC) 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 MMSC in 1981, the 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 productive well 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. Presently, the utilization factor of this power plant has reduced today to 43.6%, mainly because of depletion of steam, the superheating effect, acidification and decline of productivity and/or injectivity.

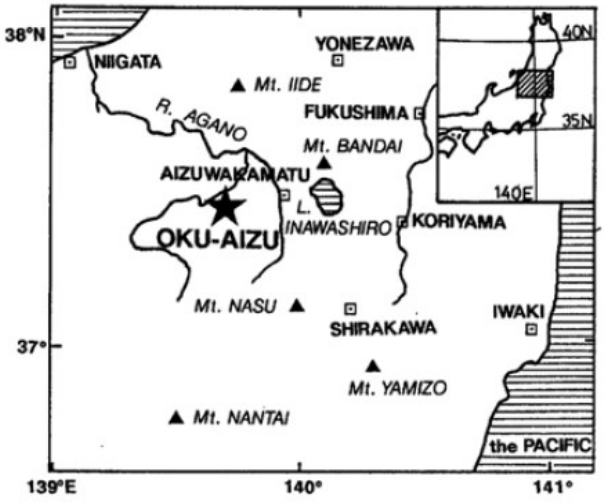


Figure 1: Location map of the Okuaizu geothermal field after Seki(1991).

2.2.1 Geology

The bedrock in these areas is composed of granite dating from the Paleozoic to Mesozoic era and from the late Cretaceous to the Paleogene period, where relief structures elongated in a north-south direction are found. Apart from the array of this bedrock, green tuff of the Miocene period of the Neogene, spreading over the entire region of the Tohoku District, is also formed around these areas.

The geological stratigraphy in the areas consists of, in order of lower to higher layers, the Ohizawa and Takizawagawa layers of the early Miocene period in the Neogene, the Ogino layer (including the Miyashita mudstone layers) of the early to mid Miocene

period, the Urushikubo layer of the mid to late Miocene period, the Fujitoge-Izumi layer of the late Miocene to the Pliocene periods, the Nanaorizaka layer of the early to mid Pleistocene period in the Quaternary, the Sunagohara layer (including the Yunotake rhyolite) of the early to late Pleistocene, terrace deposits of the late Pleistocene to the mid Holocene period, marsh volcanic products of the late Holocene period, and the Alluvium.

The Ohizawa layer, located at the northern edge of the Aizu Basin, has been found in the core 1,800 meters deep in these areas, where sandstones originating mainly from neutral to acid volcanic products have developed so as to give an inter-finger relationship with conglomerate stones. The Takizawagawa layer is widespread across areas ranging from the Tadami to Miyashita areas and is successively distributed with a layer thickness of about 1,000 meters under the ground in these areas. This layer is composed mainly of rhyolitic pyroclastic rocks with rhyolitic lava placed there between in a transitional inter-finger manner. The Ogino layer is widely distributed across these areas, and consists of rhyolitic pyroclastic rocks that have been thought to result from acid volcanism at the bottom of the sea. Under this layer, the black-colored Miyashita mudstone layers (layer thickness in these areas is dozens of meters) have developed, playing a role of a key bed in the stratigraphic classification. The Urushikubo layer is distributed in the southern and northern parts of these areas and has lithofacies that significantly varies from place to place, consisting of mudstones, sandstones, tuff, lime stones, rhyolitic lava and others.

Judging from the distribution of geologic strata, the direction of fold axes, the direction of the intrusive rock, and the direction of faults, these areas have a prominent north-west to south-east geological structure. Typical fault structures include the Chinoikezawa fault which consists of Chinoikezawa footwall fault, Chnoikezawa fault and Chnoikezawa hanging wall fault, the Oyasuzawa fault, the Sarukurazawa fault, and the Oizawa fault (Fig. 2 and Fig.3). Others include north-east to south-west structures, represented by the Takiyagawa fault, and, in a broader region, north to south structures where bedrock relief structures have been extending.

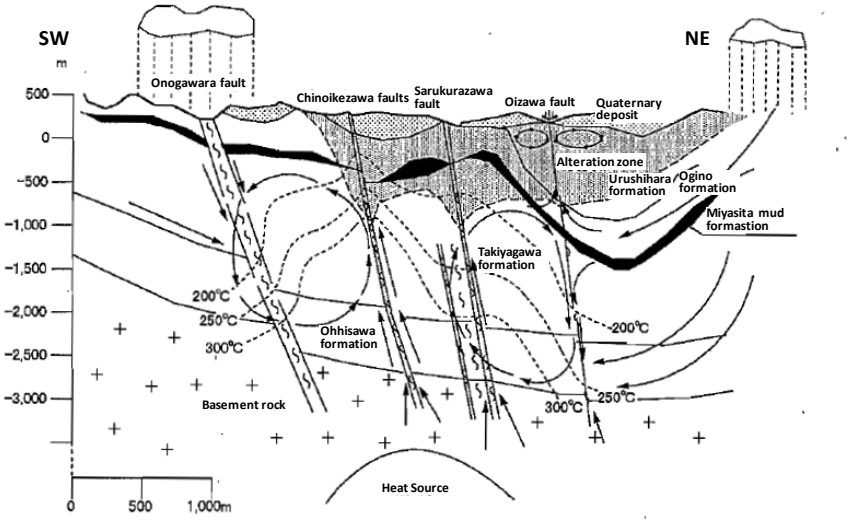


Figure 2: Cross section of the Okuaizu geothermal structure.

2.2.2 Geothermal Structures

In these areas, geothermal fluid is reserved mainly in north-west to south-east Chinoikezawa, Oyasuzawa, Sarukurazawa faults, and other fracture zones around these faults. Portions with high temperatures in excess of 300 degrees Celsius lie 1,000 meters below sea level under the fractured zones of the Chinoikezawa fault. Based on the results of temperature logging, the Takiyagawa fault (including part of the Ohizawa layer) is thought to have hot water convective zones so as to have a two-dimensional extent.

The heat source is believed to be several kilometers under the acid volcanic rocks, which have been becoming solidified. However, it remains uncertain whether it has resulted from the activities of the Yunotake rhyolite or from an association with marsh volcanic activities or from other volcanic activities that have not so far led to an eruption until now.

Concentrating on the north-east to south-west Takiyagawa fault, the alteration zones in these areas are widely distributed across the Chinoikezawa, Sarukurazawa, and Oizawa faults. As altered minerals, smectite stands out in the middle of the alteration zones, while mordenite stands out in the northern and southern parts. Also, kaolinite is locally distributed in the vicinity of an intersection between the Takiyagawa fault and the Oizawa fault. The areas where the alteration zones are distributed, as well as the Miyashita mudstone layer, have extremely low water permeability, playing a role of a cap rock that prevents the geothermal fluid from dissipating in shallow layers and prevents underground water in the shallow layers from entering the geothermal fluid reservoir.

The geothermal reservoirs in the Chinoikezawa footwall fault and Chinoikezawa southeast fault have been gradually superheated from the decrease of the pressure and some of the wells in the Chinoikezawa southeast fault had to be suspended by acidification caused by the superheating effect (Fig.3). Note the numbers in the figure show degree of the superheat.

2.2 Outline of the project

The duration of this project is five years starting from 2013, and 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 clarifying the impact of artificial water recharge on the geothermal reservoir and/or hot spring aquifer.

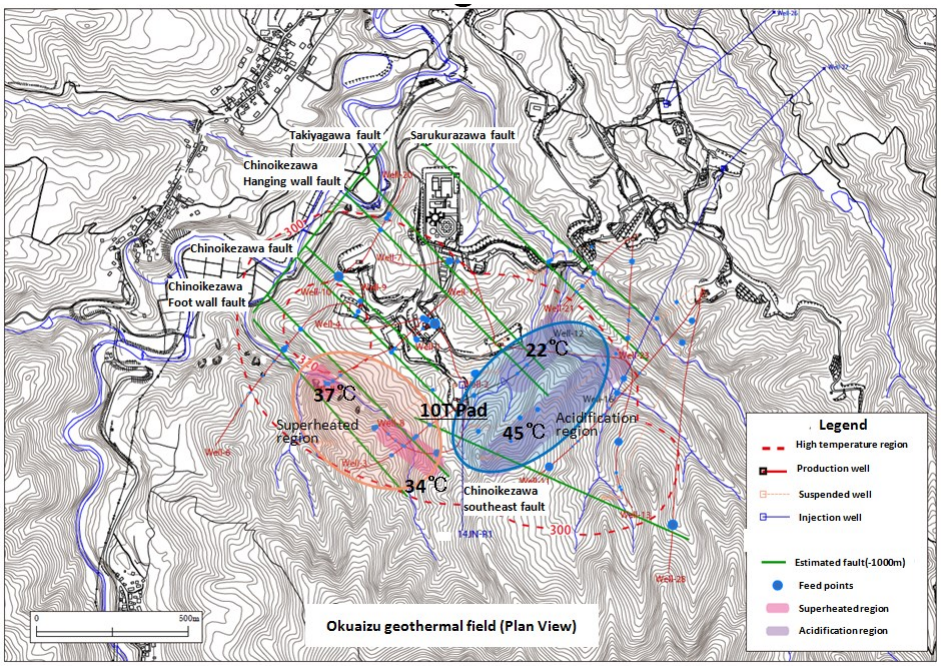


Figure 3: Outline of the Okuaizu geothermal field (Plan View).

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

I. Midterm goals of Phase I (2013-2015)

- To develop a geothermal model that includes both a shallow hot-spring system and a deep geothermal system.
- To identify recharge location based on geological model, numerical simulation results, etc.
- To evaluate future reservoir conditions at several points in time, i.e. the end of the project, after 10-years operation of recharge and after 30-years operation.
- To set up a recharge well and recharge facilities.
- To obtain background monitoring data.
- To make a preliminary assessment of the effect of recharge from an initial operation.

II. Final goals of Phase II (2016-2017)

- To reconcile actual recharge test data with numerical simulation results.
- To confirm mitigation effects in terms of superheated condition at adjacent production wells.
- To make an assessment of the effect of recharge on future production with numerical simulation. It is hoped to achieve similar or better results than realized at The Geysers.
- To establish a technique for assessment of environmental impacts (hot-spring, subsurface water, induced seismicity, etc.) of the recharge operation.
- To systematize recharge technique and prepare technical operation manual.

The five-year research plan is shown in Table 1.

3. THE PROJECT PROGRESS

Here, an extensive recharge simulation including reproduction of the Okuaizu superheated geothermal reservoir in order to determine optimal recharge well locations is described below.

3.1 Three dimensional numerical modeling of a superheated reservoir

Three-dimensional numerical simulation using the reservoir simulator TOUGH2 (Pruess et al.,1999) was carried out for the prediction of reservoir behavior, examination of additional production well drilling, etc. by OAG. We optimized the 3D model and predicted the behavior of a geothermal resource over time. The model (existing 3D model; Fig.4) is a three-dimensional numerical model matched with the natural state and the production history, and presumed the steam production decreases without artificial recharge. Although we used a single-porosity model for the natural state simulation, we used a MINC (Multiple Interacting

Continua) model in the history matching (recharge simulation was included) in order to express the fluid flow more accurately. The result of the natural state simulation is substituted as the initial condition of the MINC model.

Table 1: Five year R & D Plan.

Research & Development	Contents	Phase I			Phase II	
		FY2013 (2013.4-2014.3)	FY2014 (2014.4-2015.3)	FY2015 (2015.4-2016.3)	FY2016 (2016.4-2017.3)	FY2017 (2017.4-2018.3)
Project Planning, Design & Management	• Management of project and data	←	—	—	—	→
Survey and Modeling	• MT method, AMT method, Gravity survey • Integrated analysis, Development of geological model, geothermal model • (supplemental survey as needed to update models)	↔		←	—	→
Design and Construction of Test Facility	• Design and drilling/construction of a recharge well and recharge facilities (water intake, piping)	←	→			
Well Test and Logging	• Before recharge test: Well test and logging for monitoring well/s and recharge well • After commencement of recharge test: PTS sampler logging for production wells	←	—	—	—	→
Operation of Water Injection	• Recharge of surface water (increase recharge rate in stages so as to adjust at proper level)		←	—	—	→
Numerical Reservoir Simulation	• Before recharge test: Forecast calculation for several cases to optimize recharge conditions • After commencement of recharge test: Update numerical model with using actual data obtained, and forecast calculation	←	—	—	—	→
Monitoring	• Down-hole continuous PT monitoring on monitoring well • Multi phase tracer test • Micro-seismic monitoring • AMT method • Hot-spring sampling	←	—	—	—	→
Preparation of Technical Operation Manual	• systematize recharge technique and prepare technical operation manual				←	→

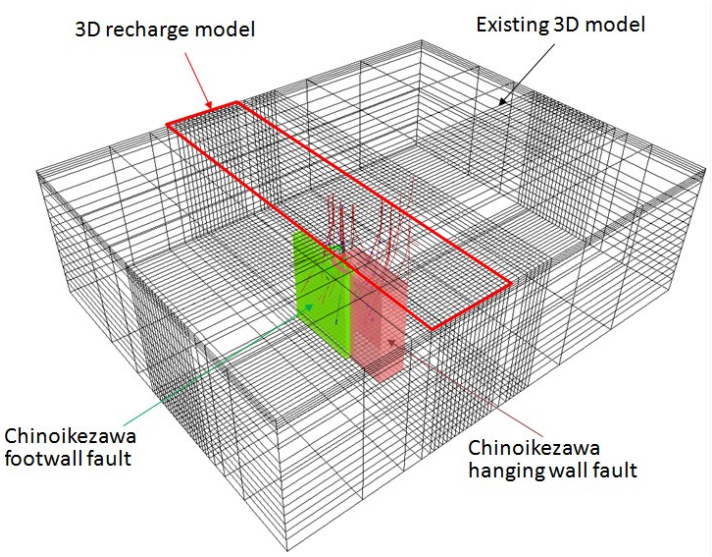


Figure 4: Simulation models.

Although the geothermal reservoir is superheated from the decrease of the pressure in the Okuaizu geothermal field, it is thought that the superheated region spreads to depth as well. At the beginning, we tried to revise the model to produce a superheat reservoir in the deep region. However, the calculation would not stabilize and failed to reproduce the superheated condition. Then, we decided to build a two-dimensional model (2D recharge model) for the Chinoikezawa footwall fault. The 2D recharge was created to be consistent with the existing 3D model. We carried out case studies using this 2D model and successfully created a superheated reservoir following the production as well as confirming the effect of artificial recharge into the superheated region.

Next, we modeled the entire production zone to reproduce the superheated region in two faults of Chinoikezawa southeast and Chinoikezawa footwall faults where enhanced superheating was seen. The two fault models were created and simulations were carried out separately and the presence of superheated regions were confirmed in each fault model. Both models were combined together as a 3D model (3D recharge model;Fig.4, Fig.5) and a simulation was carried out based on the conditions of the 2D recharge model of the Chinoikezawa footwall fault to check if both models are superheated moderately. Subsurface interconnection among Chinoikezawa hanging wall, Chinoikezawa and Chnoikezawa footwall faults through a shallow feed point of -718mals of

well-12 was confirmed by the tracer test described in 3.3.1. A suitable permeable region and the permeability of the boundary of the two fault models were examined by changing the parameters by six patterns. Also fluid sources have been arranged at the base of the model based on the temperature distribution and the fault locations and the production history (January, 1995 - January, 2014).

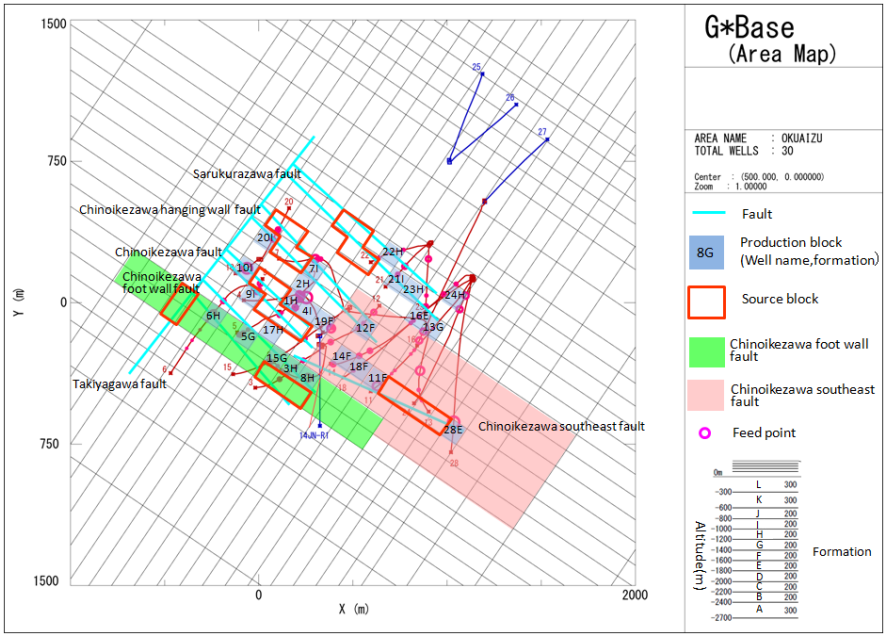


Figure 5: 3D recharge model.

In order to complete the 3D recharge model, a deliverability option was used for the recharge simulation and the productivity index was adjusted to follow the decreasing trend of flow and pressure of the history matching result. Table-2 shows the simulation parameters used for the 3D recharge model (MINC model). In order to re-create a superheated reservoir, permeability for the matrices was required to set to be very low based on the idea that fractures consist of the reservoir rather than the matrices. And thus capillary pressure is set to be zero for the matrices. Relative permeability and capillary pressure behavior of fractures is not well known and we have assumed that fracture capillary pressures are negligibly small according to the Okuaizu filed simulation history and also from Pruess and Enedy(1993) at the Geysers injection simulation and Vedova et al.(2007) at the Larderello geothermal field modeling. van Genuchten with irreducible water saturation 0.6 for liquid phase and Corey with irreducible gas saturation 0.05 for steam phase are used as relative permeability function respectively (Fig. 6). The larger irreducible water helps the enthalpy match and create the superheated reservoir. An investigation on the capillary pressure is to be done in the future. Parameters of the reservoir model include the relative permeability and capillary pressure that are to be reviewed based on an actual recharge test.

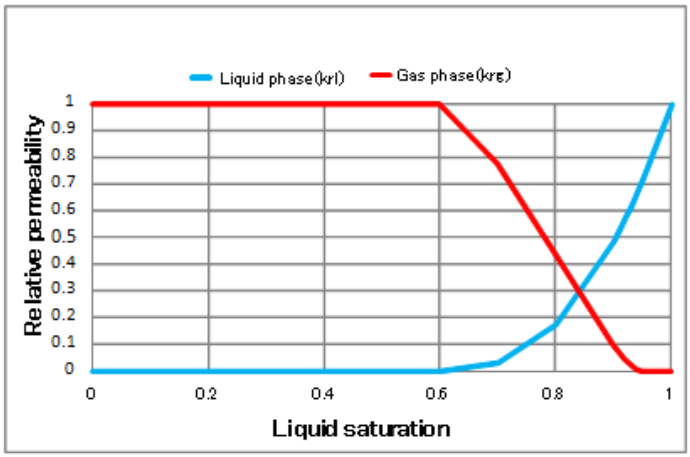


Figure 6 Relative permeability

3.2 Optimal model and recharge simulation

Calculation of the recharge simulation was conducted in parallel with the evaluation of the optimal model. Recharge simulation conditions are shown as below:

- Wellhead is set on the 10T pad (Fig.3).
- Maximum MD of the well is 2,500m.
- KOP＝200m and max inclination is 45deg.
- Feed point is located not to recharge in the same block of the present production wells
- Recharge location is shown by □ in Fig.7 based on the conditions above.

Table 2: Parameters for MINC model.

Parameter	Fracture	Matrix
Permeability	1.0～3.0E-14m^2	0.0～1.0E-25m^2
Porosity	0.1	0.001
Division number	1	1,4,8
Volume ratio	0.15	0.85
Frcature spacing	30×30×30m	-
Rock density	2.25g/cm^3	
Thermal conductivity	2.5W/m℃	
Specific heat	1000J/kg℃	
Relative permeability	Liquid:van Genuchten(irreducible water:0.6), Steam: Corey(irreducible gas:0.05)	
Capillary pressure	0	

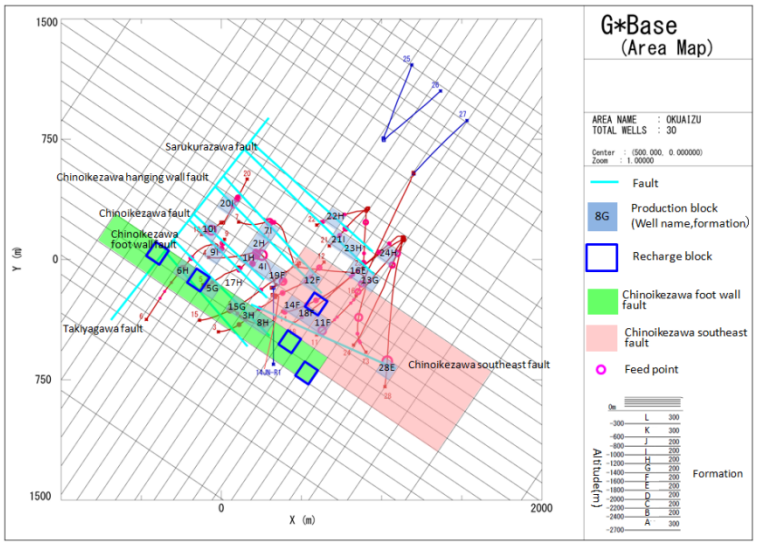


Figure7: Recharge block for the 3D recharge simulation (Plan view).

Nine recharge blocks were set up consisting of eight blocks in the Chinoikezawa footwall fault and one block in Chinoikezawa southeast fault which are important to see the recharge effect (Fig.7, Fig.8). Four recharge blocks from 1 to 3 are set in the same location (only the depth changes) of the Chinoikezawa footwall fault since we are interested in this area (a border between the Chinoikezawa footwall fault and the Chinoikezawa southeast fault). A base case without recharging was calculated using the optimal model. The recharge calculation was carried out and the effect evaluated by comparing with the base case. Recharge flow rates were set to 15 t/h, 30 t/h, 50 t/h, and 100 t/h and the temperature was assumed to be 15 °C in the simulation.

3.2.1 Optimal model

Since a MINC model was used, optimization of the model with regard to the grid size and the number of matrices was important for the recharge simulation. The optimal model was evaluated by the calculating the result of the cases to inject water in the block of 1.5, the block between 1 and 2(Fig.8), mainly.

The optimal model was determined by comparing the existing grid model (grid size X, Y= 100 m, Z= 200 m), a Z subdivision model (grid size X, Y= 100 m, Z= 50 m) and an all subdivision model (grid sizes XYZ= 50 m) with matrix subdivision number of 1, 4 and 8. In order to minimize the simulation time, we avoided the use of the whole 3D recharge model and only used the Chinoikezawa footwall fault model to determine the optimal model. Note it was confirmed that little difference on the results existed between the 3D recharge model and Chinoikezawa footwall fault model.

In the existing grid model (the block size X, Y= 100 m, Z= 200 m), some differences in the calculation results were observed between the matrix subdivision number 1 and the number of 4 and 8 (Fig.9). On the other hand, the calculation results of the matrix

subdivision number 4 and 8 were in good agreement with each other. So the results of the matrix subdivision number 1 was thought to be of insufficient precision.

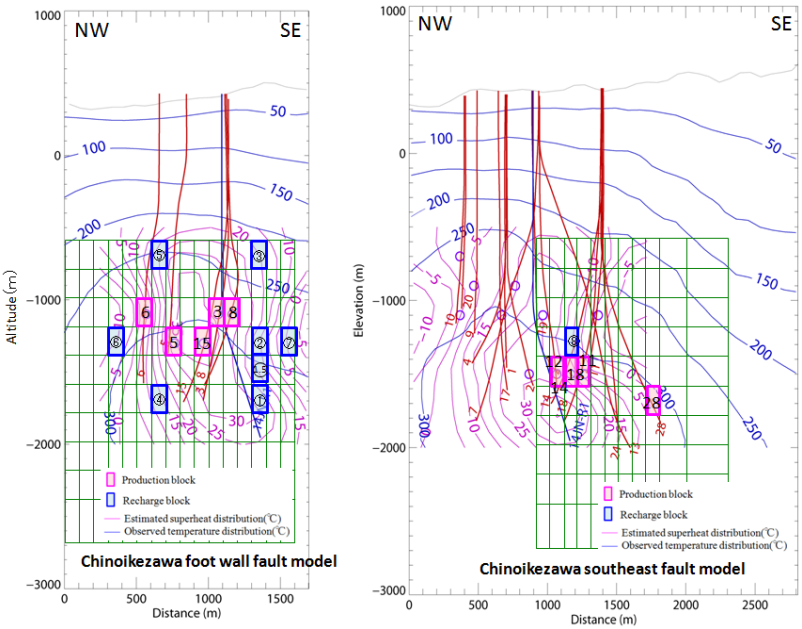


Figure8: Recharge block for the 3D recharge simulation (Cross section).

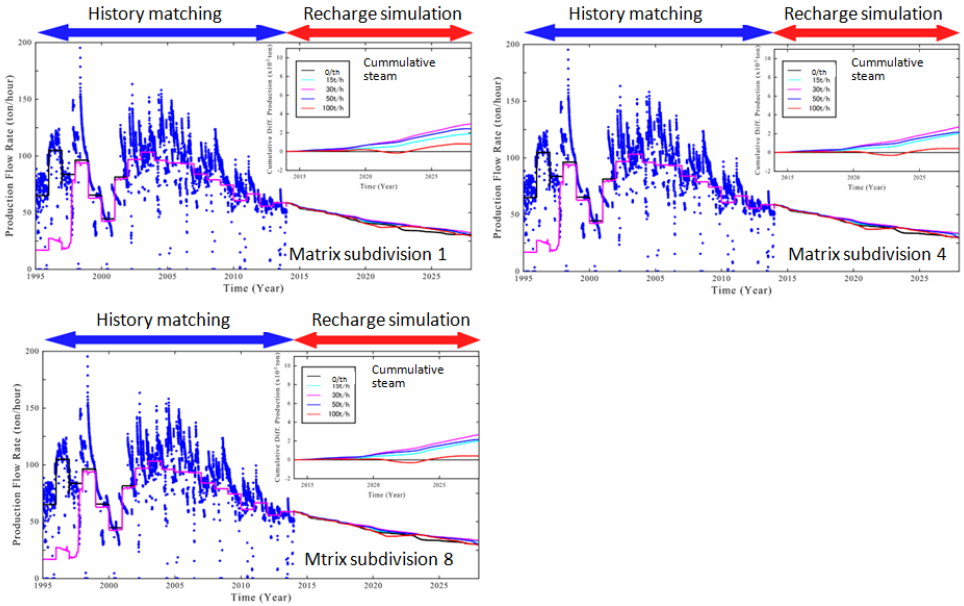


Figure9: Effect of matrix subdivision for the existing grid model (the block size X, Y= 100 m, Z= 200 m) .

In the Z subdivision model, a response differs between matrix sub-division number 1 and 4 (Fig.9). The result suggests that the matrix number is depends on the grid size. If the grid size becomes smaller, the matrix number can be selected to be smaller to maintain the same precision.

In the case of the matrix subdivision number 4 of the Z subdivision model, there is a small difference in the recharge effect with the existing grid model, clearly shown in Fig.10. The Z subdivision model seems to be require more matrix to blocks to obtain more precise results.

Examination of the recharge simulation by the grid subdivision has shown that the matrix division number should be increased when the subdivision of the grid increased. Although some simulation in the Z subdivision model and all subdivision models have not finished because of large computation time caused by increasing grid numbers, it is confirmed that the result between the existing grid model and finer models such as the Z subdivision model are consistent with each other. It is considered to be appropriate to use the recharge simulation results calculated with the matrix subdivision number 4 or 8 of the existing grid model to determine the recharge well location. Thus we decided to use the existing grid model with the matrix division number 8 as an

optimal model. Note although a value of Slr (irreducible water saturation) 0.6 is used, we confirmed there was little difference in the results between Slr=0.6 and Slr=0.3 for the recharge simulation.

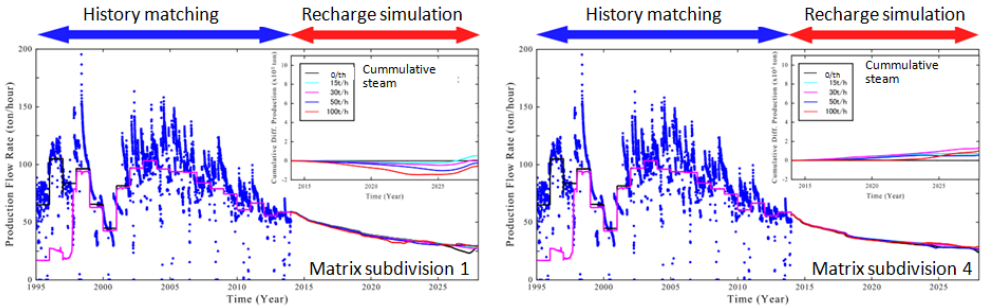


Figure10: Effect of matrix subdivision for the Z subdivsion model (the block size X, Y= 100 m, Z= 50 m) .

3.2.2 Recharge simulation

For this simulation, an increase in steam production was observed in all blocks except the recharge block 8 (Fig.11). An increase of steam was observed in the recharge blocks except for blocks 1 and 4. The recharge effect of block 3 (the shallowest recharge block) was found to be the largest. It was found that the effect tended to become smaller when the injection is deeper. The recharge effect is not necessarily proportional to the injection rate and the effect becomes less if larger amounts of injection occurred in a deeper section. The following phenomena can explain this. As a mechanism of the recharge effect, the fluid injected in the superheated region (single phase vapor) is vaporized by cold sweep, recovering the heat of the rock mass, and it is thought that this contributes to increase the steam flow rate. On the other hand, there exists a two phase zone in the deeper part of the production zone (superheated region) which contributes to the steam production. If a lot of injection fluid descends to the deeper region, the injected fluid becomes an obstacle to the flow of existing two phase flow and decreased steam flow rate as a whole.

Note the numerical model is built based on the present geothermal structural model and is calibrated with the observation data. The model will be improved as new information and/or knowledge is acquired by future investigations. Also the result of block 8 requires further consideration.

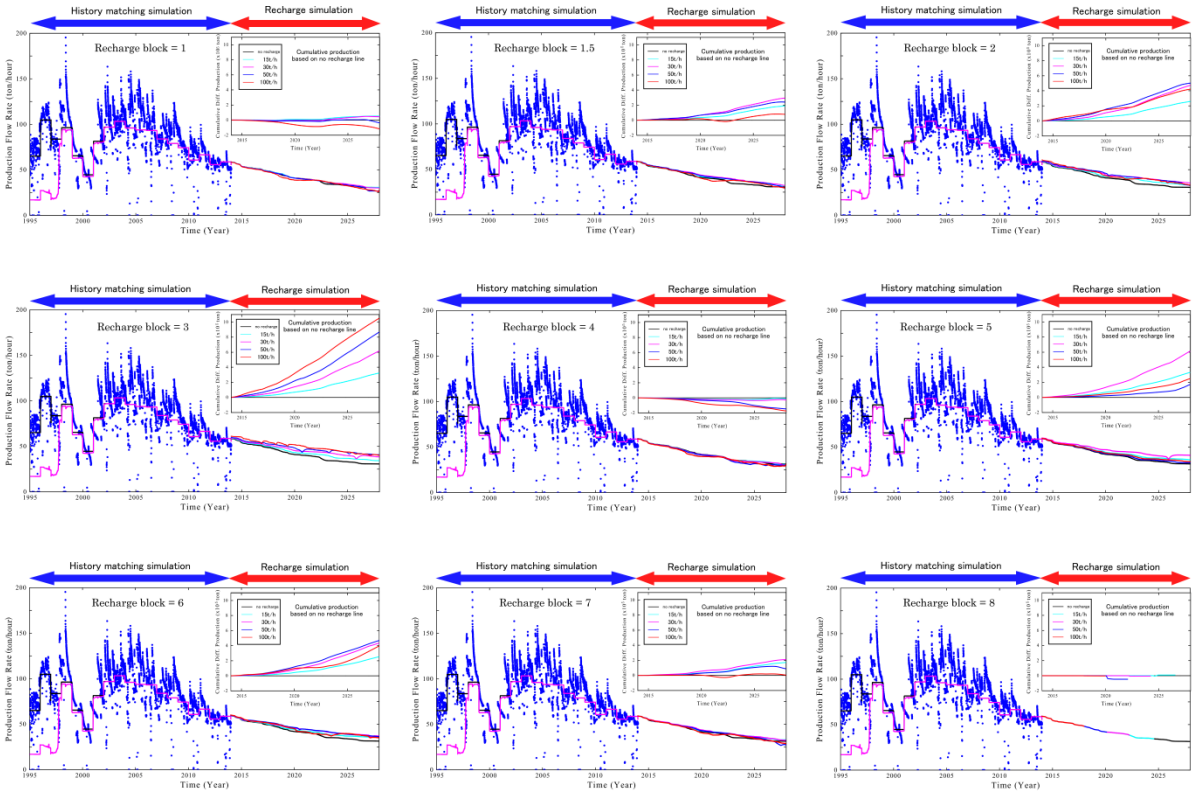


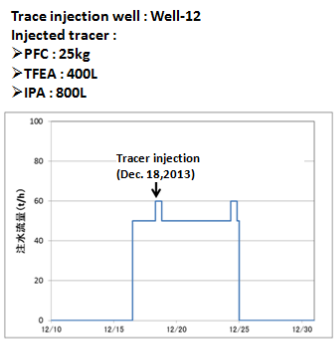
Figure11: Recharge simulation result.

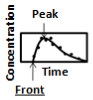
3.3 Risk evaluation

The location of the recharge well was also required to be meet a comprehensive evaluation based on drilling conditions such as drilling from 10T pad and toward to the superheated region, the recharge simulation above and risk evaluation described below.

3.3.1 Risk evaluation from tracer tests

The tracer test was carried out from December 17, 2013 to March 27, 2014 injecting tracer on December 18, 2013. Perfluorocarbon (PFC) as a gas tracer and 2,2,2-Trifluoroethanol (TFEA) and isopropyl alcohol (IPA) as two phase tracer were used. Tracer was injected from the well Well-12 and it was observed at 12 production wells (Well-1 to Well-11 and Well-13). Injection was carried out with a flow of about 50 to 60 t/h during the period from December 16 to 25, 2013. As a result of the tracer test, PFC was observed at all of the wells exceptWell-13, TFEA was observed at eight wells and IPA was observed at two wells, respectively (Fig.12). Of the 25 kg of PFC injected, 10.75 kg (about 43%) was recovered from production wells; and TFEA returned 340 kg (about 63%) from the production wells of 540 kg that was injected. TFEA is still being recovered at the end of February, 2014. This shows the phenomenon which the two phase tracer dissolved in the water (liquid phase) injected from Well-12 boiled and has revolved over a long period of time from the production well and it turns out that the recharge effect is still continuing. The tracer results of PFC and TFEA showed the interconnection among the faults of Chnoikezawa footwall, Chinoikezawa, Chnoikezawa hanging wall and Chinoikezawa southeast which were previously believed to have limited interconnectivity.

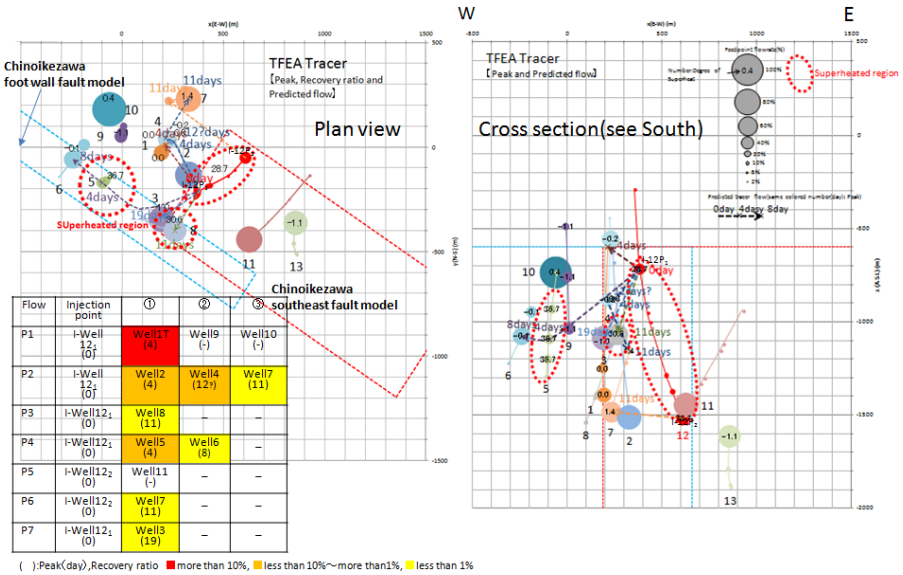




Well	PFC			TFEA			IPA		
	Front (Day)	Peak (Day)	Recovery (%)	Front (Day)	Peak (Day)	Recovery (%)	Front (Day)	Peak (Day)	Recovery (%)
Well1	<1	13	18.0	<1	4	30.2	<1	4	-
Well2	<1	17	8.7	<1	4	7.4	N	N	0
Well3	<1	11	10.5	<1	19	10.5	2	10	-
Well4	<1	12	2.6	<1	12?	4.4	N	N	0
Well5	<1	5	2.2	<1	4	9.2	N	N	0
Well6	<1	8	0.17	3	8	0.7	N	N	0
Well7	5	11	0.043	4	11	0.2	N	N	0
Well8	2	11	0.13	<1	11	0.8	N	N	0
Well9	12	18	1.0	N	N	0	N	N	0
Well10	50	50	0.002	N	N	0	N	N	0
Well11	8	8	0.008	N	N	0	N	N	0
Total(71Day)			43.4			63.4			-

Figure12: Tracer analysis result.

The tracer test result was analyzed in detail (Fig.13). There are two major feed points in the wellWell-12, the shallow one at -718masl and the deeper one at -1,516masl. PCF and TFEA injected from the shallow feed point of Well-12 were detected within one day at Well-1, 2, 3, 4 and 5 from the production wells in Chnoikezawa footwall, Chinoikezawa, Chnoikezawa hanging wall and Chinoikezawa southeast suggesting interconnection of the faults. PCF injected from the deeper feed point was detected eight days later and TEFA was not detected from the production well Well-11 in the Chinoikezawa southeast. The tracer test suggested that there the fractures flow quickly so that short circuit will occur and injection water from the shallow depths may cause severe influence on production wells locally (for example, Well-5).



Flow	Injection point	①	②	③
P1	I-Well 12₁ (0)	Well1T (4)	Well9 (-)	Well10 (-)
P2	I-Well 12₁ (0)	Well2 (4)	Well4 (12?)	Well7 (11)
P3	I-Well12₁ (0)	Well8 (11)	–	–
P4	I-Well12₁ (0)	Well5 (4)	Well6 (8)	–
P5	I-Well12₂ (0)	Well11 (-)	–	–
P6	I-Well12₂ (0)	Well7 (11)	–	–
P7	I-Well12₁ (0)	Well3 (19)	–	–

Figure13: TEFA tracer evaluation.

3.3.2 Risk evaluation from past field injection tests

The presumed interference paths are shown by arrows based on the local water injection tests in Fig14 and Fig.15. In the figures the red arrows show steam increase, blue show steam decrease/stopped production and purple show both effects. Although the injection

tests affected 21 production wells in Chnoikezawa footwall fault, the effect occurred mostly within the same fault. A plan view and sectional view projected on NE-SW are shown in Fig.14 and Fig.15 respectively. The presumed interference courses are shown by the same colored arrows as the plan view. Severe interference such as stopped production has occurred when production feed points are the same level of injection points or shallower. The results suggest that the fractures which cause a local short circuit exist in a shallow region of the reservoir.

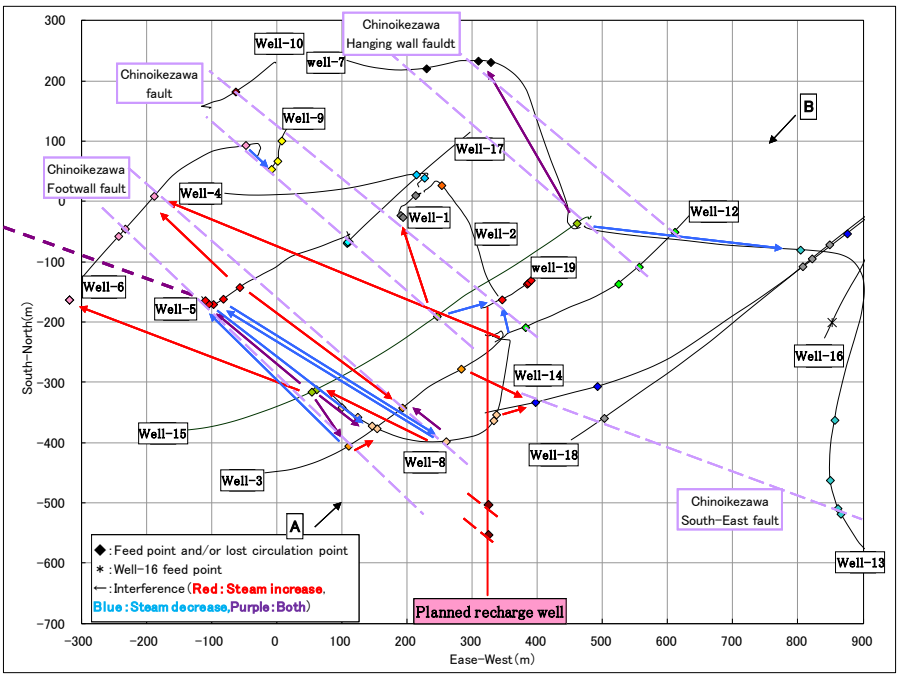


Figure14: Field injection test results(Plan view).

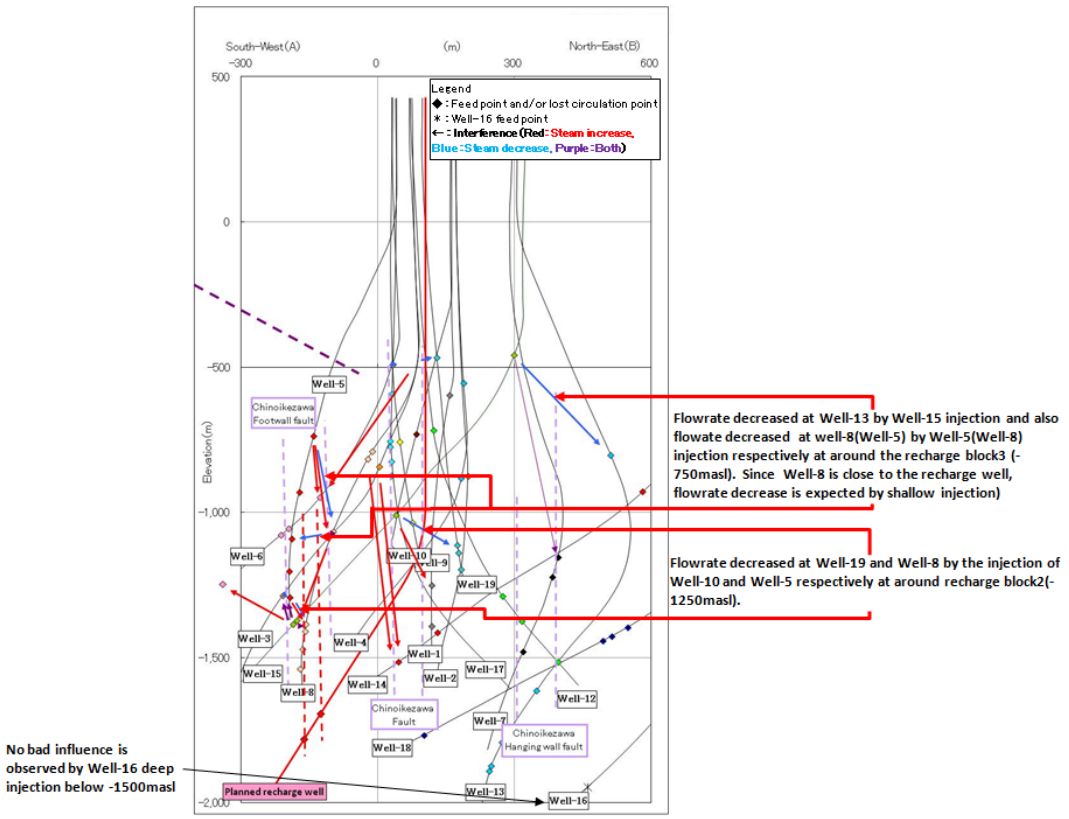


Figure15: Field injection test results(Cross section).

4. CONCLUSIONS

This paper presents the current status for the development of a technology for geothermal reservoir evaluation and control. The extensive recharge simulation including reproduction of the Okuaizu superheated geothermal reservoir in order to decide the recharge well target was reported. Results of the R&D project are summarized as follows:

- We successfully created a superheated reservoir following the production, as well as confirming the effect of artificial recharge into the superheated region through the extensive simulation study.
- Through the optimization of the recharge model, we found that if the grid size becomes smaller in MINC model, the matrix number can be selected to be smaller to maintain calculation precision.
- The recharge effect tends to become small when the injection depth is deeper. The recharge effect is not necessarily proportional to the injection rate and the effect became less if larger amounts of water are injected in the deeper section.
- Risk evaluation from the tracer test and the past field injection test suggest that there exist some fractures which lead to short circuits resulting in steam decrease and/or stopped production in the shallow parts of the reservoir.

In order to decide the location of the recharge well, we plan to conduct further recharge simulations beyond the nine blocks set above. We will also consider other simulations such as the Z subdivision model (grid size X, Y= 100 m, Z= 50 m) with matrix subdivision 8 and all subdivision model (grid sizes XYZ= 50 m) with matrix subdivision number of 1, 4 and 8. The location of the recharge well is going to be decided by the comprehensive analysis of the simulation and the risk evaluation.

Later in the year of 2014, the recharge well is going to be drilled and test injection is planned to start in early 2015 compiling an operation manual for the recharge.

REFERENCES

Capetti, G., Parisi, L. Ridolfi, A. and Stefani, G. : Fifteen years of reinjection in the Larderello-Valle Secolo area: Analysis of the production data. Proceedings of the World Geothermal Congress 1995, Florence, Italy, May, 1997-2000 (1995).

Matsunaga, I, Niitsuma, H. and Oikawa, Y : Review of the HDR Development at Hijiori Site, Japan, Proceedings World Geothermal Congress 2005, Antalya, Turkey, 24-29 April 2005.

Kaieda, H., Ito, H., Kiho, K. Suzuki, K. Suenaga, H. and Shin, K. : Review of the Ogachi HDR Project in Japan, Proceedings World Geothermal Congress 2005, Antalya, Turkey, 24-29 April 2005.

New Energy Development Organization, Geothermal development research report. No.8. Okuaizu region (in Japanese) (1985).

Nitta, T., Suga, S., Tsukagoshi, S. and Adachi, M. Geothermal resources in the Okuaizu, Tohoku district, Japan., Chinetsu24, 26-56 (in Japanese) (1987).

Nitta, T., Suga, S., Tsukagoshi, S. and Saiki, K. : Recent development of geothermal energy in the Okuaizu field, Fukushima prefecture. Annual Meeting Geotherm. Res. Soc. Japan Abst., D-14 (in Japanese) (1990).

Pruess, K. and Enedy, S. : Numerical modeling of injection experiments at the Geysers, Proceedings - Workshop on Geothermal Reservoir Engineering 26-28 (1993).

Pruess, K., Oldenburg, C. and Moridis, G. : TOUGH2 USER'S GUIDE, VERSION 2, Lawrence Berkeley National Laboratory Report, LBNL-43134 (1999).

Seki, Y. : The physical and chemical structure of the Oku-aizu geothermal system, Japan, Geochemical Journal, Vol. 25, pp. 245 - 265 (1991).

Sanyal, K. and Enedy, S. : Fifty Years of Power Generation at the Geysers Geothermal Field, California; the Lessons Learned., Proceedings - Workshop on Geothermal Reservoir Engineering 191 (2011).

Vedova, B. D., Claudio Vecellio, C., Stefano Bellani, S., and Tinivella, U. : Thermal modelling of the Larderello geothermal field (Tuscany, Italy), Int J Earth Sci (Geol Rundsch) (2007).