PROCEEDINGS, Thirty-Sixth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 31 - February 2, 2011
SGP-TR-191

DEVELOPMENT OF THE OPTIMUM NUMERICAL RESERVOIR MODEL OF THE TAKIGAMI GEOTHERMAL FIELD, OITA, JAPAN

Saeid Jalilinasrabady[1], Ryuichi Itoi[1], Hiroki Gotoh[2], Toshiaki Tanaka[1]

[1]Department of Earth Resources Engineering, Faculty of Engineering, Kyushu University, Fukuoka 819-0395, Japan
[2]Idemitsu Kosan Co. Ltd., Tokyo, Japan
e-mail: jalili@kyudai.jp

ABSTRACT

The natural state model was developed in the Takigami geothermal field, using TOUGH2 simulator. Conceptual model of the field was constructed as well as numerical model. The rock types were assigned to each grid block in several layers. Initial and boundary conditions were defined according to available data.

For the optimum model, permeability values of assigned rock types, mass flow rates, enthalpies and locations of recharge zones were estimated according to matching between computed temperature for wells and their temperature profiles before the exploitation. Observed and calculated temperature profiles confirmed the validity of the conceptual model and provided the first stage of calibration of the numerical model. Developed three dimensional model was calibrated by using iTOUGH2 simulator. The best model could successfully reproduce the initial temperature profiles of 13 wells located mainly in production area.

INTRODUCTION

The Takigami geothermal field is located in the southwestern part of Oita prefecture, Kyushu Island, Japan. Central Kyushu is cut by a volcano-tectonic depression that has developed within a tensile stress field since the Neogene, resulting in Plio-Pleistocene to recent volcanism (Hase et al., 1985). The northeastern part of Central Kyushu, known as the Hohi region, is one of the most active geothermal areas of Japan (Figure 1). Although the Takigami system lies within the very active Hohi geothermal region, there is no surface manifestation in the immediate area. The nearest hot springs are located 1-2 km north and east of the area. (Furuya et al., 2000). Geothermal exploration in the Takigami area was started in 1979 with various surveys and drilling.

In and around the Takigami area, gravity and electromagnetic prospectings have been conducted since 1979, while resistivity logging began in 1981 (Aoki, 1988). These surveys confirmed the existence of three main layers in the resistivity structure of field that extends laterally in the area. The intermediate layer has an extremely low resistivity, while the bottom layer has relatively high resistivity. The second, conductive layer is shallow and thin in the east and deepens and becomes thicker to the west (Furuy et al., 2000).

A geochemical model of the Takigami area was discussed by Takenaka and Furuya (1991). Relatively low salinity and the low non-condensable gas concentration in steam characterize the Takigami geothermal fluids (Furuy et al., 2000). Fairly good estimates of reservoir parameters were obtained by analyzing pressure interference tests on the basis of an infinite reservoir model for wells by Itoi et al. (1993).

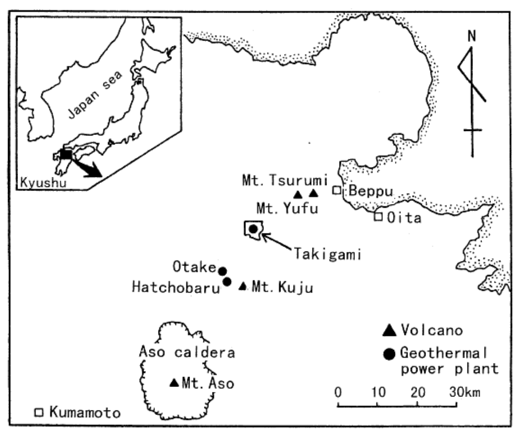


Figure 1: Map of the Hohi geothermal region, northeast Kyushu, showing the location of the Takigami area, the major Quaternary volcanoes and the Otake-Hatchobaru geothermal area (Furuya et al., 2000).

Gotoh (1990), stated that a production of 1850 t/h of geothermal fluid should be able to be maintained for more than 30 years with small decreases in reservoir pressure and temperature in the production zone.

The Takigami power station started an operation in November 1996 with installed capacity of 25 MW, its produced power has been increased to 27.5 MW since June 2010. Five production wells are located in the southwest; seven to ten reinjection wells in the north of the field. Idemitsu Oita Geothermal Co., Ltd is in charge of production and reinjection operations and supplies separated steam to the power station that is operated by Kyushu Electric Power Co., Inc.

A three dimensional numerical reservoir model of Takigami was developed by inverses analysis method and discharged enthalpies from production wells during about 11 years in the exploitation history (Nakatani et al., 2007). A wellbore flow model was coupled the numerical reservoir model in order to improve the model (Hozumi, et al., 2009).

In an attempt to achieve more improved model using previous experiences a new numerical model for the Takigami geothermal field is under development. The simulation with the objective of developing of natural state model of the field was carried out using the TOUGH2 computer code (Pruess, et. al., 1999).

Conceptual model of the field was constructed as well as numerical model. The rock types were assigned to each block in several layers. Initial and boundary conditions were defined according to existence data. Model validation was conducted by matching available downhole temperature (Jalilinasrabady, et. al., 2010). This requires running the models to steady state and comparing the simulated data with the known or interpreted conditions in the system (Noorollahi et al., 2008). This is an iterative process that continues until a good match is obtained and requires changing model properties, such as permeability, rock density, specific heat capacity and inflow/outflow conditions. With every set of reservoir properties, vertical heat flow and temperature distribution in each layer were also analyzed using Mulgraph (O'Sullivan, 1995). Developing a reliable numerical reservoir model using this method is time consuming. The objective of this study is to develop a numerical model of Takigami geothermal field by inverse analysis method.

CONCEPTUAL MODEL

The Takigami area is surrounded by the late Pleistocene volcanoes in the Beppu-Shimabara Graben, which traverses middle Kyushu from east to west. This water-dominated field is characterized by the absence of surface geothermal manifestation such as hot spring and fumarole. There are a number of E-W, NW-SE, and N-S trending faults and fractures (Figure 2).

The N-S trending Noine fault is important because it divides the area into eastern and western parts. The E-W trending faults such as the Teradoko fault are estimated to have a small vertical displacement. High permeability zone and feed zone of the wells appear along these fault sets (Hayashi et al., 1988).

Geological structure of the Takigami geothermal field is as follows (Hayashi et al., 1988). A thick layer of Quaternary volcanic and associated rocks overlies the Tertiary Mizuwake Andesite, which is estimated to overlay the basement. The Quaternary volcanic rocks are classified into four formations from top to bottom, the Noine-dake volcanic rocks, Kusu, Ajibaru and Takigami formations. These units consist of layers of andesitic and dacitic volcanic rocks. Mizuwake andesite is composed mainly of altered andesite lava flows and pyroclastic rocks.

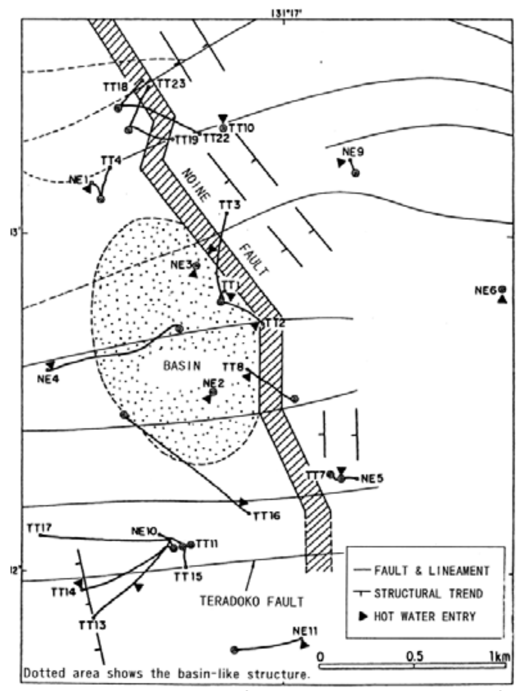


Figure 2: Location of Takigami geothermal field and conceptual geological structure.

The thermal structure of this field is basically composed three layers (Furuya et al., 2000). The first layer is isothermal (50°C). The second layer is impermeable and has a steep and constant thermal gradient. The third layer is characterized by high temperature that ranges from 160°C in the northeast to 250°C in the southwest.

The geothermal reservoir corresponds to the same layer for production and reinjection, but communication between them is small due to the low permeable zone suggested from the interference tests of wells. The low permeable zone is estimated to be located on the northeastern side of the Noine fault (Figure 3).

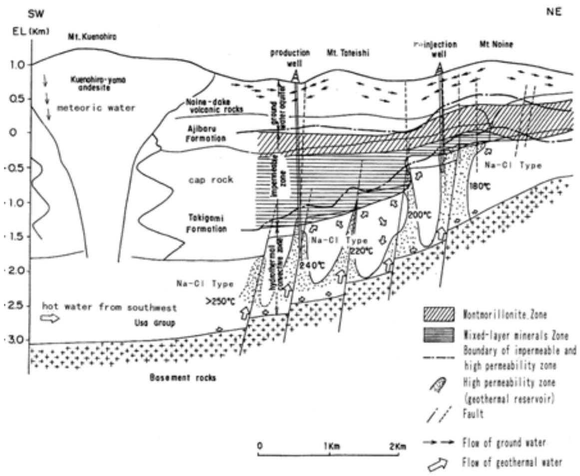


Figure 3: Schematic cross-sectional model of the Takigami geothermal system (modified from Takenaka and Furuya, 1991).

NUMERICAL SIMULATION

An automatic calibration of a numerical model is inversion technique, iTOUGH2, is an optimization code that allows estimation of any input parameters of the nonisothermal, multiphase flow simulator TOUGH2 (Finterle et al., 1997). The iTOUGH2 code allows us to estimate TOUGH2 input parameters based on any type of observation for which a corresponding simulation output can be calculated. At the same time iTOUGH2 carries out a residual and error analysis that allows us to choose an optimum model. This simulator systematically modifies the values of a small set of parameters and uses mathematical optimization techniques to improve the match to the field data. The process requires a selection of parameters to be adjusted (i.e. to construct the objective function, Finsterle et al., 1999).

According to available literatures about the Takigami geothermal field and on the basis of undertaken studies about its conceptual model, a three dimensional numerical model was developed. The model was calibrated using try and error method based on available data from natural state conditions of reservoir to obtain good match. Results of this matching were used as a initial parameters for inverse modeling.

The iTOUGH2 allows us to simulate both natural state simulation and exploitation history. These simulations are carried out sequentially in a single run of iTOUGH2 (Finsterle, 2000). However, this method may take a long computing time to achieve optimum values of parameters. In order to solve this problem, natural state simulation was conducted in this study, firstly. Then, both natural state and exploitation history was simulated sequentially using estimated parameters of natural state simulation as initial conditions.

Grid system and layers

A grid system was assigned for modeling purpose. The grid system covers the square area of 9.6 km by 9.6 km with 3 km depth below sea level (b.s.l) (Figure 4). The model consists of 12 horizontal layers, thickness of layers varies with steps of 200 m to 800 m. Surface elevation was taken into account by layers bb and cc with thickness of 300 m and 200 m respectively, below sea level layers dd, ee, ff, gg and hh are 200 m and layers ii, jj and kk are 400 m, and ll is the bottom layer with 800 m thickness. Each layer has 414 grid blocks with various sizes of 2400×2400m, 2400×800m, 2400×400m, 2400×200m, 800×800m, 400×800m, 200×800m, 200×400m, and 400×400m, finer grids with size of 200×200m were assigned for the area that covers wells and power plant locations. The codes Mulgeom and Mulgraph (O'Sullivan et al., 1995) were used as pre-and post-processor.

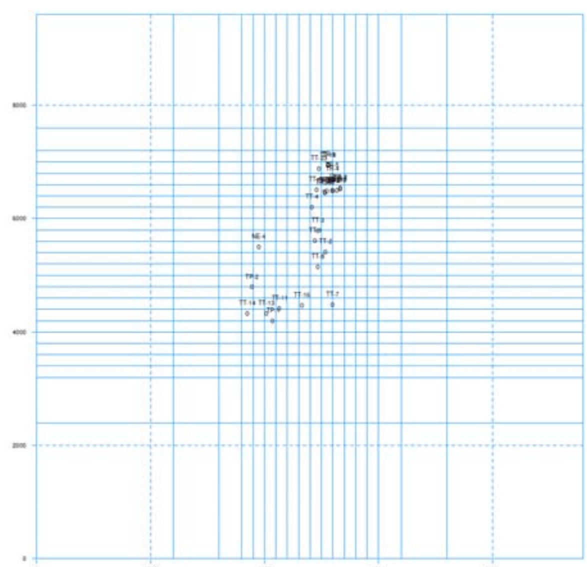


Figure 4: Grid system of the model.

Rock properties

Density, permeability, thermal conductivity, porosity and specific heat were taken into account as rock properties. The model input file requires rock properties as a given data, these data were provided according to available information on geology, reservoir system, faults situations. Permeability values play very important role in order to achieve most realistic model. Each layer of grid system was divided to zones with different permeability values according to available data. Initial estimates of rock properties were made according to conceptual model, locations of main faults, low and high permeable zones and previous models to reproduce hydrogeological characteristics of subsurface formation.

Table 1: Initial rock parameters.

Rock type	Permeability (m^2)		Thermal Conduct. (W/m^2K)
	K_{XY}	K_Z	
ATM (A_T)	1.00E-10	1.00E-10	3.0
NVR (N)	1.00E-14	1.00E-12	3.9
KLY (K)	1.00E-14	1.00E-15	2.6
LOW (L)	1.00E-18	1.00E-19	2.6
ALY (A)	1.00E-16	1.00E-17	2.5
MED (M)	1.00E-13	1.00E-14	3.6
MED1 (M_1)	1.30E-12	5.00E-14	1.3
MED2 (M_2)	1.00E-14	1.00E-15	1.3
MED3 (M_3)	7.90E-15	3.20E-15	2.1
UTL (U)	1.00E-15	1.00E-13	1.5
LTL (L_T)	1.00E-13	1.00E-16	2.3
MAL (M_A)	1.00E-14	1.00E-16	4.0
UHW (U_H)	2.00E-12	5.00E-14	1.8
UBAS (U_B)	1.00E-14	1.00E-15	2.0
LBAS (L_B)	1.00E-13	1.00E-15	2.7

Initially 18 rock types were applied to whole reservoir; and Table 1 summarizes these rock types, their abbreviation and the permeability values in each direction after simulation. A reason for large number of rock types was to investigate the sensitivity of each layer and each zone, especially in the central part of the model which covers the power station and all wells. Some of the rock types in Table 1 have similar permeability values; they didn't have equal initial values, but as a result of optimization they ended up with same permeability values. This method was very useful to understand the system sensitivity to each layer and each zone.

Table 2: Rock types in each layer of the model.

Layers	Rock Types
bb	N, M_1
cc	K, M_1, M_A
dd	A, M_1, M_A
ee	A, U, M_2, M_A, M_1, M
ff	U, L, M_A, M_1, M
gg	L_T, L, M_A, M_1, M
hh	L_T, M_A, U_B, L, M_3, M_1, M
ii	M_A, L, U_B, M_1, M_3, M
jj	M_A, L, M_1, U_B, M_3, M
kk	L_B, U_H

Permeability values vary between 9.20×10^{-21} m^2 and 1.00×10^{-12} m^2. The rock types of MED, MED2 and MED3 represent high permeable zone such as Noine fault. Table 2, shows the distribution of rock types in different layers. Porosity was specified to 10% of all rock types and density of 2500 kg/m^3 was assigned to all rock types.

Calibration of the model

The objective of natural state simulation is to reproduce the initial temperature and pressure distributions before any exploitation. The numerical simulations of the model should be carried out over a long time that allows the geothermal system to be equilibrated. This involves running the simulation until approximately steady conditions are obtained which takes a simulation period for about 1 million years (Nakatani et. al, 2007). The results of natural state simulation were compared with the measured temperature data from 20 wells. Estimated parameters were permeablities, flow rates and enthalpies of recharges.

As for initial conditions, it was assumed that all grids were saturated with 15ºC water and pressure equilibrated. The cap rock was assigned to the lowest initial permeability of 1.0×10^{-18} m^2, while the maximum initial permeability was amounted to be 2×10^{-12} m^2. The thermal conductivities were assigned in a range from 1.3 to 4.o W/m^2K.

Table 3: Rock parameters in final model.

Rock type	Permeability (m^2)		Thermal Conduct. (W/m^2K)
	Kxy	Kz	
ATM (A_T)	1.00E-10	1.00E-10	3.0
NVR (N)	1.50E-14	3.90E-15	3.9
KLY (K)	8.80E-17	3.60E-15	2.6
LOW (L)	9.20E-21	2.70E-20	2.6
ALY (A)	8.50E-16	1.60E-20	2.5
MED (M)	6.10E-14	3.30E-13	3.6
MED1 (M_1)	4.80E-16	1.30E-14	1.3
MED2 (M_2)	5.60E-14	6.80E-13	1.3
MED3 (M_3)	1.80E-15	1.90E-13	2.1
UTL (U)	3.20E-15	8.40E-18	1.5
LTL (L_T)	1.50E-15	1.00E-19	2.3
MAL (M_A)	1.30E-15	1.40E-14	4.0
UHW (U_H)	1.00E-12	3.80E-15	1.8
UBAS (U_B)	1.00E-14	3.60E-16	2.0
LBAS (L_B)	1.20E-15	4.40E-16	2.7

Constant temperature of 15ºC and pressure of 0.879 bar were applied to the layer above the top layer as a boundary condition. Peripheries of the model were assumed to be impermeable to mass and adiabatic to heat. The bottom layer (kk) was assigned two recharge zones. High temperature fluid recharge (R1), was given to the south east of finer grids of model, another recharge (R2), was assigned to the west of finer grids of model's bottom layer.

History matching was conducted using production and reinjection data of 10 years of field operation. Estimated parameters of permeability and recharge flowrates with their enthalpies were modified. Table 3, summarizes the estimated values of permeabilities. Fluid recharges are calculated to be 12 kg/s with enthalpy of 946 kJ/kg for R1 and 15.7 kg/s with enthalpy of 1110 kJ/kg for recharge R2. A heat flux of 80 mW/m^2 was given to all grids of bottom layer. Figure 5, shows the initial and estimated values of rock types in the model.

SIMULATION RESULTS

The constructed model was evaluated in iterative manner in order to create the initial conditions. Available subsurface data plays an important role to build up more realistic conceptual model. A model was evaluated with matching of the natural state conditions in the system. As mentioned before, the permeability values were key parameters to be adjusted after each run of the model.

According to suggested conceptual model modified from Takenaka and Furuya (1991), the subsurface fluid probably flows from southwest to northeast, and maintains chemical and thermal equilibrium with alteration minerals. The heat flow pattern was one of the criteria to be taken into account in each run, in order to confirm the flow directions. An attempt was made to create surface discharges in the northern and eastern parts of the field, there was relatively good match between available data and the best model.

Temperature distribution in each layer was also one of the parameters to be taken into account parallel with matching of measured temperature from the wells and computed results. The magnitude and locations of recharge zones were also adjusted in order to achieve satisfactory match.

The measured well data from the Takigami geothermal field was compared with computed temperature profiles. Appendix I, compares measured and simulated temperature profiles of ten wells. These plots were produced using calculated values of both the optimum and initial models. Relatively good match were observed for Well TT-1, TT-2, TT-3, TT-4, TT-8, TT-13, TT-14, TT-16 and NE-4. Well NE-5 located to the east of Noine fault also shows a good match except at depth of -100 m.b.s.l. The model can successfully reproduce the temperature profiles of 13 wells in general.

CONCLUSIONS

A numerical model of the takigami geothermal field was constructed by inverse analysis method. Parameters such as permeabilities, flow rates and enthalpies of recharges have been estimated. The best model can successfully reproduce the initial temperature profiles of 13 wells with natural state simulations. Recharges zones were estimated to be 12 kg/s of 946 kJ/kg and 15.7 kg/s of 1110 kJ/kg at two different locations.

ACKNOWLEDGMENT

Authors thank Idemitsu Oita Geothermal Co. for permission to publish their data. Thanks are also extended to the geothermal Institute of the University of Auckland for permission to use MULGRAPH. The authors would like to extend their gratitude to GCOE program "Novel Carbon Resource Sciences", Kyushu University.

REFERENCES

Aoki, M., (1988). "Geophysical exploration at Takigami geothermal field in Oita Prefecture, Japan", *Abst., Int. Geothermal Symp*., Kumamoto and Beppu, Japan 567-568.

Finsterle, S., Pruess, K, Bullivant, D.P., O'Sullivan, M.J. (1997). "Application of inverse modeling to geothermal reservoir simulation". *Proc. Twenty-Second Workshop on Geothermal Reservoir Engineering Stanford University*, California, 309-316.

Finsterle, S., Pruess, K (1999). "Automatic Calibration of Geothermal Reservoir Models through Parallel Computing on a Workstation Cluster". *Proc. Twenty Forth Workshop on Geothermal Reservoir Engineering Stanford University, California*, 123-130.

Finsterle, S (2000) iTOUGH2 User's Guide, Earth Sciences Division Lawrence Berkeley National Laboratory.

Furuya S., Aoki M., Gotoh H. and Takenaka T., (2000), "Takigami geothermal system, northeastern Kyushu, Japan", *Geothermics* 29, 191-211.

Gotoh, H., (1990), "Reinjection plan in Takigami geothermal field, Oita Prefecture, Japan", *Geothermal Resources Council Trans.* 14 (2), 897-899.

Hase, H., Ogawa, K. and Kimbara, K. (1985), "Research in the Hohi geothermal area: outline and summary", *Rept. Geol. Survey Japan No. 264*, pp. 13-25 (in Japanese with English abstract.

Hayashi, J., Motomatsu, T., and Kondo, M. (1988), "Geothermal resources in the Takigami geothermal area, Kyushu, Japan", *CHINETSU*, Vol.25, No2, 112-137 (in Japanese with English abstract).

Hozumi, S., Itoi, R., Tanaka, T. and Gotoh, H. (2009), "Development of Numerical Model of Takigami Geothermal Reservoir, Oita, Jaoan, Incorporated with Wellbore Flow Simulation", *proceedings*, International Symposium on Earth Science and Technology, Fukuoka, Japan.

Itoi, R., Fukuda, K., Jinno, K. and Gotoh, H., (1993). "Interference Test Analysis at the Takigami Geothermal Field, Japan", *Proceedings*, Eighteenth Workshop on Geothermal Reservoir Engineering, Stanford University.

Jalilinasrabady, S., Itoi, R., Gotoh, H., Tanaka, T., (2010). "The Natural State Numerical Model of Takigami Geothermal Reservoir, Oita, JAPAN." *Proceeding, Thirty-Fifth Workshop on Geothermal Reservoir Engineering.* Stanford University, Stanford, California.

Nakatani, A., Itoi, R., Gotoh, H. and Tanaka, T., (2007), "Development of Numerical Model of Takigami Geothermal Reservoir, Kyushu, Japan, Using iTOUGH2 Simulator", *Proceedings*, 29th NZ Geothermal Workshop.

Noorollahi, Y. and Itoi, R. (2008), "Numerical Simulation for Development Scenarios of NW-Sabalan Geothermal Reservoir, IRAN," *Proceedings, Thirty-Third Workshop on Geothermal Reservoir Engineering, Stanford University.*

O'Sullivan, M.J., Bullivant, D.P., (1995), "A Graphical Interface for the TOUGH Family of Flow Simulators", Proceedings of the TOUGH Workshop 1995, Lawrence Berkeley Laboratory *Report LBL-37200*, Berkeley, CA, USA, 90-95.

Pruess, K., Oldenburg, C., Moridis, G., (1999), "TOUGH2 User's Guide, Version 2.0", Lawrence Berkeley National Laboratory, *Report LBNL 43134*, Berkeley, CA, USA, p. 197.

Takenaka T. and Furuya S., (1991), "Geochemical model of the Takigami geothermal system, northeast Kyushu, Japan", *Geochemical Journal*, Vol.25, pp. 267-281.

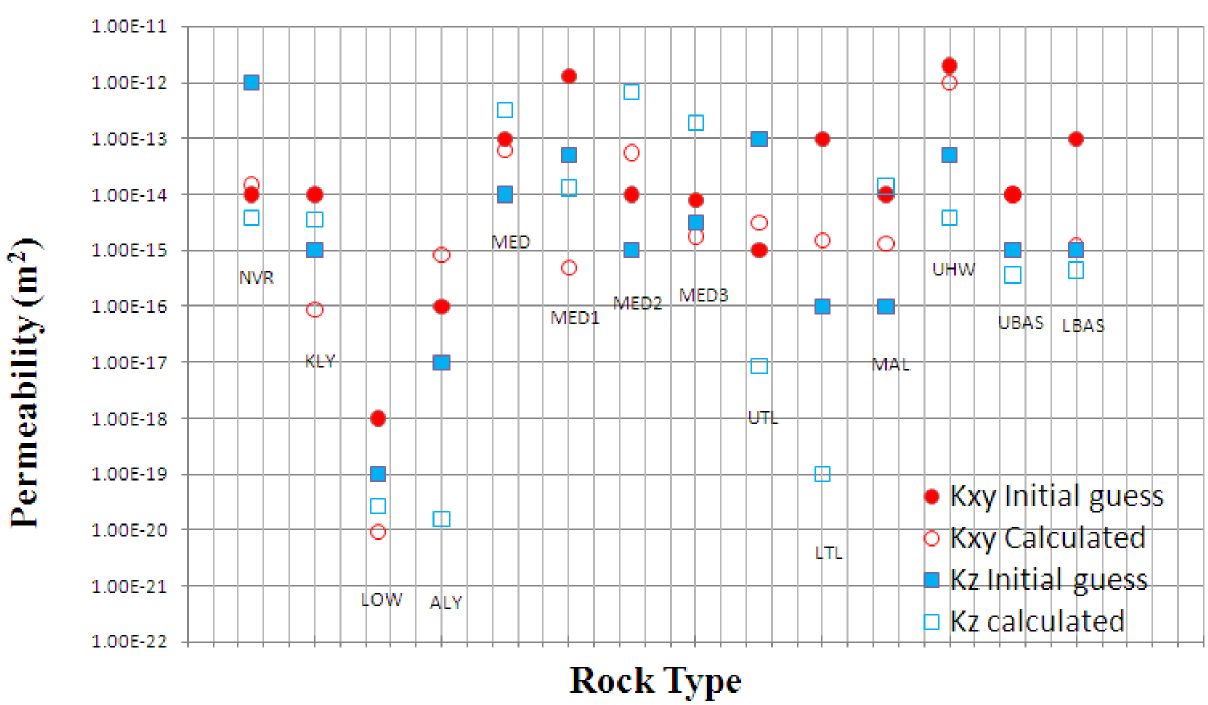
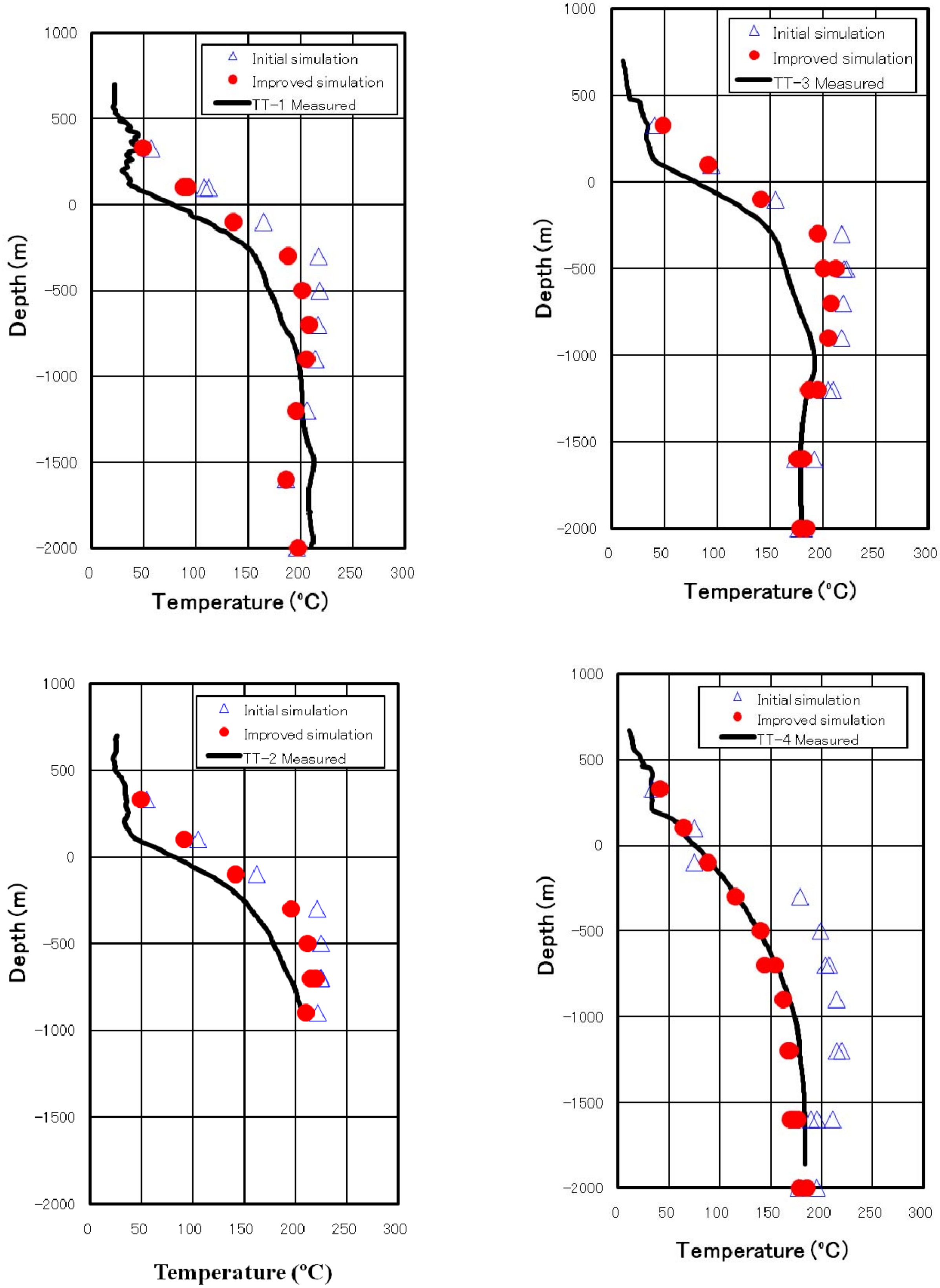
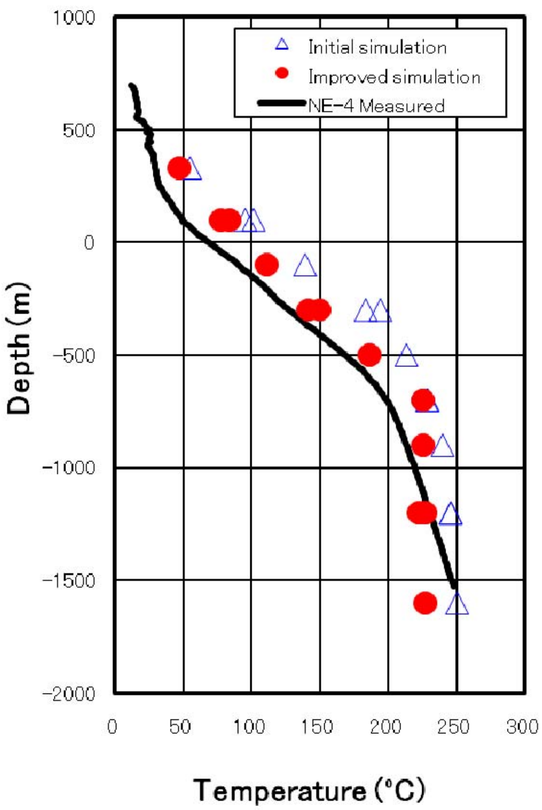
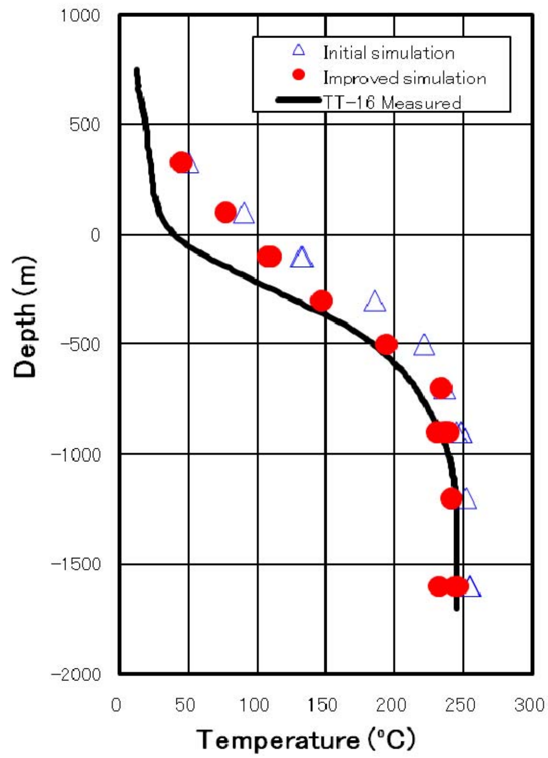


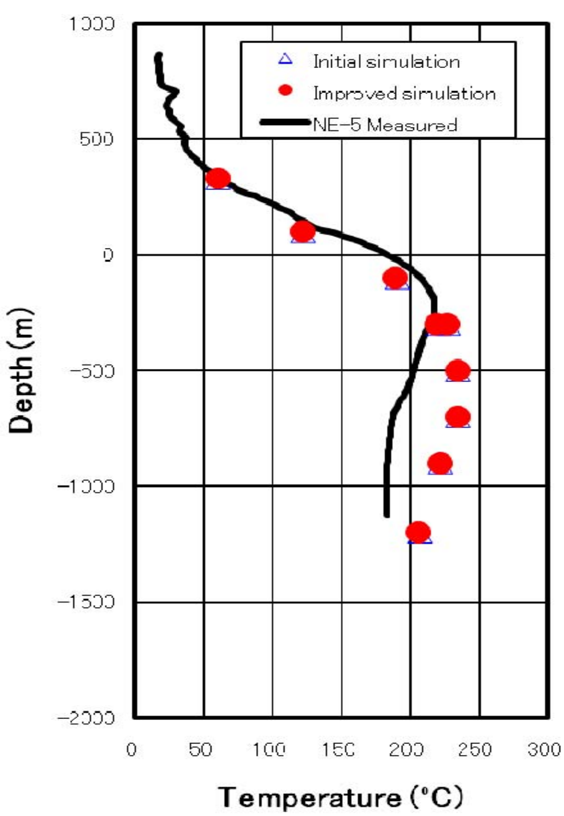
Figure 5: The initial and estimated values of rock types in the model.

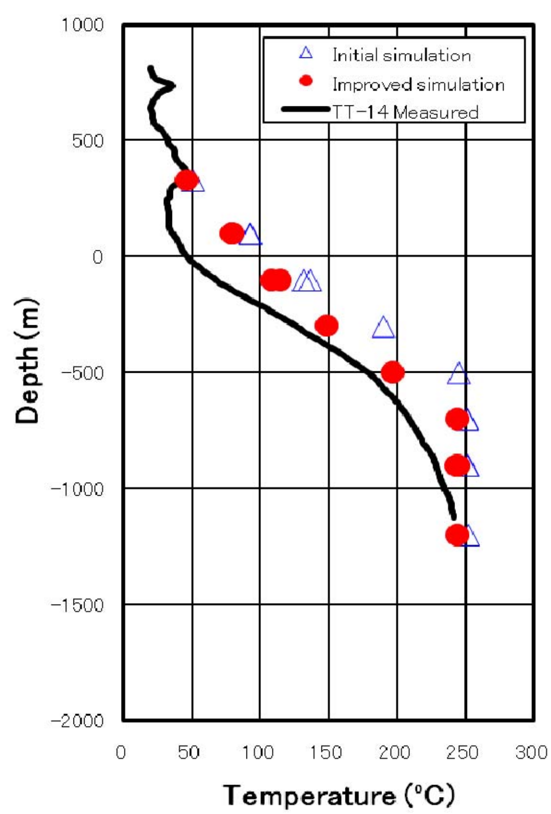
Appendix I: Comparison between measured and simulated temperature profiles.

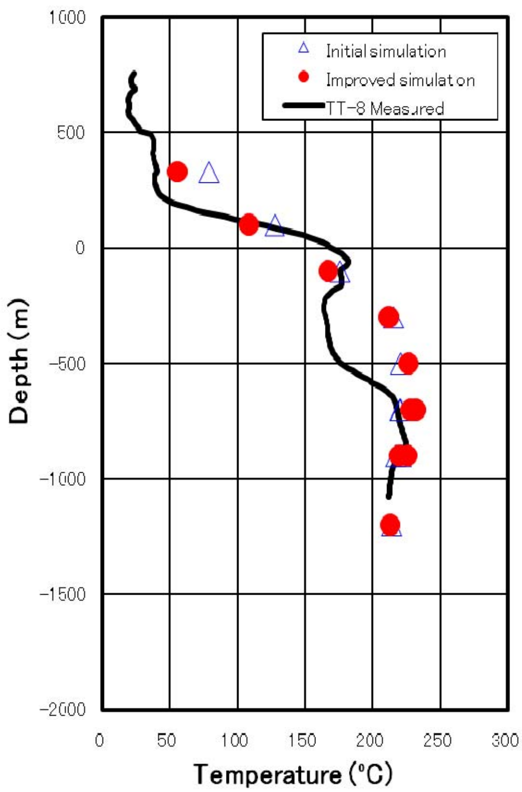



Initial simulation
Improved simulation
NE-4 Measured
Depth (m)
Temperature (°C)

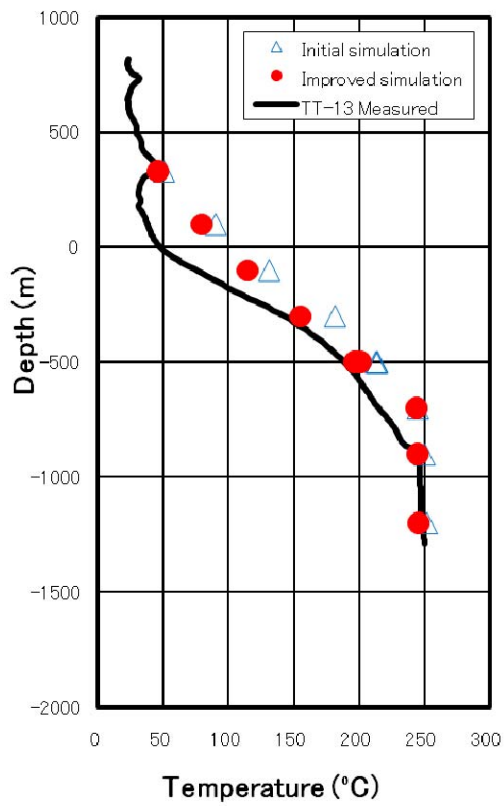

Initial simulation
Improved simulation
TT-16 Measured
Depth (m)
Temperature (°C)


Initial simulation
Improved simulation
NE-5 Measured
Depth (m)
Temperature (°C)


Initial simulation
Improved simulation
TT-14 Measured
Depth (m)
Temperature (°C)



1000
500
0
-500
-1000
-1500
-2000
0
50
100
150
200
250
300
Depth (m)
Temperature (°C)
Initial simulation
Improved simulation
TT-8 Measured



1000
500
0
-500
-1000
-1500
-2000
0
50
100
150
200
250
300
Depth (m)
Temperature (°C)
Initial simulation
Improved simulation
TT-13 Measured