Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

MODELING STUDIES OF SIBAYAK GEOTHERMAL RESERVOIR, NORTHERN SUMATRA, INDONESIA

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Key Words: Sibayak geothermal field, conceptual model, numerical simulation

ABSTRACT

The Sibayak geothermal field is located in the Singkut caldera. Exploration surveys conducted at the field since 1989 indicated at least 4.5 km^2 of prospective reservoir area. Geologically, the field consists of altered volcanic rocks in the shallow zone from the surface down to about 1150 m depth and meta-sedimentary rocks in the deeper zone. Main water loss zones of high temperature are present at the boundary of these zones and extend along fault systems. A conceptual reservoir model of Sibayak is proposed using data from ten exploration wells; high temperature fluid flows up in a zone beneath Mt. Sibayak and flows laterally southeast toward the caldera rim. A numerical simulation of the natural state of Sibayak was carried out. The simulated results successfully explained both the fluid flow pattern of the conceptual model and measured temperatures in wells.

1. INTRODUCTION

The Sibayak geothermal field is located in North Sumatra province, Sumatra Island (Figure1). The field lies inside the Singkut caldera at elevations between 1400 and 2200 m and there are three active volcanoes: Mt. Pintau (2212 m), Mt. Sibayak (2090 m) and Mt. Pratetekan (1844 m).

Preliminary studies over an area of 20x20 km including Mt. Sibayak were carried out during 1989 to 1991. The result of these studies suggested a potential area for further prospecting near Mt. Sibayak. Reservoir assessment studies, including natural state modeling using the data from three exploration wells, indicated a potential of producing steam for power generation of 39 MW(e) for 30 years for the proven area of 4.5 km^2 (Pertamina, 1994). By 1997, seven additional exploration wells had been drilled in the same area to understand the thermal structure of the reservoir in detail and to confirm the presence of an upflow zone.

In this paper a conceptual model of the Sibayak field has been developed on the basis of the field data, and numerical simulations of a two dimensional vertical cross section for the natural state were performed with the TOUGH2 code simulating program (Pruess, 1991).

2. EXPLORATION DATA

2.1. Geological Setting

The Sibayak area is geologically composed of a pre-Tertiary - Tertiary sedimentary formation in the lower part, unconformably covered by a Quaternary volcanic rock formation. The sedimentary formation predominantly consists of sandstone followed by shale and limestone. Figure 2 shows a geological map of Sibayak (Hasibuan and Ganda, 1989). Within the Singkut caldera, the Quaternary volcanic rock formation has been divided into pre and post caldera development: the former are Singkut dacite-andesite and Singkut laharic breccia, and the latter are Simpulangin pyroxene andesite, Pratetekan hornblende andesite, Pintau pyroxene andesite and Sibayak hornblende andesite. Drilling data showed that the sedimentary formation is generally found below 1150 m from the surface. This formation consists of sandstone and intercalates shale and sometimes limestone. Intensive hydrothermal alteration of silicification and argilization has changed the rock formation into meta-sedimentary rocks. The volcanic rock formation is composed of andesite lava, andesite volcanic breccia and tuff breccia. Relatively moderate hydrothermal alteration of argillization and chloritization was found within this formation (Pertamina, 1992a, 1992b, 1993, 1995a, 1995b and 1997).

The geological structure in Sibayak is mainly controlled by volcanic activities along with regional tectonic activities. A caldera structure, elongated to the NW-SE, was formed by volcanic explosive activities of Mt. Singkut. Several faults are present within the caldera with NW-SE orientation and extend to the center of Mt. Sibayak- Mt. Pintau where the NE-SW fault (F5) disappears (Figure 2). These fault systems within the caldera are associated with subsided blocks, which are reflected to the surface topography. Intensive faults were encountered at shallow and deep zones during drilling, which caused water losses.

2.2. Geophysical Prospecting

A combined analysis of the Schlumberger resistivity and the magnetotelluric surveys concluded that the upper layer is of low resistivity (15-50 ohm-m) and the bottom of this layer locally appeared at a shallow level, such as elevation 1400 m in the area of Mt. Sibayak. This probably represents a zone of low to medium temperature, and also a presence of steam heated ground water. The thickness of the layer is about 400 m, indicating that high temperature zone may be found below it. Where this layer is thicker, it implies that any high temperature zone lies at deeper levels. This interpretation is consistent with the temperature structure deduced from the results of temperature logging conducted in deep exploration wells. Below this low resistivity zone, moderate resistivities are only detected in the zone immediate west and south of Mt. Sibayak. This suggests that the area of high temperature reservoir might be rather limited. The measurement stations for the survey were not set in a sufficient density, and thus insufficient results were obtained to make a reliable estimate of the boundary locations in the lateral direction (Pertamina, 1994).

2.3. Thermal Manifestations

Hot springs and steaming grounds are distributed in the southwestern part of the Singkut caldera. High temperature fumaroles and solfatara exist on the top and also on the southeastern flank of Mt. Sibayak. Temperatures of hot spring water ranges from 30 to 63 ºC and the springs are slightly acidic (pH 5.5 - 6) although some of them are very acidic (pH 2.2 - 2.5) (Hantono et al., 1990). Chemical analysis indicates that the hot spring waters are of sulfate-chloride type. Temperature of fumaroles ranges from 90 to 116 °C and gas content is 2.7 % wt. Concentrations of H2S and SO2 in the gas are 19.75 mol % and 164 ppm, respectively. Condensed water of fumarolic gases showed high chloride concentration (Sunaryo and Sarwadi, 1989).

Hot springs are also situated outside the caldera; at Sinabung area about 14 km southwest of Mt. Sibayak and Negeri Suoh area about 7 km southeast of Mt. Sibayak. Discharge waters at Sinabung are of low to moderate temperature and of bicarbonate- sulfate type. Discharge waters at Negeri Suoh are of temperature ranges 40 to 60 °C, neutral pH and of bicarbonate-chloride type. Travertine and mofet deposits are found near these hot springs (Hantono et al., 1990).

2.4. Feed Zones

Depths of the feed zones for each well were determined based on water circulating loss data and pressure and temperature well logging data. Well data evaluation studies indicated that the main water loss zones are chiefly present on the boundary of the volcanic and the sedimentary formations. Well completion test provides that injectivity of wells ranges from 1.3 to 22.8 kg/(sec bar) and permeability-thickness product from 0.3 to 13.1 darcy-m (Pertamina, 1992a, 1992b, 1993, 1995a, 1995b and 1997). Lateral distributions of water loss zones at several different depths were evaluated using the water loss data. Figure 3 shows distributions of the magnitude of water loss at elevation -450 m. An area of large water loss in the southern part seems to be bounded by the caldera rim. Narrow zones of low permeability extending to north-south may be present between the well pads A and B. These low permeable zones are present at depths of elevation from -100 m to -450 m. A large water loss zone may also extend to the north of Mt. Sibayak and Mt. Pratetekan as well as the area near the bottom of well SBY-2, outside the caldera.

2.5. Temperature and Pressure

There are five wells drilled at well pad A. They are vertical well (SBY-1), directional wells oriented to the north (SBY-6, SBY-7 and SBY-8) and directional well to the south (SBY-2) (Pertamina, 1992a, 1992b and 1997). Figure 4 shows temperature profiles of these wells. Except well SBY-2, temperatures rapidly increase from elevation 1200 m to about 250-400 m and then remain constant or increase slightly with depth down to the bottom of wells. The maximum temperatures in wells SBY-1, SBY-6 and SBY-8 were measured to be 225 ºC, 278 ºC and 258 ºC, respectively. Temperatures in well SBY-2 rapidly increase from 44 °C at elevation 1184 m to the maximum of 165 ºC at elevation 800 m, then gradually decrease to 82.6 ºC at the bottom of well.

Four directional wells - SBY-3, SBY-4, SBY-5 and SBY-10 - were drilled toward Mt. Sibayak on well pad B and one well, SBY-9, was drilled to the northeast on well pad C (Pertamina, 1993, 1995a and 1995b). Figure 5 shows temperature profiles of the wells. Temperatures of SBY-3, SBY-4 and SBY-5 increase rapidly from 40 °C at the near surface down to elevation 150-250 m, then slightly increase to the bottom. The maximum temperatures in wells SBY-3, SBY-4, SBY-5 and SBY-10 were measured to be 264 °C, 250 °C and 310 °C, respectively. The temperature of well SBY-10 gradually increases from 40 °C at the surface to the maximum 137 °C at the bottom. Temperature of well SBY-9 rapidly increases from 36 °C at the near surface to 146 °C at elevation 1137 m and then slightly increases up to 205 °C at the bottom.

Figure 6 shows temperature distributions at elevation -500 m. Temperatures seem to increase toward Mt. Sibayak and Mt. Pratetekan. Temperature may also rise higher than 250 °C from elevation 0 m to deeper zone. On the other hand, temperature distributions indicate rapid cooling to the south, where the caldera rim exists.

Figure 7 shows pressure distributions at elevation 0 m. This figure indicates that the lower pressure zone extends toward Mt. Sibayak - Mt. Pratetekan and that higher pressures exist near the caldera rim. At the shallower zones, pressures show inverse conditions: higher pressures in the north and lower pressures in the south. These conditions suggest that an upflow zone of hot fluid may be present beneath the area between Mt. Sibayak and Mt. Pratetekan, and a down flow of cool water along the caldera rim.

2.6. Chemistry of Reservoir Fluid

Fluids discharged from wells at Sibayak are nearly neutral (pH 6.2 - 8.2); chemical analysis from separated water indicates high content of chloride (up to 1132 ppm) and silica (975 - 1814 ppm). Chemical analysis for non-condensable gas indicates that CO2 is dominant (80-90 mol %) for wells SBY-1, SBY-4 and SBY-6 (Pertamina, 1992a, 1992b, 1993, 1995a, 1995b and 1997).

3. CONCEPTUAL MODEL

The geological structure of Sibayak seems to control the areal extent of the geothermal system that is bounded by the caldera rim at the southwestern and southern end (Figure 2). Drilling data and geophysical data suggest that the area of reservoir is approximately 4.5 km^2, distributed between Mt. Sibayak - Mt. Pratetekan and the caldera rim of southern end. Several faults running southeast-northwest in this area contribute to forming the reservoir. These fault structures accompanied by fractures in the sedimentary formation formed permeable zones where hot fluids flow.

Distributions of temperature and pressure suggest that there is a recharge of high temperature fluid at the deep zone (below -500 m) flowing upward in the area beneath Mt. Sibayak - Mt. Pratetekan, and there is a lateral flow directing southeast at the shallow zones (elevation 0 to 500m). Pressure distributions at elevation 0 m and 500 m imply an existence of no-flow barriers running south - east in the area between the well pads A and B, and between the well pads B and C. These barriers can be attributed to a series of formation displacements. Linear increases in temperature at shallow zones imply conductive heat transfer and also the presence of a low permeability formation.

Figure 8 represents a conceptual model of the Sibayak field. This cross section is drawn in the plane of the top of Mt. Pintau and well bottoms of SBY-4 and SBY-2. The total length for this cross section is 5300 m.

The location of the caldera rim on the southeast part, and of Mt. Sibayak and Mt. Pintau on the northwest part is also shown in this cross section. The upper limit of the reservoir is set at the depths of shallowest feed zones in each well. Vertical temperature distributions show that hot fluids flow upward beneath Mt. Sibayak, then flow laterally southeast and downward near the caldera rim. In the reservoir the highest temperature of 280 °C was measured beneath Mt. Sibayak in well SBY-5 and temperatures gradually decrease southward to about 200 °C in well SBY-1.

Hot springs and steaming ground on the surface are generally formed along the faults. A high concentration of chloride in several hot spring waters implies a direct connection between the reservoir and the hot springs.

4. NATURAL STATE NUMERICAL SIMULATION

4.1. Gridding and Rock Properties

Figure 9 shows the grid block layout and the rock types given to the model. The model was divided into 306 blocks, consisting of 18 layers and 17 columns, with the highest elevation at 2400 m and the lowest at -2000 m. The central part of the model was represented with a fine grid block of 200 m x 200 m. The thickness of the two bottom layers is 500 m. The outer column width of both side boundaries is 1000 m and the column immediately in from the outer one at the northwest is 500 m. These coarse grid blocks were used due to the sparse well data.

Permeability and other rock properties were assigned to each of the grids on the basis of the well testing data, the geological information such as lithology, water loss zones, the geophysical data, and the presence of hydrothermal alteration zones.

Low permeability was given to the both lateral barriers, the cap rock and the bottom rock. The reservoir consists of rocks with medium to high permeabilities. Nine different rock types were used for input data of numerical simulations and are summarized in Table 1.

4.2. Boundary and Initial Conditions

The upper boundary above the land surface, representing atmosphere, is given a constant pressure (1 bar) and temperature (20 °C) and filled with air. In TOUGH2, a constant pressure and temperature condition can be set by assigning a large volume (10^{50} m^3) and setting up a short distance (10^{-10}m) between the center of the grid block and the associated interface (Pruess, 1991). Thus, their thermodynamic conditions would remain practically unchanged during simulation.

Lateral boundaries were impermeable to fluid, and no heat was able to enter or leave the model through the sides. The bottom boundary was set to be impermeable but mass and heat fluxes are given at the specified grid blocks to express recharges of mass and heat.

Initial conditions of the model were first determined by simulating under isothermal conditions and hydrostatic gravitational equilibrium.

In natural state simulations, a total mass flux of 1.08 kg/s and enthalpy of 1964 kJ/kg were given to those grid blocks corresponding to the bottom of the recharge zone. A small amount of cold water (0.03 kg/s) was also set for a flow into the system through the blocks of the outside of caldera rim. A magnitude of mass fluxes was determined so as to obtain a good match with temperature profiles in wells.

5. RESULTS AND DISCUSSION

The best model in natural state simulation was obtained from several runs with different configurations of permeability and mass flux set for the model. A steady state condition was obtained at about 50,000 years of simulation.

Figure 10 shows comparison of temperature profiles between wells SBY-1, SBY-2 and SBY-8 and the simulated results. There is a good agreement between the well bore temperature profiles and the calculated temperature of grid blocks. The simulated temperature distribution implies that a conductive heat transfer is dominant in the upper zone because of linear temperature increase having a large gradient in this zone. Reverse temperatures in the deeper zones indicate fluid flowing laterally.

Figure 11 shows temperature distributions and mass flow vectors of the best model at 50,000 years. A flow pattern implied by flow vectors seems to be in good match with that of the conceptual model. For example, an upflow zone is developed at depth below Mt. Sibayak. A lateral flow from NW to SE is found at elevation -250 m to 250 m, which is consistent with the measured well temperatures shown in Figure 10. Further southwest, flow vectors changed to downward, indicating a down flow along a fault system associated with the caldera rim. Relatively large amounts of heat and mass are discharged through the blocks corresponding to Mt. Sibayak where temperature is approximately 100 °C. This discharge is consistent with the presence of fumaroles located between Mt. Sibayak and Mt. Pintau. The flow pattern also indicates that a convection system is formed in the central part of the model.

6. CONCLUSIONS

A numerical model of the Sibayak geothermal field was developed for a two-dimensional vertical cross section. Simulated results for natural state show relatively good agreement with temperature profiles for wells SBY-1, SBY-2 and SBY-8. A conceptual model suggesting the presence of an upflow zone below Mt. Sibayak and a lateral flow in the bore field was proved to be consistent with the simulated results.

ACKNOWLEDGEMENTS

We are grateful to the Geothermal Division, PERTAMINA State Oil & Gas Company and Geothermal Research Grand Team, Petroleum Engineering Faculty, UPN Veteran University for their help collecting the data and permission to publish this paper.

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Table 1. Rock properties and rock types assigned for grid blocks.

Rock type	Density (kg/m^3)	Porosity (-)	Permeability (m^2)		Thermal conductivity (W/m°C)	Spec.Heat capacity (J/kg°C)
			kx	kz		
Atmosphere	1	0.99	1×10^{-6}	1×10^{6}	0.021	1004
Very low	2600	0.05	3×10^{-17}	1×10^{-17}	2.1	1100
Low 1	2600	0.10	6×10^{-16}	2×10^{-16}	2.1	1100
Low 2	2650	0.10	1×10^{-15}	7×10^{-16}	2.1	1100
Low 3	2700	0.05	5×10^{-17}	3×10^{-17}	2.1	1700
Medium 1	2650	0.10	5×10^{15}	3×10^{15}	2.1	1100
Medium 2	2680	0.10	5×10^{15}	2×10^{15}	2.5	1200
High 1	2680	0.10	7×10^{15}	3×10^{15}	2.5	1200
High 2	2700	0.10	1×10^{14}	5×10^{15}	2.1	1700

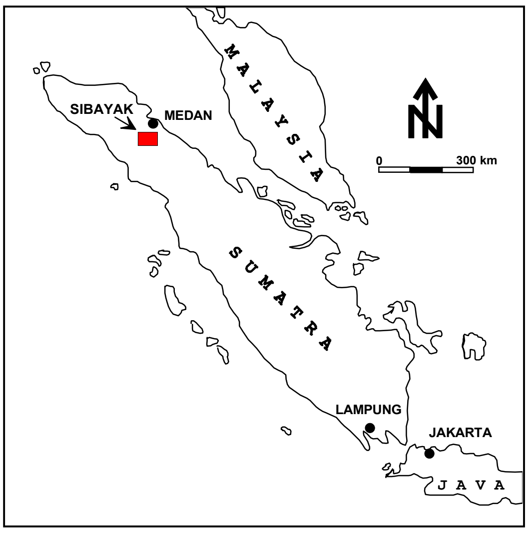

Figure 1. Location map of Sibayak geothermal field

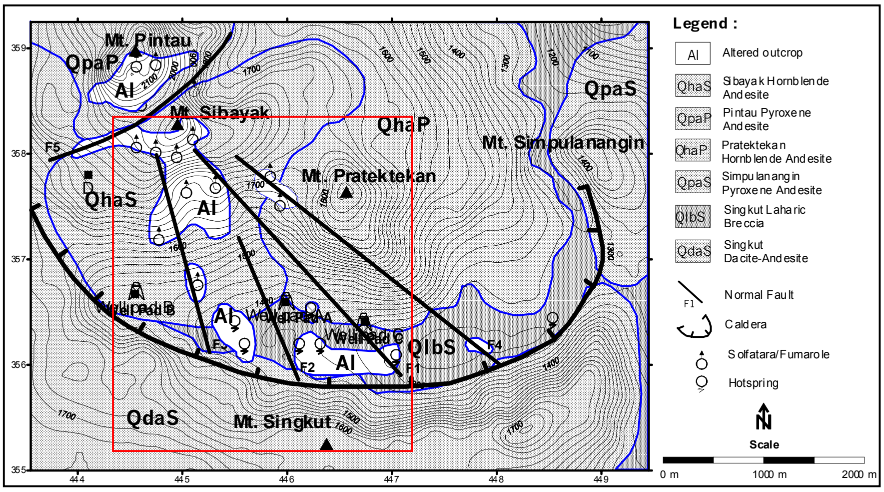

Figure 2. Geological map of Sibayak geothermal field.

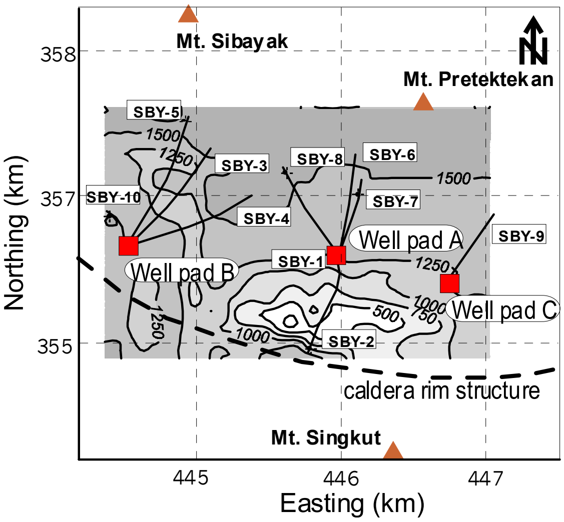

Figure 3. Distribution of water loss circulation (l/min) at elevation -450 m.

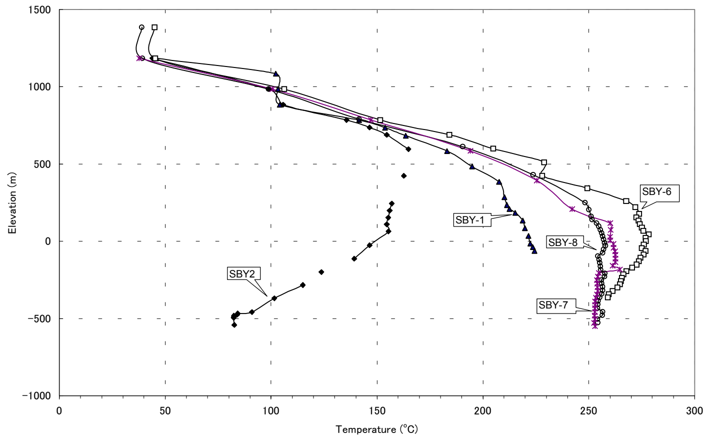

Figure 4. Temperature profiles of wells SBY-1, SBY-2, SBY-6, SBY-7 and SBY-8.

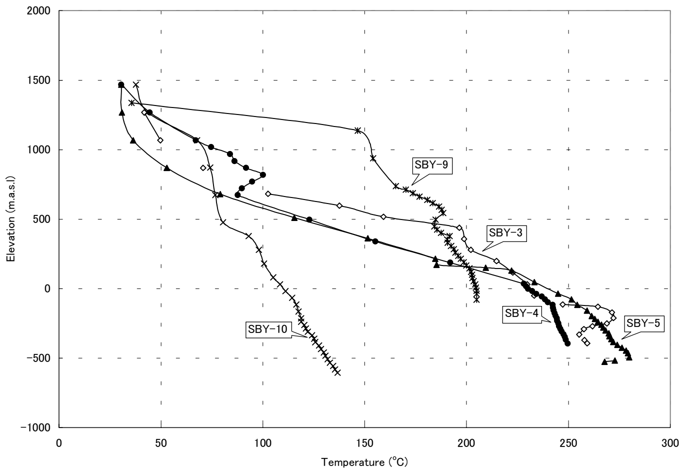

Figure 5. Temperature profiles of wells SBY-3, SBY-4, SBY-5, SBY-9 and SBY-10.

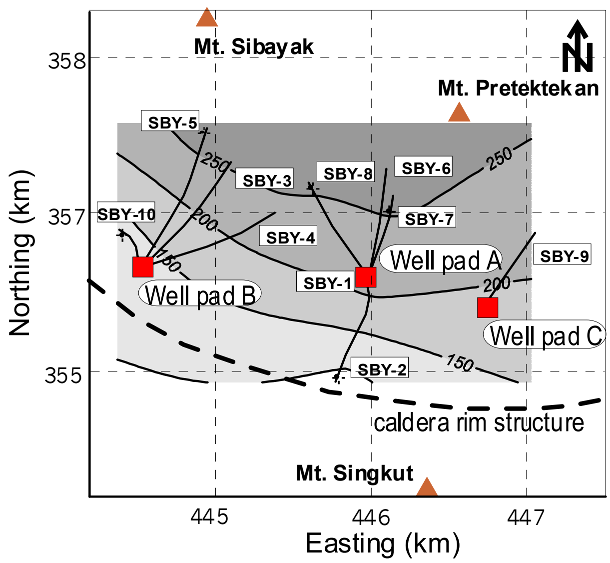

Figure 6. Distribution of temperature (°C) at elevation -500 m.

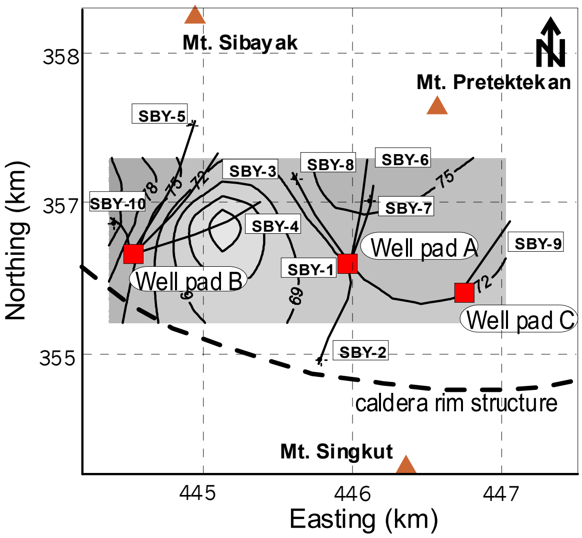

Figure 7. Distribution of pressure (bar) at elevation 0 m.

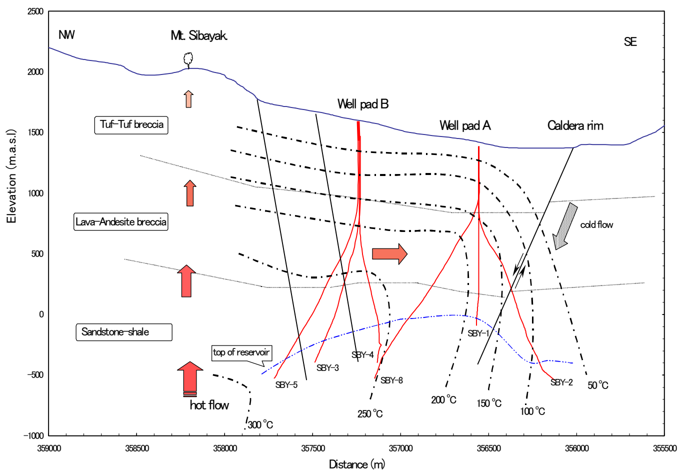

Figure 8. Conceptual model of Sibayak geothermal field.

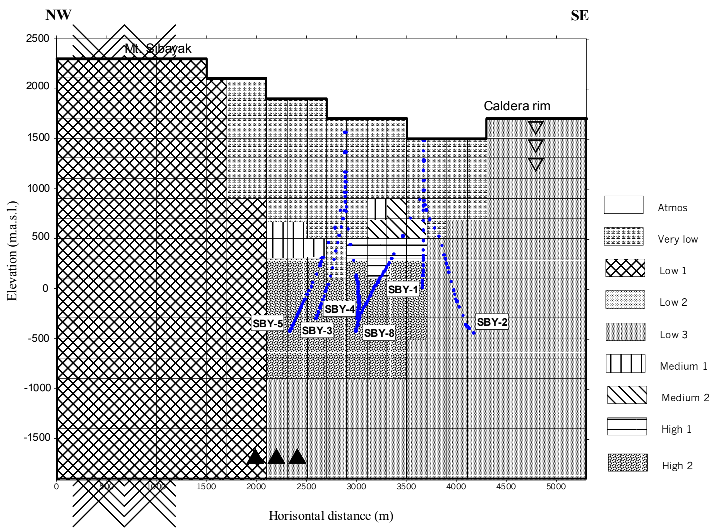

Figure 9. Numerical model of the Sibayak geothermal field. Recharge of high temperature fluid is indicated by (▲) and of cold fluid by (▽).

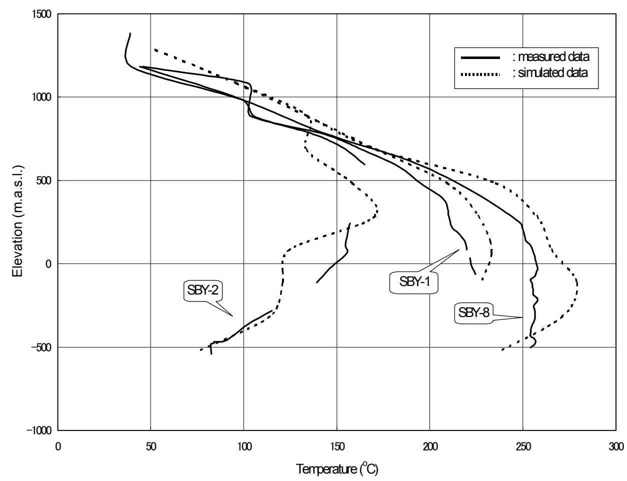

Figure 10. Comparison of temperature profiles between wells SBY-1, SBY-2 and SBY-8 and the simulated results.

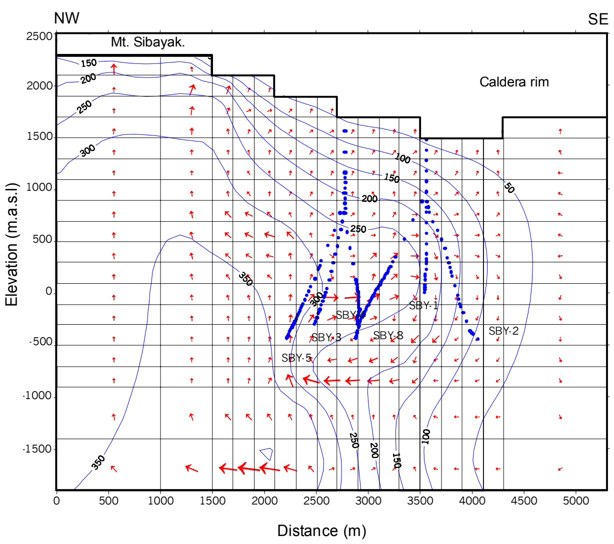

Figure 11. Temperature distribution and flow pattern of the Sibayak model at 50,000 years of simulation.