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NUMERICAL MODELING STUDY OF SIBAYAK GEOTHERMAL RESERVOIR, NORTH SUMATRA, INDONESIA

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ABSTRACT

A three-dimensional numerical model of porous type for the Sibayak reservoir is developed which covers an area of 8 x 8 km^2 and a depth 2500 m below sea level. In natural state simulations, good agreements are achieved between simulated and measured temperatures in ten wells. In order to assess the reservoir behaviors upon production, simulations are carried out for different well locations. Production simulations without reinjection indicate remarkable decreases both in reservoir pressure and steam production. In this case for generating 30 MWe, steam production decreases by 40 % after 30 years. Reinjecting wastewater at a rate 800 t/h and temperature 120 ^{o}C in the layer above production zone moderates the decline of steam production from 40 % to 27 % and also maintains the steam production above 250 t/h for 30 years. This suggests that the Sibayak geothermal field can produce enough steam for 30 MWe over 30 years.

INTRODUCTION

The Sibayak geothermal field is located in North Sumatra, Indonesia (Figure1). The field is located inside the Singkut caldera about 1400 m.a.s.l. Exploration surveys including three exploration wells were carried out during 1989–1991. These results suggested a potential area near Mt. Sibayak for further prospecting and a proven area of 4.5 km^2 (Pertamina, 1994). Seven additional exploration wells were drilled in the same area to understand thermal structures of the reservoir more in detail and to confirm a presence of up-flow zones.

In this paper, three-dimensional numerical modeling of porous type was carried out to simulate natural state conditions of the Sibayak field. The performances of reservoir were predicted for several production schemes by giving different locations and depths for production and reinjection wells. The simulations were performed using TOUGH2 (Pruess, 1991), and the results were graphically processed with MULGRAPH (O'Sullivan and Bullivant, 1995)

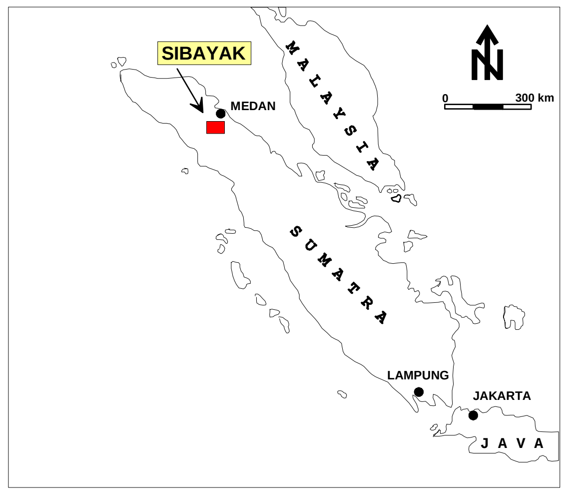

Figure 1. Location map of the Sibayak geothermal field.

HYDROTHERMAL SYSTEM

The promising area in the Sibayak field is located within the caldera system and is bounded by the caldera rim of an elliptic-circle. Figure 2 shows a three-dimensional conceptual model of hydrothermal system in the Sibayak field. There are three volcanoes inside the caldera: Mt. Pintau (2212 m), Mt. Sibayak (2090 m) and Mt. Pratetekan (1850 m). The caldera rim located southern part of the field plays a barrier to fluid and a recharge zone of low temperature shallow water. This caldera structure may be formed after eruption of Mt. Singkut. Hydrothermal manifestations are found inside the caldera as hot springs, steaming grounds and fumaroles, and also outside the caldera as hot springs in the area about 3 km northeast from Mt. Pratetekan.

The Sibayak reservoir is of hot water dominated type and formed in the fractured zones of pre-Tertiary to Tertiary sedimentary rocks below –200 m.a.s.l. (Hasibuan and Ganda, 1989; Atmojo, et al., 2000). A conceptual model of hydrothermal system in the Sibayak field can be illustrated as follows: high temperature fluids flow up below Mt. Sibayak, and then most of them flow laterally to southeast, and the rest of the fluid flows toward the north and northeast. These fluids then flow out to the surface through fractures as hot springs whose water is slightly acidic of pH5.5-6 (Hantono et al., 1990). A small amount of high temperature fluid flows up through the fractures below Mt. Sibayak forming fumaroles at temperatures about 100 ^{o}C at the surface.

Lateral flows occur in the northeastern area along an apparent fault with SW to NE strikes near Mt. Pratetekan. Hot springs in this area about 3 km northeast of Mt. Pratetekan confirm the lateral fluid flow to be feasible.

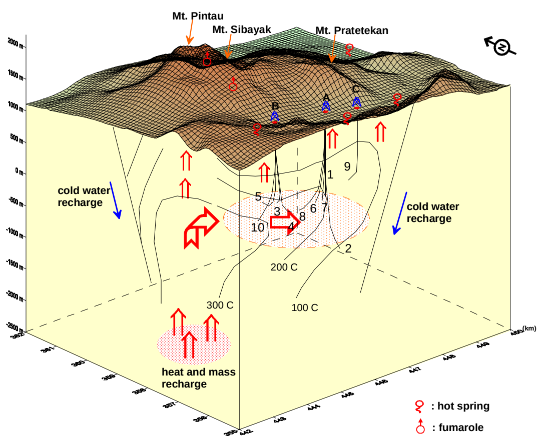

Figure 2. A three-dimensional conceptual model of hydrothermal system in the Sibayak field.

GRIDS AND ROCK PROPERTIES

The model was divided laterally into 165 blocks and vertically into 7 layers, totaling 1155 blocks. Large size blocks of 1x1 km^2 represented outer boundaries of the field. The areas where enough data were available from wells were divided into small size blocks of 250m x 250m. Medium size blocks of 500m x 500m were used for areas where hot springs, fumaroles and faults locate. Figure 3 shows the plain view of grid system of the numerical model. The bottom of the surface layer was allocated to 900 m.a.s.l, and consisted of blocks with various surface elevations ranging from1000 to 2200 m.a.s.l. Very few water loss zones occurred in the shallow zone. Thus, two layers with 300 m thickness each beneath the surface layer were assumed to have low permeability. The next two layers below with 400 m thickness each were assumed to be a reservoir shown in Figure 5 as hatched area. There are two layers with 1000 m thickness each at the bottom. Twelve kinds of rock types including atmosphere were assigned to the model. As the data in blocks of the bottom layers and outer boundaries were not available, rock parameters for these blocks were adjusted to fit well temperature data. Table 1 summaries the rocks types used for the optimum model for natural state simulations. The general description of the permeability distribution in the model can be illustrated as follows: outer boundaries have low permeability, very low permeability were given to a cap rock above reservoir and a vertical boundary representing the southern caldera rim. The reservoir was composed of medium to high permeability rocks. Most of grids consisting the bottom layer are of low permeability except the blocks where high temperature fluid recharges.

Table 1. Rock types and their permeability.

Rock type	Permeability (m^2)		
	kx	ky	kz
Atmos	1×10^{-14}	1×10^{-14}	1×10^{-14}
Top	6×10^{-16}	6×10^{-16}	2×10^{-16}
Side 1	2×10^{-16}	2×10^{-16}	5×10^{-17}
Side 2	3×10^{-16}	3×10^{-16}	6×10^{-17}
Low	3×10^{-16}	3×10^{-16}	5×10^{-17}
Vlow	3.5×10^{-18}	3.5×10^{-18}	7×10^{-19}
Med 1	1×10^{-15}	1×10^{-15}	5×10^{-16}
Med	1.5×10^{-14}	1.5×10^{-14}	4×10^{-15}
High	2.5×10^{-14}	2.5×10^{-14}	5×10^{-15}
Bott	1×10^{-14}	1×10^{-14}	2×10^{-15}
Barr	1×10^{-18}	1×10^{-18}	1×10^{-19}
Barr1	3.5×10^{-18}	3.5×10^{-18}	7×10^{-19}

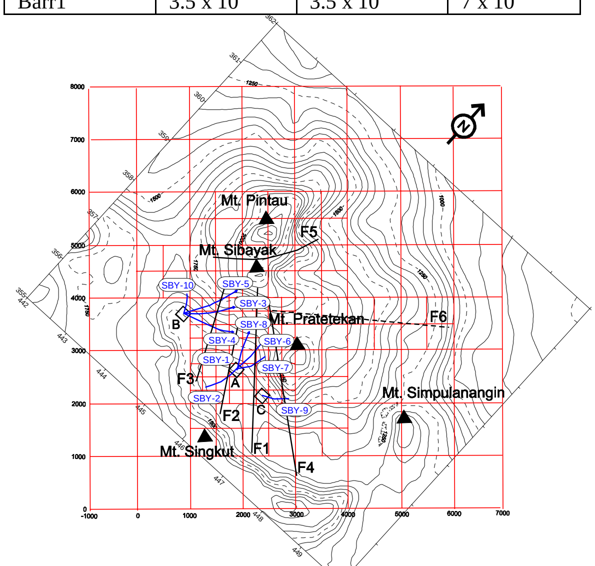

Figure 3. Grids system of the numerical model.

BOUNDARY AND INTIAL CONDITIONS

The top boundary of the model was specified by a single block of Atmos and filled with water of 1 bar and 20 ^{o}C. The outer boundaries were impermeable and insulated. The bottom boundary was impermeable, but it was assumed that high temperature fluid recharges into the system through several blocks of the bottom. The magnitude and location of the fluid recharge was obtained in a manner of try and error during simulations. Heat and mass outflows at the surface were modeled as pressure-dependent flows using wells on deliverability. The wells on deliverability were located in the blocks below the area where the surface outflow occurs such as fumaroles and hot springs. Values of productivity index (PI) and well bottom pressure (Pwb) used for calculation were also adjusted. The model was first assigned under an isothermal (20 °C) and a hydrostatic pressure

NATURAL STATE CONDITIONS

The optimum results of natural state conditions were attained by assigning a mass flow of 56 kg/s with enthalpy 1561 kJ/kg of fluid recharged at the bottom. This fluid recharge was distributed into 16 blocks over an area of 16 km^2 below Mt. Sibayak and Mt. Pintau. Mass and heat outflow at the surface as hot springs and fumaroles were realized by implementing fluid discharge from wells on deliverability in the four blocks. These deliverability blocks produce fluids at a rate of 53.6 kg/s in total that indicates a good agreement with an estimated rate of 60 kg/s in the field based on a value reported by Hasibuan and Ganda (1989). The natural state conditions of the model were attained at 450,000 years simulation run, when static thermodynamic conditions reached over a whole system. Figure 4 shows a temperature distribution and a fluid flow pattern in Layer dd under the natural state condition. Temperature distribution forms a NW-SE elongated circle, where a high temperature zone presents in the area below Mt. Pintau and Mt. Sibayak. Low temperature zones, however, extend along the caldera rim. The flow pattern shows that the fluid mainly flows from the central part toward the southeast and a part of the fluid flows northeast and east. Figure 5 shows a vertical temperature distribution and a fluid flow pattern in NW-SE vertical cross-section. This figure shows that the high temperature zone extends upward and a vertical upflow presents below Mt. Sibayak. The figure also presents that the most of the fluids laterally flow southeast. Fluid outflows at the surface indicated by small arrows occur within the caldera, which explains the hot springs. Fluid recharges from the surface in an area outside the caldera confirm that the presence of down flow of low temperature water.

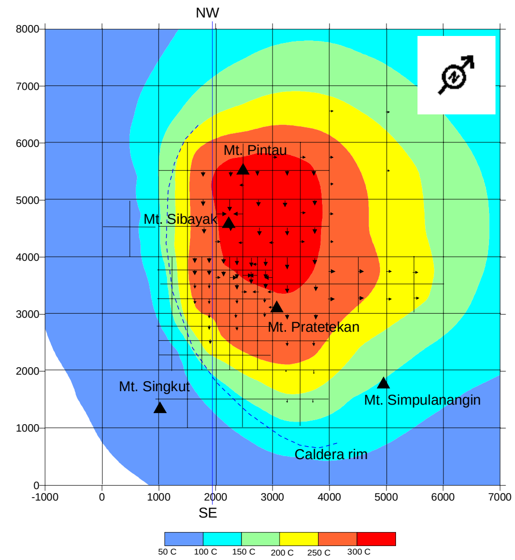

Figure 4. Temperature distribution and fluid flow pattern in Layer dd.

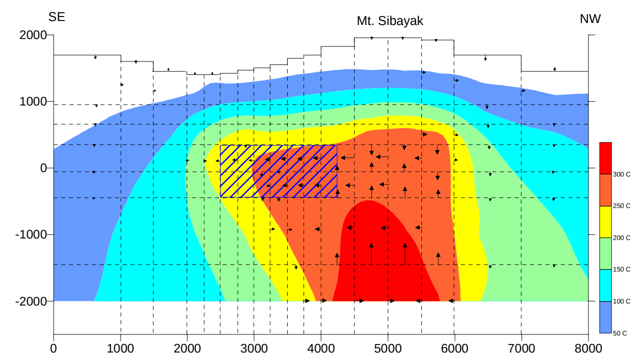

Figure 5. Temperature distribution and fluid flow pattern in SE-NW vertical cross-section under the natural state condition. Hatched area represents the reservoir.

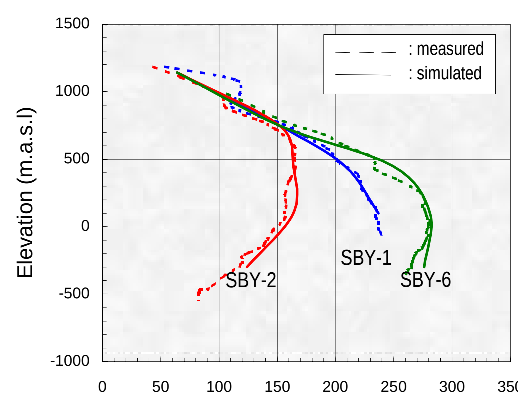

Figure 6. Comparison of temperature profiles between simulated results and well data in Wells SBY-1, SBY-2 and SBY-6.

Figure 6 shows the results of the matching of temperature profiles in Wells SBY-1, SBY-2 and

SBY-6. Temperature profiles in the grid system for the natural state simulation have good agreements with those in measured data at the wells.

RESERVOIR PERFORMANCES

Numerical simulations were conducted for predicting reservoir performances by assigning production and reinjection wells. As for production zones, we first examined distributions of permeable zones. Figure 7 shows location map of the production and reinjection areas. The production zones were located in the area where Wells SBY-5, SBY-4, SBY-8, SBY-6 and SBY-7 were drilled. In the area where Wells SBY-1 and SBY-9 locate, permeabilities are rather small resulting less productive. A high permeable zone may be found in an area below the flank between Mt. Sibayak and Mt. Pratetekan. This zone is interpreted as a junction of faults F4 and F6. And also in an area between Mt. Sibayak and Mt. Pintau, a high permeable fractured zone may be developed along the fault F5, but produced fluid from a Well SBY-5 drilled near this zone has high acidity.

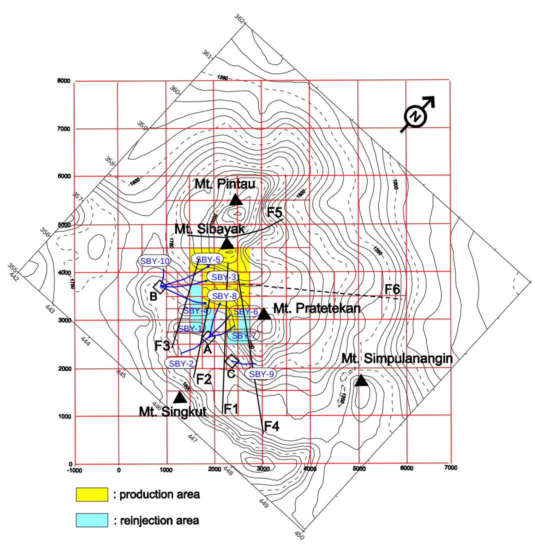

Figure 7. Location map of production and reinjection areas in the Sibayak geothermal field.

Two areas are selected for reinjection areas: southern slope of Mt. Pratetekan near Well SBY-7, and an area between Wells SBY-4 and SBY-1. In the simulations, reinjecting into two different layers: above and in the same depth with the production zone, are evaluated.

Production Simulation Schemes

Three kinds of production schemes for 30MW electricity power generation for 30 years were simulated. The production rates of fluid and steam were calculated using well on deliverability assigned to production blocks at a separation pressure of 5.5 bar.

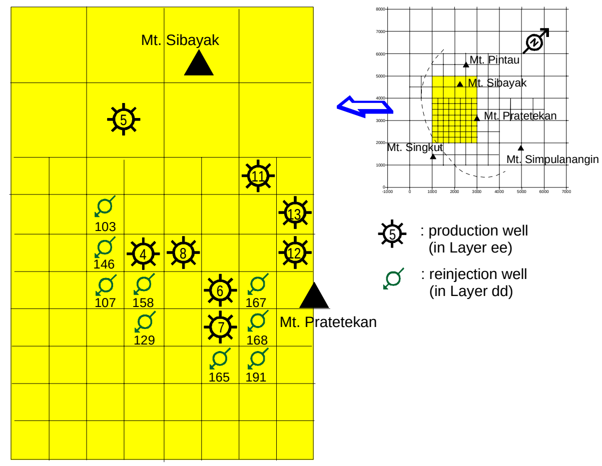

Figure 8. Scheme of production and reinjection wells for Run2.

To provide enough steam for 30 MWe, five production wells of SBY-4, SBY-5, SBY-6, SBY-7 and SBY-8, and three additional production wells of SBY-11, SBY-12 and SBY-13 are required. The wastewater is estimated to be about 800 t/h and 120 ^{o}C. Run1 represents a production simulation without reinjection. In the case of Run2, reinjection wells were allocated in two areas: an area near Well SBY-7 and an area between Wells SBY-1 and SBY-4 (Figure 8) and they were assigned at 9 blocks in the layer above the production zone. In the case of Run3, 7 blocks are required for reinjection wells that were allocated in an area near Well SBY-7: three blocks above the production layer and other four blocks at the same layer as the production zones (Figure 9).

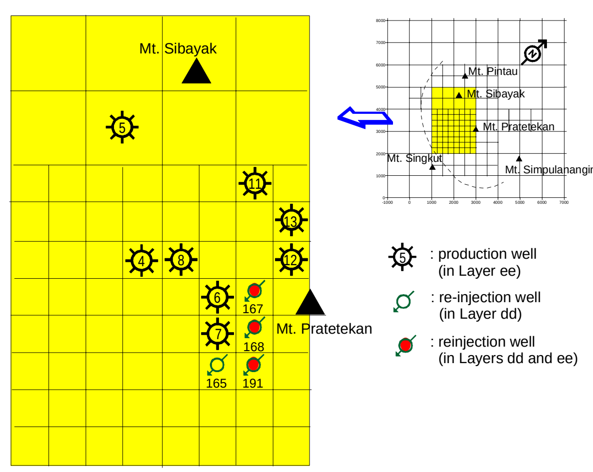

Figure 9. Scheme of production and reinjection wells for Run3.

Results of Production Simulations

Figure 10 shows mass rates of total fluid and steam with time. Both flow rates drop rapidly at the early periods. In the case without reinjection (Run1), the steam production dropped from 460 t/h to 250 t/h at the beginning, and then decreases down to about 150 t/h after 30 years, which is 40 % decrease compared with the early period. The reinjecting wastewaters both in Runs 2 and 3 moderated the reductions in flow rates of total fluid and steam with time. The assignment of reinjection zone above the production layer in Run2 resulted in the steam production rate above 250 t/h through out the simulation period. At the early period, the steam production dropped to 370 t/h, and then decreases slowly to about 270 t/h at 30 years. This decreased steam production is about 27 % of the rate at the early time. In the case of Run3, where reinjection zones were assigned in two layers: above and the same depth with the production layer, steam production rates at the early period reaches to 380 t/h. Steam rate, however, decreases to 225 t/h after 30 years or 41 % drop from the early production rate. Figure 11 shows the pressure declines in the block ee146 (Well SBY-7) for three cases. All three cases show a rapid pressure drop at the beginning. The pressure for Run3, however, remains almost constant for the rest of the period.

Figure 10. Comparison of flow rates for total fluid and steam among Run1, Run2 and Run3.

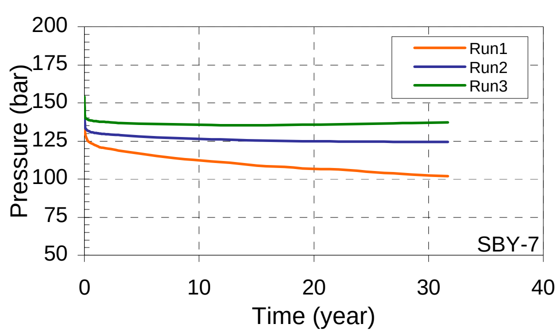

Figure 11. Comparison of reservoir pressures in the block ee146 (Well SBY-7) among Run1, Run2 and Run3.

This constant pressure may be supported by the reinjecting wastewater into the production zones. The reinjecting wastewater in Run2 also supports the pressure in the production zone in spite of only reinjecting into the layer above the production zones. When there is no reinjection, for Run1, pressures continuously decrease with time and drop down by 50 bar after 30 years compared with its initial value. This marked decrease in steam flow rate may be caused by mixing of heat depleted wastewater into the production zones. A large volume exploitation of fluid without reinjection causes a marked in reservoir pressure, which is observed, for example in the grid blocks of ee150 (Well SBY-4) and ee148 (Well SBY-8). These pressure drops resulted in a cease of steam production at these wells after 5 and 3 years, respectively.

Figure 12 shows average enthalpy of produced fluids with time for three cases. Initial enthalpy of fluids was calculated to be 1229 kJ/kg at the start of production. Increase in enthalpy to 1256 kJ/kg after 30 years for Run1 may be caused by high temperature fluids flow into the production zones and resulted in increase in fluid temperature in production zones. The enthalpy for Run2 first increases to 1241 kJ/kg during the first 10 years then it decreases to 1216 kJ/kg at 30 years. This decrease in enthalpy

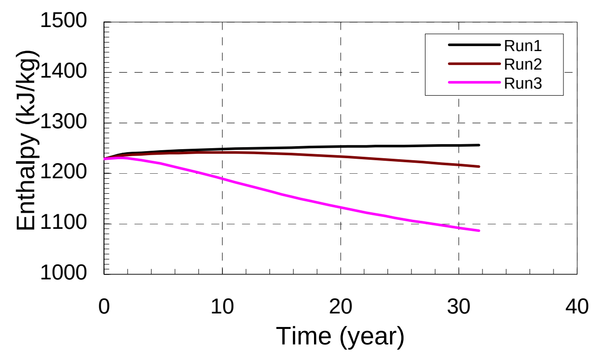

Figure 12. Comparison of average enthalpy of production fluids among Run1, Run2 and Run3.

implies that cooling effect of reinjection on produced fluids start to appear. On the other hand, enthalpy continuously decreases to 1092 kJ/kg after 30 years for Run3.

Figure 13 shows temperature contour in Layers dd and ee after 30 years simulation for Run2. In Layer ee, production zone, temperature decreased zone can be seen only in a limited area near Wells SBY4 and SBY-7. However, it extends in a wider area in Layer dd, reinjection zone. Figure 14 also shows temperature contour in Layers dd and ee after 30 years simulation for Run3. Temperature decreased zones are recognized in both Layers dd and ee, and

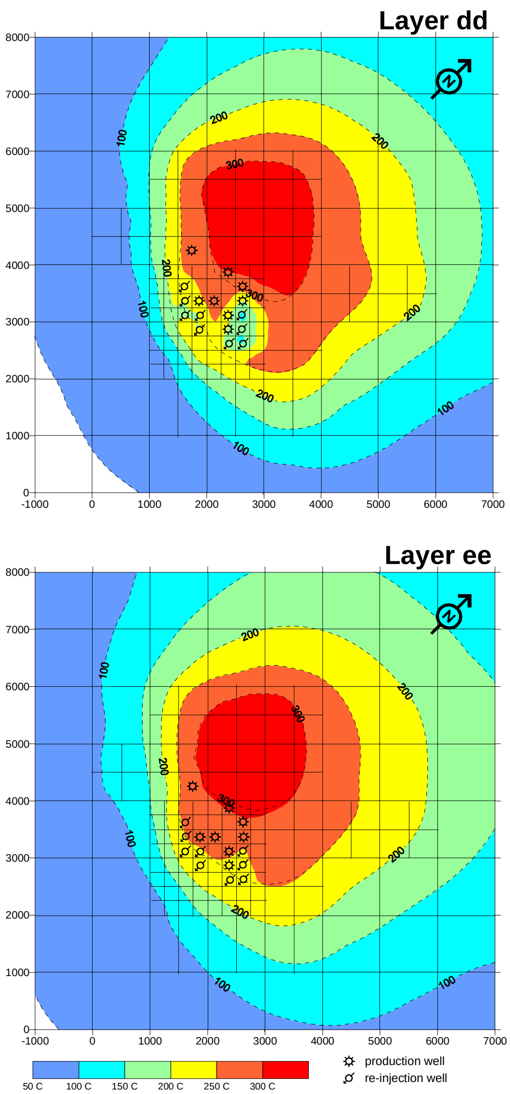

Figure 13. Temperature contour in Layers dd and ee at 30 years for RUN2.

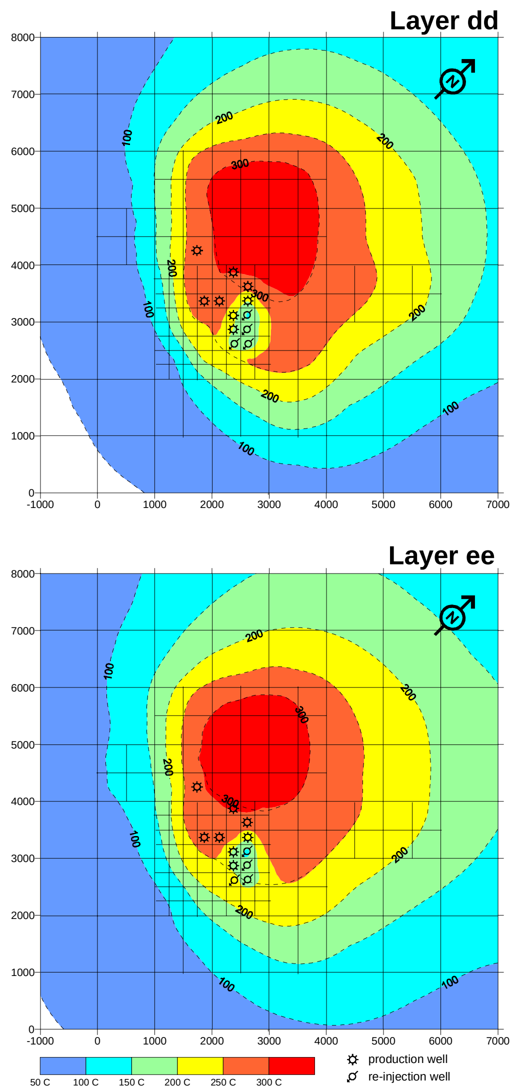

Figure 14. Temperature contour in Layers dd and ee at 30 years for RUN3.

they extend in a same magnitude. The difference in extension of temperature decreased zone in Layer ee between Run2 and Run3 resulted in enthalpy changes depicted in Figure 12.

A future study should be done for verify permeability distributions in the area proposed for additional wells.

CONCLUSIONS

The natural state simulations have been carried out in the Sibayak geothermal field. The optimum natural state conditions were attained by 450,000 years simulation. The results indicated good agreements in temperature distributions between simulated and measured temperatures in the wells. High temperature fluid at a rate of 56 kg/s with enthalpy 1561 kJ/kg recharged over an area 16 km^2 at the bottom below Mt. Sibayak was estimated. Lateral flow of fluid in the reservoir in the conceptual model was well reproduced in the simulated results.

Production simulations by assigning reinjection wells above the production zones indicated least decline insteam production rate for 30 years compared with other two cases: no reinjection and reinjection in two layers. The results showed that the steam production over 250 t/h could be maintained for 30 years, which is enough for 30 MW electricity power generation.

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