3D NATURAL STATE MODEL OF KARAHA-TALAGA BODAS GEOTHERMAL FIELD, WEST JAVA, INDONESIA

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ABSTRACT

Karaha-Talaga Bodas (KTB) Geothermal Field is classified as one of the vapor dominated systems located in Western Java, Indonesia. The KTB field is divided into two areas, Karaha (northern) and Talaga Bodas (southern). The KTB geothermal field has steam zone underlain by deep brine reservoir. The steam cap in KTB field formed due to liquid reservoir evolution and it extends from south to north where the southern area has the thickest steam cap. The understanding of the actual reservoir performance of the KTB field in an early stage of development, it is important to build a numerical model. It was built based on an existing conceptual model which is obtained from Geological, Geochemical and Geophysical (G-G-G) survey results and wells data. The natural state model of the KTB geothermal field was developed using TOUGH2 and was built using non-isothermal-pure water equation of state (EOS1). The surface of the model follows the topographic contour so that the water table in shallow zone can be represented. The output of the natural state model was validated by seven wells of the actual measurement data also heat and mass flow from the conceptual model. The additional of the heat source in the northern area below Karaha Crater shows a good match of the validation and it will update the existing conceptual model. The southern area has a moderate to high permeability with the range of 10 to 100 mD and the northern area has a low to moderate permeability with the range of 1 to 20 mD. This is the first generation of the KTB numerical model with a good result.

1. INTRODUCTION

KTB geothermal field is one of the vapor dominated field, located contiguous with Galunggung Volcano West Java, Indonesia as shown in Figure 1 (Allis et al., 2000). KTB geothermal field consists of two areas, Karaha in the north area and Talaga Bodas in the south area. The temperature range of KTB reservoir varies from 250^{O}C to 350^{O}C, the highest reservoir temperature value based on the temperature measured in the deep brine reservoir zone, with the highest temperature area located in the south area, the temperature gradually decreased while heading to the north (Nemčok et al., 2007). The first exploration program of KTB field was conducted in 1994 by Karaha Bodas Company (KBC) within area 7 km x 14 km. A total of 29 thermal gradient and production wells have been drilled by KBC during the exploration phase. The first phase of exploration drilling focused in the northern part around Karaha Crater. Several core holes have been drilled to measure the temperature gradient, followed by full-sized production wells to confirm subsurface condition and energy content for generation. The exploration result in the northern area did not show good results and the exploration drilling phase was continued to the center of Karaha area and Talaga Bodas area. The exploration drilling result in both areas shows several commercial productive wells. Until 2010 total 14 production wells have been drilled in KTB geothermal field. KTB geothermal field was operated by Pertamina Geothermal Energy (PGE) with 220 MWe operation contract capacity with PLN and the commercial operation date (COD) generating unit of 1x30 MWe will begin in the final quarter 2017 (Bayu et al., 2010).

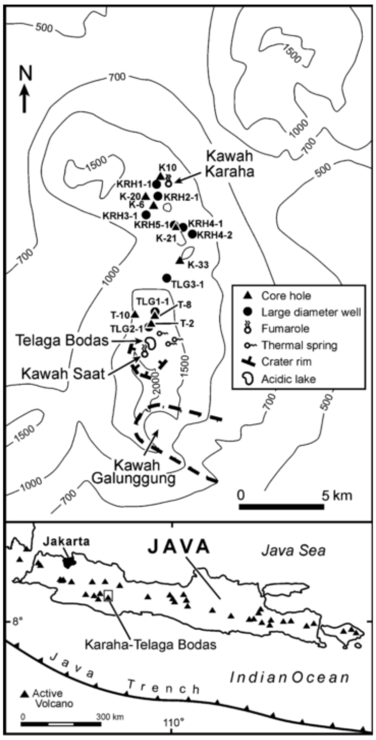


Figure 1: Map of KTB field (Nemčok et al., 2007).

Nowadays there is no published numerical model of KTB geothermal field. This study purpose to make a numerical model that can represent the actual reservoir performance in an early stage and during the production phase, based on the integration data of geoscience survey and well data records, so that the model can be used to estimate the reservoir performance of several development scenario programs.

2. RESERVOIR CHARACTERISTIC OF KTB FIELD

2.1 Geology Review

The KTB geothermal field is situated in a North-South trending andesitic ridge. Based on geological history, the rock constituent of KTB field is quaternary volcanic rock. KTB reservoir rock is formed by andesitic and basaltic lava flow and pyroclastic rock origins from granodiorite intrusion (Moore et al., 2002b) which is confirmed by granodiorite finding material in several observed wells below depths of about 3 km (GeothermEx Inc, 1998). Intrusion indicates a correlation with young volcanic activity within the field. Intrusion occurred by a lava flow to the shallow depth and solidified to form dike intrusion. Cooling intrusion rock is the heat source of the geothermal system in the volcanic zone.

The presence of multiple crowns in KTB field surrounding area as shown in Figure 2 and the appearance of several thermal surface manifestation show high degree maturity of KTB geothermal system as explained by Wohletz and Heiken (1992).

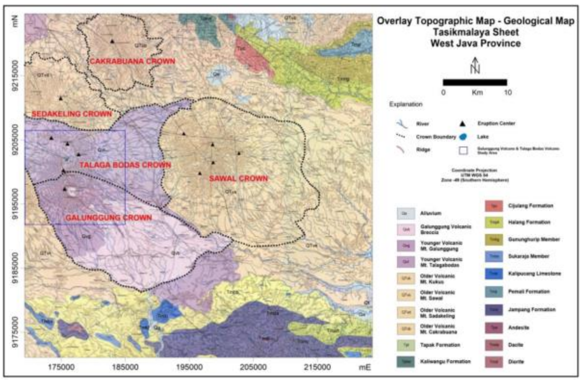


Figure 2: Geological map of Galunggung Volcano Surrounding area (Budhitrisna, 1990).

Based on the study that proposed by Nemcok et al (2004), fluid flow in the reservoir is mainly controlled by fractures. The surface geological survey has been conducted by Budhitrisna (1986), geological structures in KTB field are dominated by a structure with NW-SE and NE-SW directions. GeothermEx Inc, (1998) has reported several faults appearance that shows in KTB field using aerial interpretation, as shown in Figure 3.

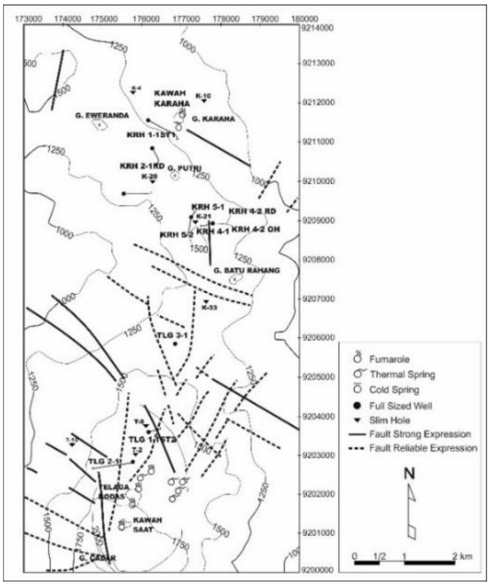


Figure 3: Faults interpretation map of KTB field (redraw from GeothermEx Inc, 1998).

2.2 Geochemical Review

Based on surface manifestation distribution which spread in the south and north area of KTB as shown in Figure 3, the geothermal system might have occurred in area of 5x13 km^2 (Raharjo et al., 2002). These manifestations are controlled by subsurface structures which are indicated by the presence of faults around manifestation areas, as shown in Figure 3. Manifestation types that appear in the southern area are fumarole at Saat Crater, Talaga Bodas acid lake and several thermal springs that discharge acid sulfate-chloride and neutral pH bicarbonate, while in the northern area there are fumarole at Karaha Crater. The appearance of fumarole manifestation in both Talaga and Karaha area indicate those areas are up-flow zone. The outflow zone based on GeothermEx Inc, (1998) fluid chemistry manifestation sampling results located in the east of the concession boundary (Pamoyanan, Cicilap and Cipancing). The KTB geothermal field is a vapor dominated field due to deep liquid reservoir transition which undergoes shallow evaporation to form a steam zone. The evidence of the vapor zone transition is shown by the deposition of chalcedony and quartz in observed core holes T2, T8 and K33 (Moore et al., 2002a).

Powell et al (2001) have performed an analyzed of all the brine samples collected from several wells in the KTB field, which were collected during drilling and well flow tests. All of samples were calculated and corrected to reservoir chemistry in the geothermal system.

All the results were tabulated in Table 1. The results of the analysis show cation and quartz geothermometer have stable values and low magnesium has concentration relatively low, which indicates fluid already or at least most of the part has under reservoir equilibrium condition.

The potential relationship of the reservoir fluid is described in Cl-Li-B ternary diagram, as shown in Figure 4. All geothermal water that has a high content of Cl as compared to Li and B content indicates that the water comes from the old hydrothermal system where the fluid flows from the basement rock. Based on the interpretation result, the KTB system is divided into old and young hydrothermal system. Fluid samples in Talaga area indicate a younger system than Karaha area, a younger hydrothermal system showing a low maturity level than old system.

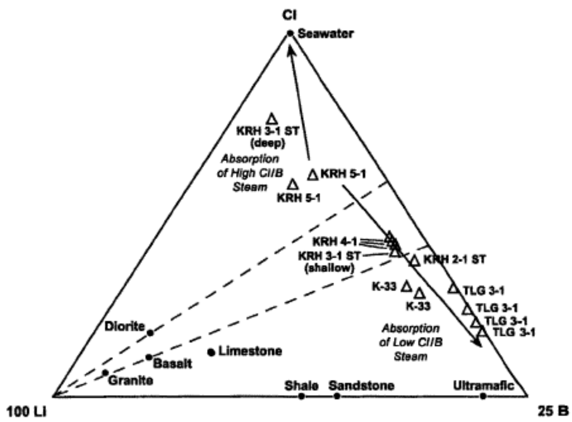


Figure 4: Cl-Li-B ternary diagram (Powel et al., 2001).

Moore et al (2002a) has made a relationship plot between N2/Ar and Ar/He ratio in fluid inclusion from T2, T8, and K33, as shown in Figure 5. The result shows that fluid from southern wells (T2, T8) are acidic due to magmatic gas

Table 1: Reservoir chemistry and geothermometers calculation (Powel et al., 2001)

Sample	Res stm frac	Na ppm	K ppm	Ca ppm	Mg ppm	Li ppm	B ppm	Si ppm	Cl ppm	SO_4 ppm	T-nkc °C	T-nkcm °C	T-qtz °C	T-anh °C
KRH 2-1ST	7%	424	52	3.7	0.31	0.72	33.0	348	534	128	228	227	223	300
KRH 3-1b	15%	497	96	2.6	0.018	1.68	43.4	541	826	58	268	268	267	unsat
KRH 4-1a	70%	1313	201	24.8	0.039	3.82	105.8	391	2247	29	248	247	233	260
KRH 4-1b	74%	1251	188	24.0	<0.0042	3.51	103.4	365	2107	27	245	245	227	262
KRH 4-1c	67%	1428	230	42.6	0.21	4.07	110.0	402	2450	22	247	247	236	255
KRH 5-1a	22%	2983	832	675	0.92	24.24	102.4	110	6909	20	272	271	143	220
KRH 5-1b	34%	2983	999	726	1.03	17.94	1.05	528	7014	14	285	285	264	232
KRH 5-1c	11%	3547	1069	929	2.31	19.56	129.4	70	8033	3.6	278	278	118	287
K-33a	25%	140	35	4.7	0.34	0.10	3.1	273	35	57	249	239	203	unsat
K-33b	25%	133	34	3.9	0.75	0.13	3.0	331	38	84	251	211	219	unsat
TLG 3-1a	85%	770	112	46.7	0.0094	0.26	165.1	502	1315	79	225	225	258	198
TLG 3-1b	88%	671	101	77.5	0.021	0.28	189.4	148	1223	79	218	218	161	183
TLG 3-1c	88%	769	120	143	0.025	0.35	143.6	186	1539	50	217	217	175	187
TLG 3-1d	87%	794	132	190	0.024	0.35	303.0	424	1660	45	219	218	241	186

influence, while fluid from center Karaha well, K33, is meteoric water without magmatic gas influence indication.

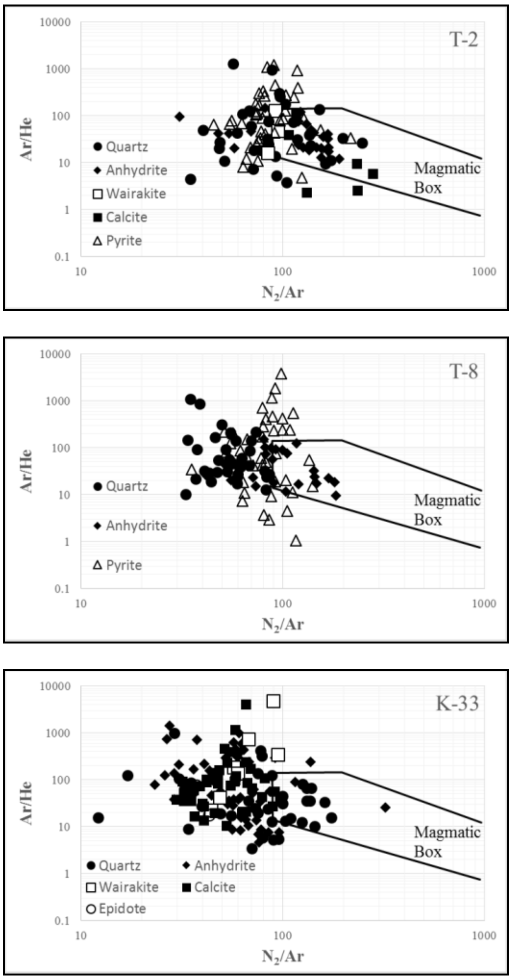


Figure 5: Ratios of N2, Ar and He in fluid inclusion (redraw from Moore et al., 2002a)

2.3 Geophysic Review

Several geophysics surveys have been conducted in the KTB field such as magnetotelluric (MT) and gravity. An MT survey covered the area shown in Figure 6. The survey divided into 3 phases. The first phase was conducted in Karaha with 10 MT sites. The second phase was conducted in Talaga Bodas with 11 sites and the third phase was conducted in both area Karaha and Talaga Bodas with 43 sites (GeothermEx Inc, 1998).

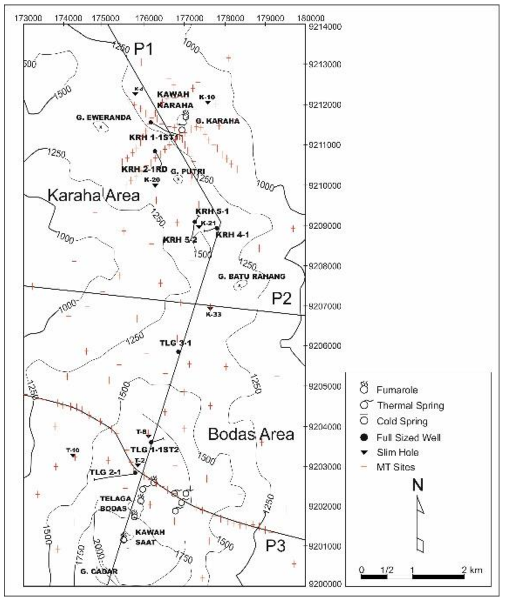


Figure 6: MT station location of KTB field (GENZL, 1997).

The analysis of MT data shows that the KTB geothermal field has a low resistivity value which represents a conductive layer. The conductive layer which has resistivity value lower than 10 Ωm is associated with reservoir seal cap and productive reservoir has ranging in resistivity from 15 to 60 Ωm, increasing in resistivity value has an effect on the decrease of material porosity. Most of the conductive layer in the KTB field is argillic type alteration (Moore et al., 2002b). This layer extends 12 km from Talaga Bodas to Karaha area. Raharjo et al (2002) interpret all MT data site by constructing both a forward and an inverse model of the conductive layer. The inverse model is used for interpretation of the conductive layer. The result of the interpretation shows that Talaga Bodas area has a low resistivity of 1-10 Ωm with the conductive layer thickness of 1000-1200 m, this layer extends along 7 km to the north. The conductive layer becomes thinner to 700 m and the resistivity value increase to 5-14 Ωm as it happened from 7 km to 12 km. Figure 7 shows the result of conductive layer interpretation from south to north, the conductive layer extent forms a tongue shape as the result of alteration from upflow to the outflow zone.

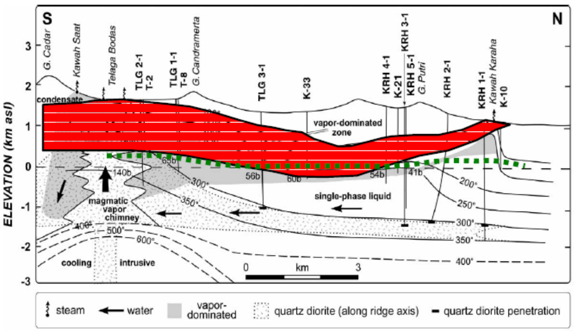


Figure 7: The interpretation of conductive layer (Raharjo et al., 2002).

A gravity survey was conducted in the KTB field using 2.3 g/cc value for the topography. Adapted from the GENZL survey, the Bouger gravity data result shown in Figure 8. The south area between Saat Crater and Talaga Bodas show a high gravity anomaly indicating an intrusion of a heat source into the geothermal system.

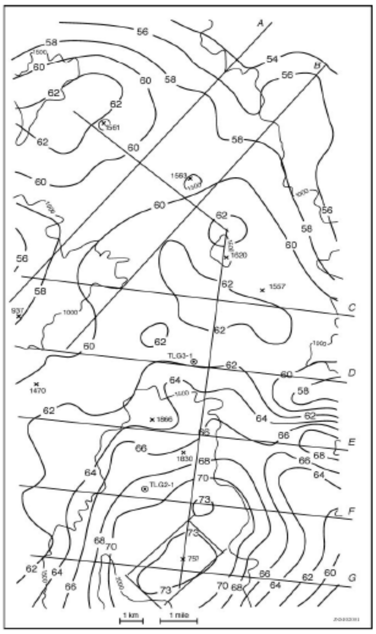


Figure 8: Bouger gravity map (GENZL, 1997).

2.4 Well Data

KBC has successfully drilled nine full-sized wells. Based on the drilling and well test reports, only five wells were categorized as a productive, with depths ranging from 1854 to 3076 meters. KRH 1-1, KRH 2-1, KRH 3-1 are classified as a non-commercial wells, while KRH 4-1, KRH 5-1 and all wells in Talaga Bodas are classified as a commercial wells. Seven of the wells located in KTB field were used for model validation, five wells as representative of Karaha area (KRH 1-1, KRH 2-1, KRH 4-1 and KRH 5-1) and three wells as representative of Talaga Bodas area (TLG 1-1, TLG 2-1, TLG 3-1). The characteristic of each well is shown in Table 2. The calculation of the reservoir thickness based on the origin of reservoir thickness added with 500 m. The fluid phase in the reservoir is based on an analysis of the boiling point depth each well.

Table 2: The characterization of all wells in KTB field

Well	Tmax (^{O}C)	Reservoir Thickness (m)	Reservoir Fluid phase
TLG1-1	289	1328	Superheated Steam
TLG2-1	350	1175	Superheated Steam
TLG3-1	286	1493	Steam zone underlying deep liquid reservoir
KRH1-1	235	1592	Compress Liquid
KRH2-1	269	1417	Compress Liquid
KRH4-1	263	1504	Steam zone underlying deep liquid reservoir
KRH5-1	272	1924	steam zone underlying deep liquid reservoir

2.5 Conceptual Model

The Conceptual model is obtained from geology, geochemistry, geophysics study results, and well data. The Conceptual model describes several information such as heat source, natural fluid flow pattern, geological setting, caprock, upflow and outflow zone and recharge (Grant & Bixley, 2011). The existing conceptual model has been made by Allis et al., (2000) as shown in Figure 9.

From Figure 9, heat source locations were estimated to be beneath Saat Crater and Talaga Bodas Lake. The upflow zone is located in Talaga and Karaha which is shown by the presence of multiple surface manifestations such as fumaroles; Talaga Bodas acid lake; several thermal springs; and the outflow of system is located in east of concession boundary.

Karaha-Talaga Bodas geothermal field is categorized as high temperature reservoir. The liquid reservoir is overlaid by a vapor zone. The highest temperature and pressure are found in well TLG 2-1. The south area has the thickest steam zone. The steam zone become thinner in direction toward north and its northern limit lies between wells KRH 2-1 and KRH 1-1.

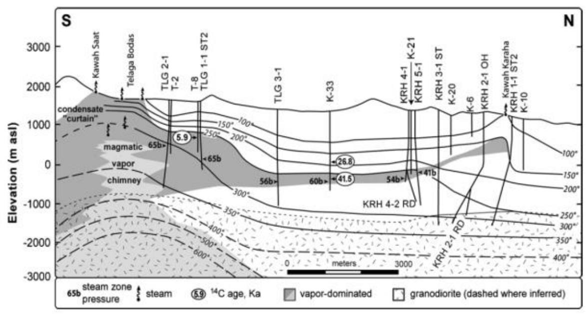


Figure 9: Conceptual model of Karaha-Talaga Bodas (Allis et al., 2000).

3. NUMERICAL MODEL

3.1 Grid System

The numerical model covers a total area 55 km^2, from 174000 to 179000 E and 9201000 to 9212000 N. The maximum elevation of surface model reaches 2087 m.a.s.l and the bottom of model was set to -2000 m below sea level. the grid block size varies from the smallest 250x250 m to the biggest 500x500 m. The grid is shown in Figure 10.

The model was constructed in single porosity with a rectangular grid and used 14 layers. The model was divided into 4 rock type layers that are surface, caprock, reservoir, and basement. The surface layer has a thickness of 10 m, the caprock thickness is up to 1300 m, the reservoir of 2000 m and basement 500 m. The model was built using TOUGH2 software and the model was assumed pure water, therefore, EOS 1 was chosen for the equation of state. The total of number element or block is 11088. A 3D view of the model can be seen in Figure 11.

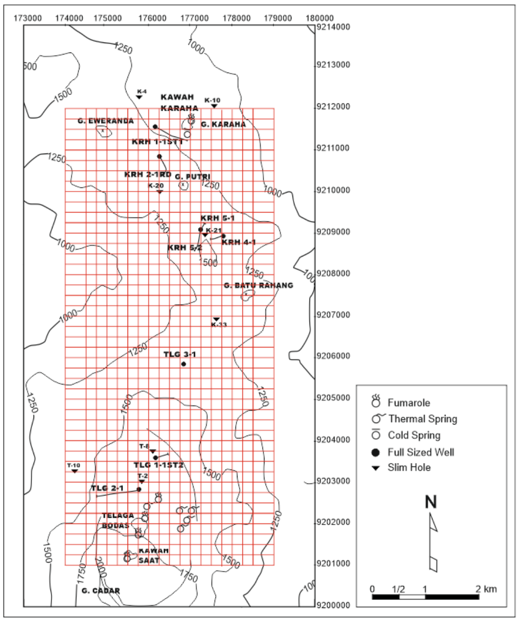


Figure 10: Grid system of the model.

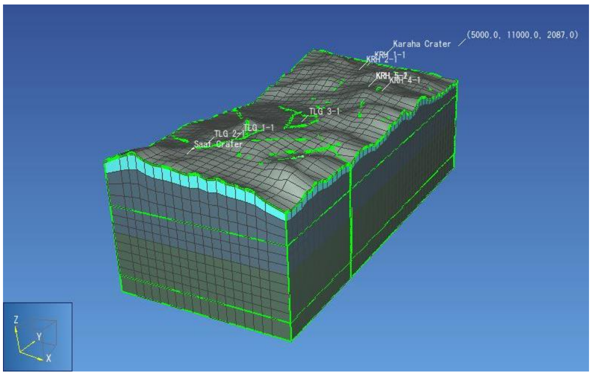


Figure 11: 3D model of KTB field.

3.2 Initial and Boundary Condition

Top Boundary

The Top Layer represents the atmospheric layer. Atmospheric condition is assigned to 1 bar and 20^{O}C. The volume factor of the atmospheric layer was also set to $1x10^{20}$ so that this layer cannot be affected by reservoir condition.

Bottom Boundary

High temperature fluid recharge with enthalpy of 1650 kJ/kg and mass rate 5 kg/s was assigned in bottom model. The location of deep recharge is in north area between KRH 1-1 and KRH 2-1 wells. The determination of the recharge mass and heat flow; and its location is based on the result of calibration process. The heat source was also assigned in the bottom model using 16 blocks in the southern area with maximum pressure and temperature reservoir are 165 bars, 350^{O}C and volume ratio set to $1x10^{38}$.

Internal Boundary

In this model, faults are represented by internal boundaries. Material properties of faults were assigned in each region of that internal boundary. Figure 12 show the 3D model of faults that were used in model.

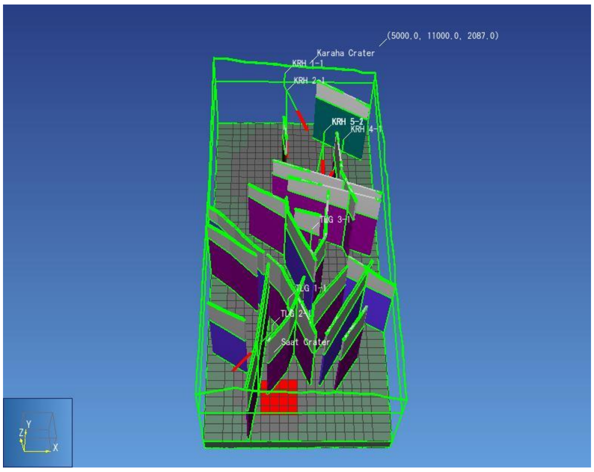


Figure 12: 3D Fault model.

Side Boundary

All side boundaries are assumed to be sealed so heat or mass cannot flow in or out into the system. Pressure and temperature of the side boundary using hydrostatic pressure and normal temperature gradient to represent environment condition. The delineation of the reservoir side boundaries is based on distribution of wells location and MT data

3.3 Material Properties

In the natural state modelling, the selection of material properties plays an important role. The most important property to give the best match in the natural state calibration process is permeability. Permeability will affect pressure and temperature distribution as well as the fluid movement direction in model.

Table 3: Material properties.

Rock Type		Desc.	Permeability kx, ky, kz (mD)			ϕ
SRF1		Surface	0.4	0.4	0.2	0.05
SRF2		Surface	0.9	0.9	0.5	0.05
SRF3		Surface	10	10	5	0.05
SRF4		Surface	1	1	0.8	0.05
CPR		Caprock	0.001	0.001	0.001	0.05
RSV1		Reservoir	100	100	50	0.07
RSV2		Reservoir	80	80	40	0.07
RSV3		Reservoir	20	20	10	0.07
RSV4		Reservoir	1	1	0.8	0.07
RSV5		Reservoir	10	10	4	0.07
RSV6		Reservoir	20	20	8	0.07
BON1		Boundary	1e-4	1e-4	1e-4	0.05
BON2		Boundary	0.01	0.01	0.01	0.05
BON3		Boundary	0.001	0.001	0.001	0.05
BASE		Basement	15	15	4	0.05
HEAT		Heat	1	1	0.7	0.05
FLT1		Fault	10	10	5	0.1
FLT2		Fault	40	40	20	0.1
FLT3		Fault	0.08	0.08	0.04	0.05

Rock Type		Desc.	Permeability kx, ky, kz (mD)			ϕ
FLT4		Fault	8	8	4	0.1
FLT5		Fault	20	20	10	0.1

Table 3**Error! Reference source not found.** displays all of the permeability and porosity materials that were used in model. The permeability value ranges from 0.0001 to 100 mD. Other material properties such as density, specific heat and wet heat conductivity are specified to 2600 kg/m3, 1000 J/(kg.^{O}K) and 2 W/(m.^{O}K). The distribution of material properties can be seen in Figure 13

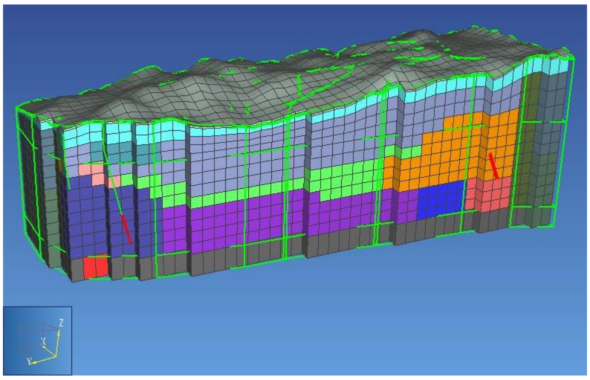


Figure 13: Material distribution.

4. NUMERICAL MODEL VALIDATION

During the natural state process, the model was run until a steady state condition was reached. Several validation processes have been used to check the reliability of model, such as pressure and temperature matching, steam zone presence, and heat and mass flow direction. To obtain a good fit between the model and actual measurement, several steps were enacted using an iterative process such as a change in permeability value, determining the amount and enthalpy of deep mass recharge, adjustment the location of deep recharge, and block refinement using a new rock type to improve matching process.

4.1 Pressure and Temperature Matching

The pressure and temperature of model are validated using 3 wells in Talaga (TLG 1-1, TLG 2-1, TLG 3-1) and 5 wells in Karaha area (KRH 1-1, KRH 2-1, KRH 4-1). Figure 14 shows the comparison between the model and measured data, the figure also shows a prediction of deeper reservoir pressure and temperature profile. The pressure and temperature matching of all wells give reasonable match. The Model has been able to reproduce shallow (steam reservoir) and deep reservoir condition (brine reservoir). The pressure and temperature in the shallow reservoir show a steam static pressure and convective temperature profile near saturation which is indicative of a steam dominated reservoir. The steam static pressure in the vapor reservoir occurred due to the equilibrium mass flux of steam moving up and water as the condensed steam moving down. The steam reservoir pressure in the south area is higher than the common reservoir pressure in vapor dominated systems of 30-40 bar (Allis et al., 2000). The pressure and temperature in the deep reservoir show a hydrostatic pressure and conductive temperature profile below temperature saturation which is indicative of a liquid dominated reservoir.

There was a shallow pressure mismatch in both KRH 1-1 and KRH 2-1 wells. This anomaly might be caused by high hydrostatic pressure and steam accumulation which led to increased pressure due to low of permeability around KRH 1-1 and KRH 2-1 area.

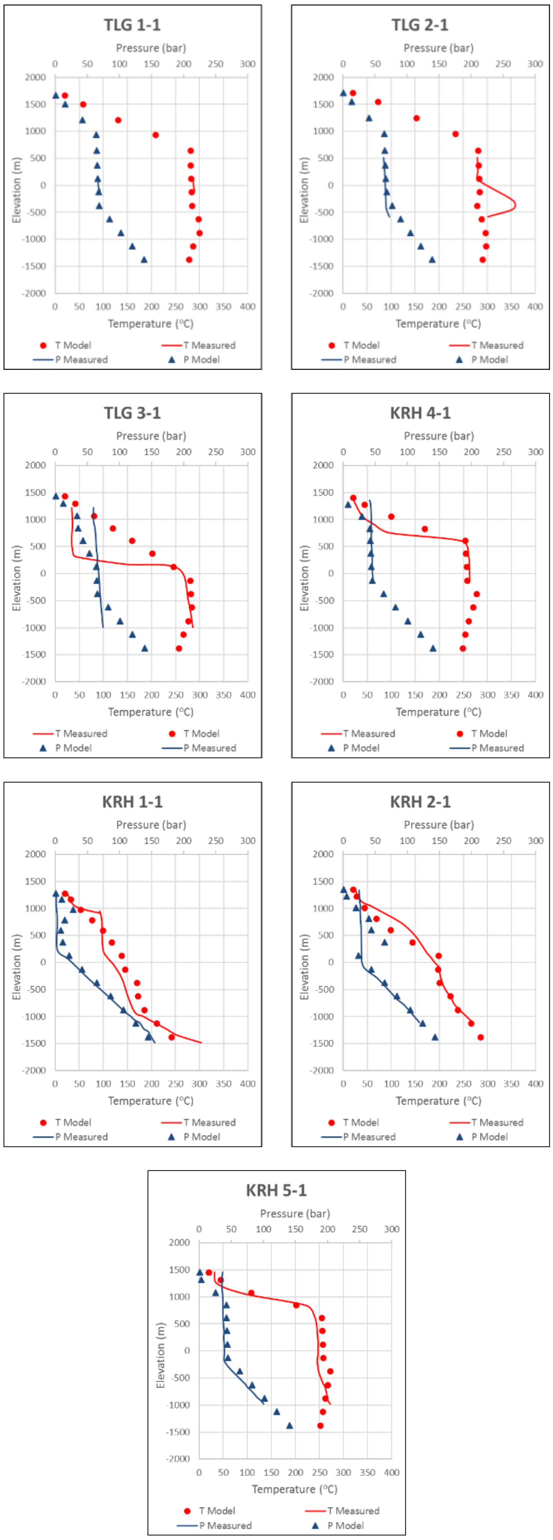


Figure 14: Pressure and Temperature matching results

All wells in the southern area show a convective profile while the northern area wells show a more conductive profile as shown in KRH 1-1 and KRH 2-1. The liquid reservoir in the southern area has the thickness range of 1000-1250 m while in the northern area its 1250-1750 m. In the southern area boiling occurred at -625 m below sea level and in the center area boiling zone occurred at -375 m below sea level.

4.2 Heat and Fluid Flow Direction

Based on the existing conceptual model in Figure 9, the heat source is located in the southern area beneath Saat Crater and Talaga Bodas Lake. Heat flows from the heat source to the north. A steam zone has formed at shallow depth and extends from south to north where it is thickest in the south. Figure 15 shows a temperature heat flow model in a south-north cross section. The results show that the model has already described the heat and fluid flow direction and steam zone extent similar to the conceptual model. During the natural state simulation, permeability plays role to control heat and mass flow movement.

There are some flow paths from the deep reservoir flowing toward the heat source which represents deep recharge from the basement or reservoir rock. In the model, convective heat transfer is indicated by a circular flow direction. Circular flow occurred due to density differences. At shallow depths, the heat transfer mechanism is mostly conduction.

There is heat anomaly in the northern area beneath KRH 1-1 and KRH 2-1, it is occurred due to deep mass recharge as seen in the model. High temperature inflow to the reservoir may represent a heat source in northernmost of Kahara that controls pressure and temperature in both of KRH 1-1 and KRH 2-1 wells. The presence of the heat source in northernmost portion of the model may update the previous conceptual model.

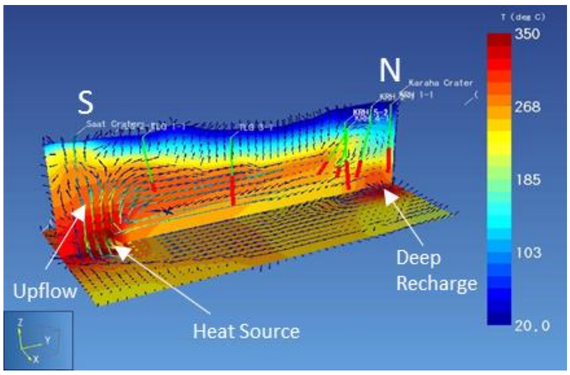
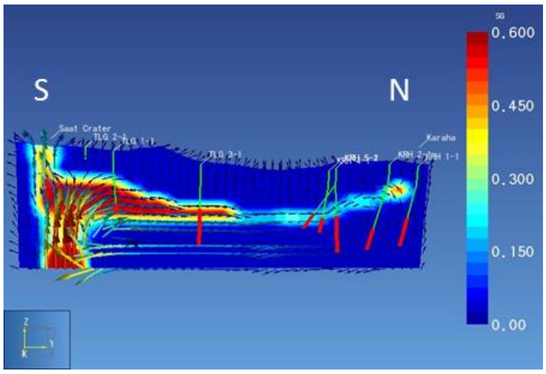


Figure 15: Heat flow model.

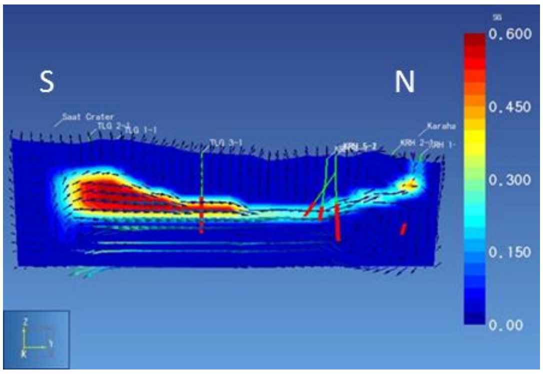
Figure 16 explains how the steam cap formed. Heat transfer occurred from the heat source to the reservoir by conduction. Steam flows originated from the south, flowing upward, after that flow laterally and spread at shallow depth to the north, an extent steam cap formed. During steam upflow, some steam can escape to the surface through a permeable opening layer as a surface manifestation. Figure 16a. shows a flowing upward steam which comes through Saat Crater, this upward stream formed a magmatic vapor chimney from heat source to surface. The challenge of this model is to reveal the steam cap underlying the brine reservoir and keep the steam cap extending to the north. Figure 16b. shows a horizontally extending steam cap where the northernmost portion of the model shows a steam stream seeping through a fault that controlled the presence of surface manifestation in the north area.

In the north area, steam moves up until it hits the caprock layer. In the caprock layer, the steam cannot flow upward due to the impermeable characteristic of the rock. Heat is lost through the caprock, some of the steam will be condensed and goes down due to the influence of gravity. It represents the counter flow heat transfer mechanism. Boiling fluid which occurred during liquid reservoir evaporation will segregate the reservoir into vapor and liquid. The rapidity of the segregation is controlled by high vertical permeability rock the reservoir and the higher temperature range of boiling.

In the steam dominated reservoir, steam occupies fracture space and water occupies matrix space. The amount of water mass is much greater than steam mass but it is in immobile condition, due to a saturated condition in the reservoir that makes water seeming mobile. The larger the boiling area, the greater the extent of the steam cap formed. This model has steam saturation value with the range of 0.2 to 0.6. As a comparison with similar vapour dominated field models, Pratama et al (2006) has design a synthetic two phase reservoir model with the result of average gas saturation value of 0.8, Ali Ashat et al (2017) designed a vapour dominated model of Ciwidey-Patuha field that has a steam cap underlying a deep liquid reservoir with an average gas saturation value of 0.65.



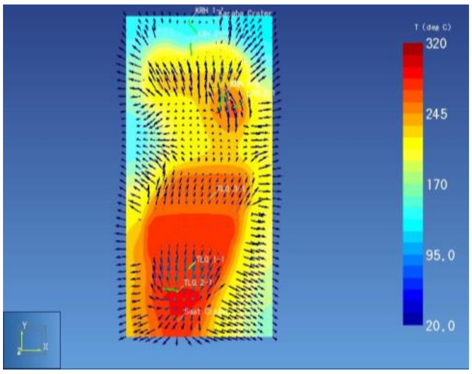
(a)



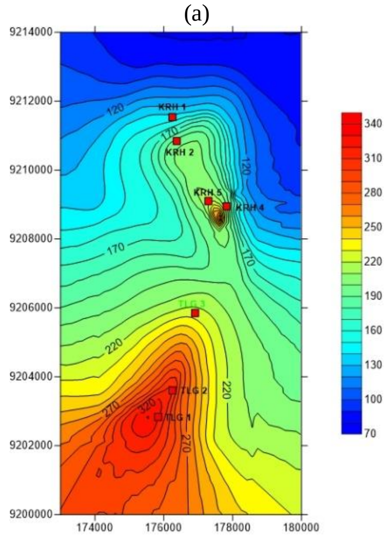
(b)

Figure 16: A horizontally extending steam cap model slicing at (a) 1800 m (b) 2800 m.

Figure 17 shows a comparison between model and measured temperature at sea level. The result shows that model is similar in lateral temperature compared with the actual measured temperature. In the center of Karaha temperature goes up around KRH 4 and KRH 5 due to high permeability around that wells. The northernmost area has a low permeability which indicated by temperature decreasing to the north.



(a)



(b)

Figure 17: Lateral temperature distribution comparison at sea level between (a) model and (b) measured temperature (redraw from GeothermEx Inc, 1998).

5. CONCLUSION

The natural state model of Karaha-Talaga Bodas which has a steam cap underlying with brine reservoir and extending from south to north, has been developed successfully. The KTB natural state model has been validated with actual pressure and temperature measurement data also with heat and mass flow from the conceptual model, hence it shows a good match and present a counter flow heat transfer. The additional heat source in the northernmost model below Karaha Crater will update the existing conceptual model, but further studies are needed to confirm this issue. The steam zone of the model formed in the deep southern area and it flows to the northern area with 0.2 to 0.6 gas saturation.

The numerical model can be used to create a development scenario strategy. Based on the results of the suitability of the model validation, the areas with moderate to good permeability (around 10 to 100 mD) are in the southern and central regions of the model, however based on geochemical data in the southern area have an acid fluid due to the influence of magmatic gas, therefore the center area of the model is the suitable location for development.

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