CORRELATION BETWEEN 3-D MAGNETOTELLURIC INVERSION MODEL WITH DRILLING DATA IN PATUHA GEOTHERMAL FIELD

KORELASI ANTARA PEMODELAN INVERSI 3-D MAGNETOTELLURIK DENGAN DATA SUMUR DI LAPANGAN PANAS BUMI PATUHA

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ABSTRACT

The Patuha geothermal field is located in West Java Province, Indonesia and developed by state owned company PT Geo Dipa Energi (Persero). The Commercial Operation Date (COD) for Patuha was in September 2014 with plant capacity of 1x60 MW. Until now, Patuha Unit I geothermal field has been running for almost 7 years. The current production wells have experienced a natural decline, which is showed by a reduction in production capacity to the initial production. This causes the steam supply to the Power Plant Unit I to be not optimal, so a make-up well program is needed. Furthermore, to support the addition of electricity production capacity from geothermal energy in Indonesia, the development of the Patuha Geothermal Field is planned to be carried out for the next Power Plant Unit's expansion (Unit 2 and Unit 3). Nevertheless, determining the location for both make-up and development drilling might still pose high risks. This is especially because the development area (where production and injection wells are located) is only concentrated in the eastern area of the contract area. Geophysical data especially Magnetotelluric (MT) has an indispensable role considering the limited data and the limited number of existing wells that cover the entire Patuha prospect area. To understanding the subsurface feature and see the correlation between MT model with well results in Patuha Geothermal Field, MT and TDEM survey were conducted in the eastern and western parts of Patuha area with total 100 stations. Considering the complexity of the subsurface condition in volcanic area, 3-D inversion of the MT data will be the most representative approach to investigate geothermal system in Patuha Geothermal Field. An obvious subsurface resistivity distribution revealed by the 3-D inversion showed a good agreement with well results especially in mapping the temperature distribution both vertically and horizontally. Generally, the resistivity distribution consists of a conductive zone (1–10 ohm-m) at the shallow part overlying a reservoir zone with a rather higher resistivity range (20–60 ohm-m). The conductive zone (<10 ohm-m) is correlated with Base of Conductor (BOC) of the wells that indicated by the presence of the argillic mineral. Meanwhile, the resistivity value around 15-20 ohm-m is correlated with Top of Reservoir of the production or injection well which is characterized by the presence of a convective temperature. In addition, from the results of resistivity mapping there is a very good correlation also in determining of reservoir boundary which is characterized by the presence of reverse temperature from the well. These results can be used as a guidance for better development strategy and drilling prognosis for the next drilling campaign especially in the area which limited number of wells.

Keywords: *Geothermal, 3-D Inversion, Magnetotelluric (MT), Patuha, Well*

ABSTRAK

Lapangan Panas Bumi Patuha terletak di Jawa Barat, Indonesia dan saat ini dikelola oleh PT Geo Dipa Energi (Persero) yang mulai beroperasi sejak September 2014 dengan kapasitas terpasang pembangkit 1x60 MW. Sampai saat ini, lapangan Panas Bumi Patuha Unit I sudah beroperasi selama hampir 7 tahun. Secara umum, kondisi sumur-sumur produksi saat ini sudah mengalami *natural decline,* sehingga terjadi pengurangan kapasitas produksi terhadap produksi awal. Hal ini menyebabkan suplai uap ke Power Plant Unit I menjadi tidak optimal, sehingga dibutuhkan sumur *make-up*. Selain itu, untuk mendukung penambahan kapasitas produksi listrik dari energi panas Bumi di Indonesia, Lapangan Panas Bumi Patuha juga merencanakan untuk melakukan pengembangan lapangan Unit 2 dan 3. Namun, dalam menentukan lokasi pengeboran sumur produksi baik untuk *make-up* maupun rencana pengembangan, masih memiliki resiko cukup tinggi, khususnya di area pengembangan yang sumur-sumur produksi dan injeksinya terkonsentrasi di area timur WKP Patuha. Data geofisika khususnya Magnetotellurik (MT) memiliki peranan yang sangat penting mengingat keterbatasan data dan jumlah sumur yang ada, belum melingkupi keseluruhan prospek area Patuha. Untuk mengetahui kondisi bawah permukaan dan melihat korelasi antara model MT dengan hasil pengeboran sumur, dilakukan penambahan survei MT dan TDEM dengan jumlah 100 titik yang tersebar di bagian timur dan barat area Patuha. Mengingat kompleksitas kondisi bawah permukaan di daerah ini, pemodelan dengan inversi 3-D MT akan menjadi pendekatan yang paling representatif untuk mendelineasi sistem panas-buminya. Hasil dari struktur resistivitas bawah permukaan yang didapatkan dari hasil inversi 3-D MT, menunjukkan korelasi yang baik dengan data sumur terutama dalam memetakan distribusi temperature, baik secara vertikal maupun horizontal. Secara umum, resistivitas bawah permukaan terdiri dari lapisan penudung (< 10 ohm-m) di bagian atas yang menutupi zona reservoir dengan nilai resistivitas yang sedikit lebih tinggi (20–60 ohm-m). Zona konduktif (< 10 ohm-m) berkorelasi dengan *Base of Conductor* (BOC) sumur yang ditunjukkan dengan kehadiran mineral argilik. Zona nilai resistivitas sekitar 15-20 ohm-m, berkorelasi dengan *Top of Reservoir* (TOR) sumur produksi atau sumur injeksi yang ditandai dengan adanya temperatur konvektif. Selain daripada itu, pada hasil pemetaan resistivitas 3-D MT terdapat korelasi yang sangat baik juga dalam penentuan batas reservoir yang ditandai dengan keberadaan *reverse temperature* dari sumur. Hasil tersebut diharapkan dapat menjadi acuan dalam memberikan tingkat kepercayaan yang lebih tinggi untuk menentukan target dan prognosis sumur pemboran terutama di area yang jumlah sumurnya masih terbatas.

Kata kunci: Inversi 3-D, Magnetotellurik (MT), Patuha, Panas Bumi, Sumur

INTRODUCTION

Patuha is a steam dominated geothermal field which hosts relatively shallow reservoir with reservoir temperature is around 217-238°C. The Patuha Geothermal Field is situated in West Java Province, Indonesia, about 50 kilometers southwest of Bandung. There are the Wayang Windu, Darajat and Kamojang geothermal fields on the eastern side which are steam dominated fields on well. The Patuha geothermal field is located in a mountainous region extending from west-northwest to east-southeast. In this mountainous region, mountains of which elevations are over 2000 m above the sea level align from northwest to southeast; Mt. Kendeng, Mt. Masigit, Mt. Patuha, Mt. Urug, Mt. Waringin and so on. Patuha Concession Area is around 350 km², exclude Cibuni Concession Area which is inside the concession area (Elfina, 2017). Drilling was started by Patuha Power Limited (PPL) with a slim hole campaign in 1996 consist of 17 wells. The field development continued by drilling of big diameter wells until 1998 including of 14 wells.
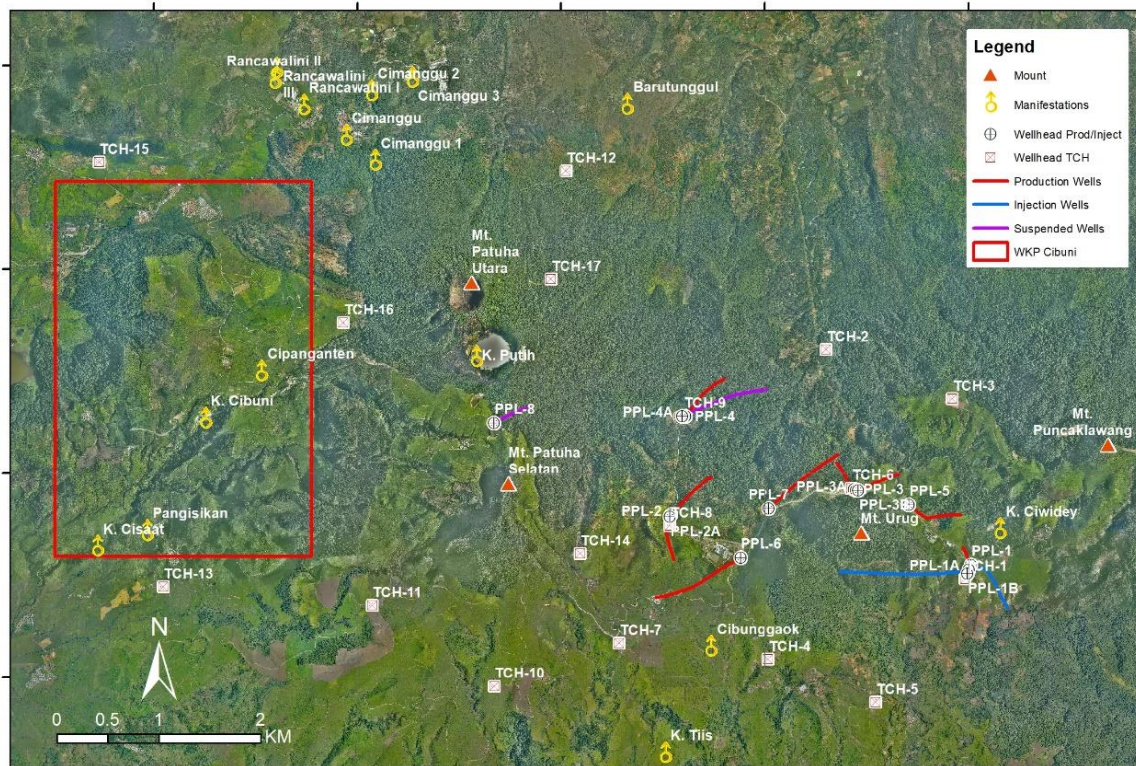
PATUHA GEOTHERMAL FIELD

Figure 1. Concession Area of Patuha Geothermal Field

All existing production and injection wells area are located in the eastern part of the field (see Figure 1). Patuha Geothermal Power Plant was started commercial operation on September 22th 2014. MT survey was conducted firstly by Geosystem and PT Tri Bawana Utama (TBU) who did MT acquisition with 35 stations in 1995. Then, in 1997, Geosystem and TBU carried out another MT survey with 85 stations. A TDEM survey was conducted with 255 stations to be able to apply static shift correction to the MT data (Elfina, 2017). After handover process between PPL and PT Geo Dipa Energi (Persero), PT Geo Dipa Energi (Persero) only obtain MT, Gravity, and TDEM surveys report in print form, while raw data of those surveys was not available. In 2013, Elnusa did digitizing and reprocessing MT data because the limitations of MT data from the previous survey.

Several previous research have been performed to delineate geothermal system

in Patuha by MT data. Pratama et al. (2015) did a combination of 2-D MT inversion and 2-D forward gravity data to represent the conceptual model based on geophysical data, while Elfina (2017) did updated the conceptual model of the Patuha geothermal field used well data with combined by 3G data. In this study, the latest MT data was used to improve quality of data from the previous MT data in 1997-1998. In 2020, PT Geo Dipa Energi (Persero) were conducted geophysical data of 100 stations MT-TDEM with a station spacing of about 500 meters in the northwest and 1000 meters in the southeast part (existing production and injection area) of Putih Crater.

Moreover, in order to get comprehensive analysis about the geothermal system in the Patuha Geothermal Field and it is correlation with the drilling data (well) result, the 3-D inversion modeling was conducted in this study. MT method was chosen because it is the most powerful

geophysical method to delineate geothermal system model based on resistivity distribution. Subsurface resistivity conditions in the real earth might be very complex. It could vary in all directions, vertically and laterally. So, the modeling using 1-D and 2-D MT inversion approach is not sufficient to represent the real subsurface condition (Daud, 2019). Possible misleading in applying 2-D inversions caused by 3-D subsurface conditions has been studied by demonstrating synthetic data (Siripunvaraporn et al., 2005) as well as real data (Simpson and Bahr, 2005; Cumming and Mackie, 2010).

DATA AND METHODOLOGY

MT data were acquisition using a Phoenix instruments and processed with the frequency about 320 Hz to 0.0001 Hz. It was conducted at 100 stations MT-TDEM (see Figure 2) with a station spacing about 500 meters in the northwest and 1000 meters in the southeast part (existing production and injection area) of Putih Crater with length of acquisition around 12 hours. Providing suitable subsurface resistivity model from MT data is about conducting all the steps in the workflow of MT technology properly Daud, 2020). It was started from provide good survey design and make sure all the instruments and operation procedure are applied properly.

Data processing workflow is beginning with time-series inspection MT data. The next steps are transforming the time-domain data to frequency domain as well as calculating the impedance tensor. The output of the process is apparent resistivity and phase vs frequency curve. The resulted curves usually display a quite low quality at the beginning. Therefore, data selection (cross power selection) should be further conducted (Daud, 2020). Careful selection is recommended rather than auto-processing (automatically processed by software) (Daud et al. 2017). This process takes much time, however could significantly improve the data quality.
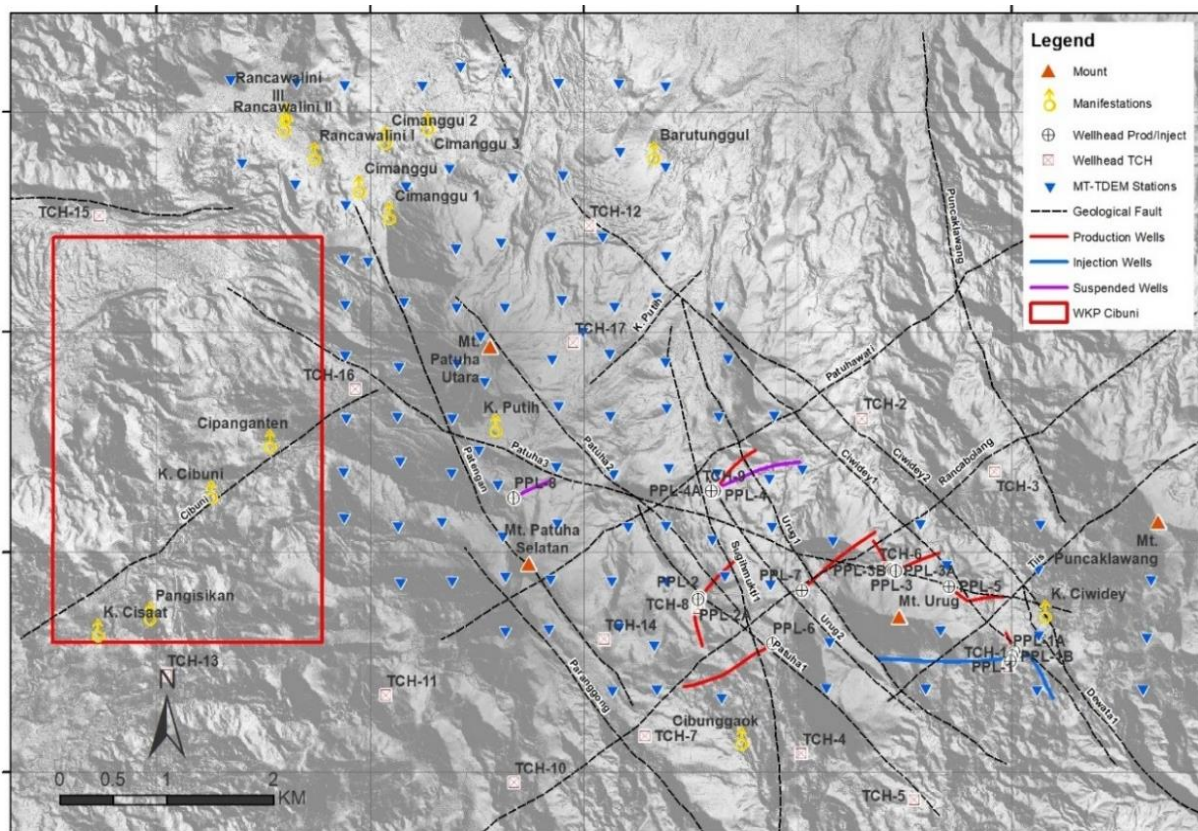

Figure 2. Distribution of MT-TDEM stations with blue solid triangle

The cross power selection was processed in a frequency range of 320 - 0.0001 Hz to get the optimal trend of MT curve. Generally, the quality of MT data after cross power selection has a smooth trend with and without small error bar as seen in Figure 3. It could increase the confidence level as an input data for further modeling. Static shift correction should be conducted before performing data modeling/inversion.

Arnason (2015) and Siripunvaraporn et al. (2005) suggested to conduct static shift correction even before conducting 3-D inversion. Time-domain Electromagnetic (TDEM) data is usually used to conduct the static shift correction. The last step is selecting Modeling/Inversion Scheme. The 3-D MT inversion was performed using a code by Siripunvaraporn that utilizes a data-space variant of the Occam approach (Siripunvaraporn et al., 2005). The 3-D inversion was running with parameters: Full components of impedance tensor, total number of model blocks was 63,360 (48×60×22 blocks) with block size (x,y,z) 200x200x10 meter and padding factor 1.5x1.5x1.5. Initial resistivity model 100 ohm-m homogeneous with an error floor set at 5% also was performed to obtain a good fit between measured and observed data. The complexity of geothermal area in the subsurface, choosing 3-D inversion scheme would be better to overcome such complex 3-D structure.

GEOLOGICAL SETTING AND GEOTHERMAL MANIFESTATIONS

Patuha geothermal field lies within quaternary volcanic zone which is originally formed by the subduction in the south of Java Island. Interaction between Indo Australian plate with Eurasian plate produce java trench which extend from Sumatra Island to the east of Nusa Tenggara, where is the Indo-Australian plate moved to the north beneath the Eurasian plate (Hamilton, 1979). The volcanic axis presumably reflects a deeply penetrating, west to northwest trending structural zone. This may be part of a major structural feature which extends for over 40 kilometers, as indicated by the similar orientation of the mountain range containing the Patuha field (Layman and Soemarinda, 2003). The surface lithology in this area is dominated by the lava flows and andesitic lahar deposits from Patuha volcano and Kendeng mountain (Koesmono et al., 1996).
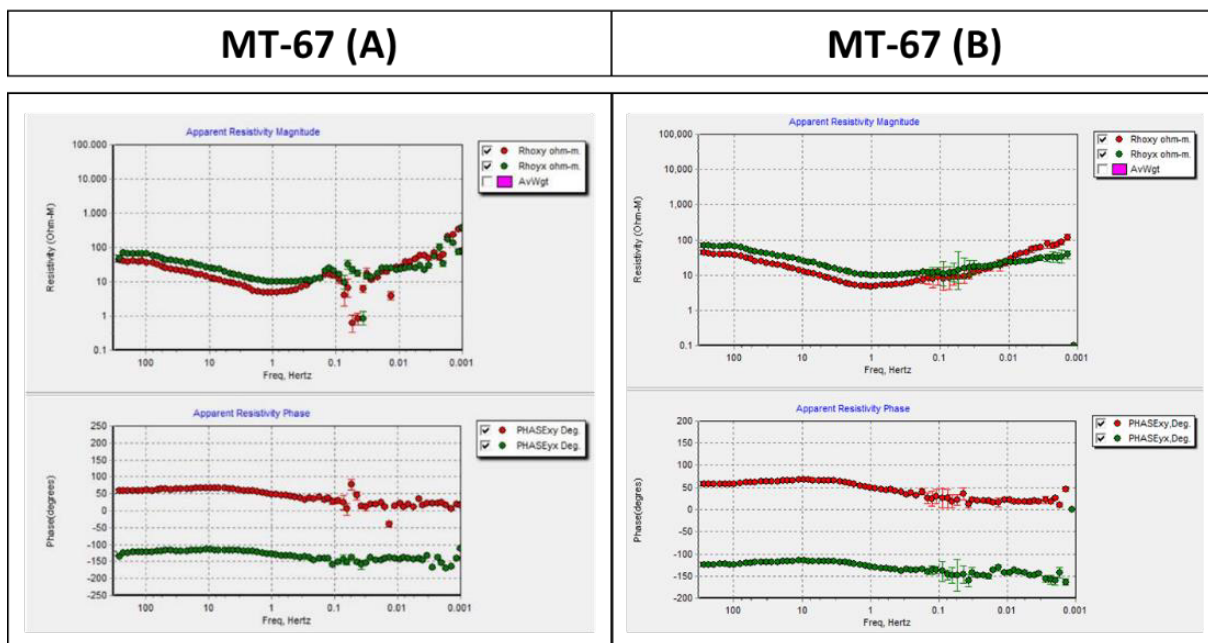

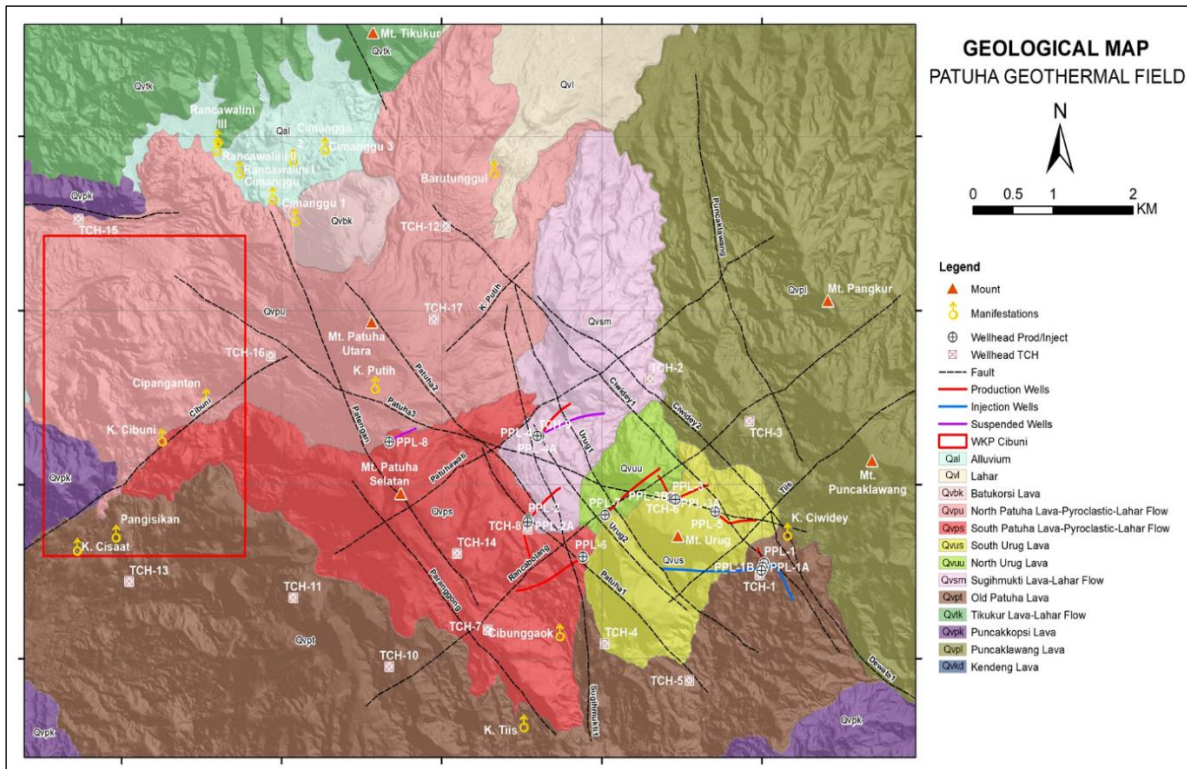**Figure 3**. Comparison between before (A) and after (B) cross power selection

Figure 4. Geological map of Patuha Geothermal Field

Generally, detailed field geology survey identified the volcanic products which constructed the Patuha field are related to Andesite-Basalt and Andesite-Dacite composition in the form of Lava, Breccia, Tuff, and other Pyroclastic types from several complex volcanic activities. There are many thermal manifestations seen on the surface such as fumaroles found in Ciwidey, Cibuni, and solfatara found in Putih Crater, hot springs found in the northern, eastern, western part of the field, warm springs found in northern, western, southern of the field (Figure 4). Kawah Putih are categorized as sulfate-chloride water type with extremely lower pH between 0.5 and 1.

RESULTS AND DISCUSSIONS

RESULTS

Well Data
The reservoir temperature in Patuha is around 217-238°C as indicated by wells. The top of reservoir (TOR) depth is interpreted from the initial state of Pressure and Temperature supported with other data such as location of Feed zones and losses. The result for the TOR depth is shown on Table 1. Table 1 shows the shallow TOR is seen around Ciwidey Crater (near PPL-01) and Putih Crater (near TCH-17 indicated with high temperature) with Range of TOR elevation around 1300 -1000 masl. Subsequently, the deeper gradient or TOR depth is directed to the thermal spring in the North, South West, South and East that indicate the flow trend from the center of the field. There are two wells that have reverse temperature at deep depths, namely PPL-1A (injection well) and PPL-06 (production well). The existence of the reverse temperature can indicate the reservoir boundary in the Patuha Geothermal field (see Figure 5). Figure 5 also shows the distribution of Temperature in Patuha at 1000 masl. The solid line on the temperature contour is delineated by the well data. The dashed line on the temperature contour is generated automatic interpolation by software because limited number of existing wells that cover the entire Patuha prospect area. This can be one of the risk factors in the development plan area in Patuha.

Table 1. List of TOR depth based on review from initial PT well data

| Well	Status	TD (masl)	Max Temp (degC)	TOR (masl)	Notes
PPL-01	Production	958	217	1198	-
PPL-1A	Injection	-325	203	1271	PPL-1A has reversal Temperature (175°C)
PPL-1B	Injection	324	172	1329	-
PPL-02	Production	16	238	1230	-
PPL-2A	Production	368	232	1191	-
PPL-03	Production	496	226	1150	-
PPL-3A	Production	1071	228	1234	-
PPL-3B	Production	905	226	1200	-
PPL-04	Production	-116	235 (?)	773	Data quality of PPL-4 is poor
PPL-4A	Suspend	647	-	-	-
PPL-05	Production	452	224	1334	-
PPL-06	Production	-349	222	1238	PPL-06 has reversal Temperature (190°C)
PPL-07	Production	554	227	1089	-
PPL-08	Suspend	1325	-	-	-
TCH-17	Idle	1289	218	1250	Possible TOR
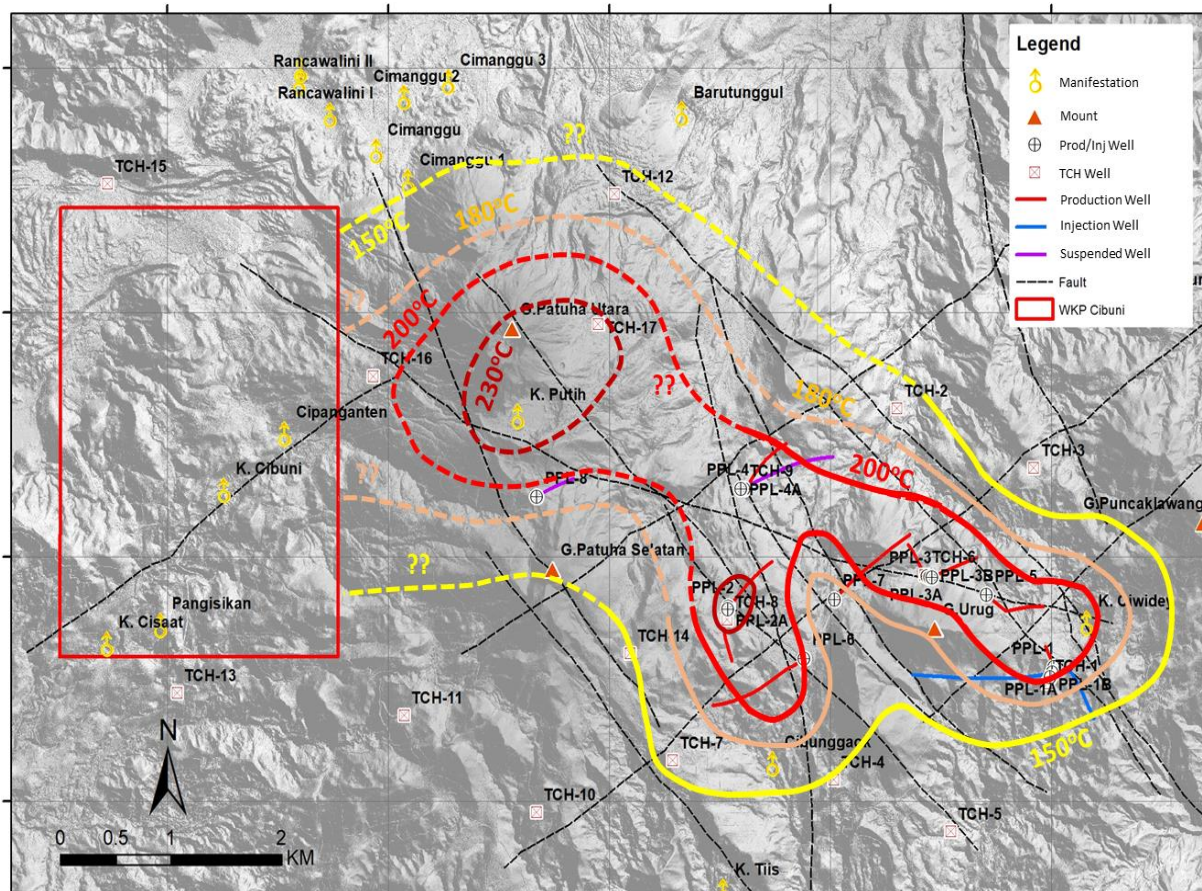
Figure 5. Distribution of Temperature (°C) in Patuha at 1000 masl. The solid line on the temperature contour is delineated by the well data. The dashed line on the temperature contour is generated automatic interpolation by software

MT Data

A. Resistivity Cross-Section

The 3-D MT inversion model was running out using a code by Siripunvaraporn that utilizes a data-space variant of the Occam approach (Siripunvaraporn et al., 2005). Static shift correction (with TDEM data) was done before 3-D inversion started to remove static effect. The imaging of geothermal system can be seen in the 3-D MT inversion results. Two vertical cross-sections of MT Line 1 and Line 2 are shown in Figure 6 and 7. The cross-section of Line 1 extends from the Mt. North Patuha (Near Putih Crater), some of production wells (PPL-4, PPL-7, PPL-3, PPL-5, PPL-1) and also Ciwidey Crater (NW-SE direction). The cross-section of Line 2 cuts across Mt. South Patuha towards some of production wells (PPL-2, PPL-7, PPL-3, PPL-5, PPL-1) and also Ciwidey Crater (W-E direction). Generally, the cross-sections show low resistivity layer in the shallow part and high resistivity in the deeper part. A low resistivity layer indicated as cap rock with the resistivity value between 1 and 10 ohm-m overlies a rather higher resistivity layer. The thickness of the cap rock varies from thinner around 500 m to thicker about 2500 m. The rather higher resistivity layer shows resistivity values ranging about 15 to 60 ohm-m which is indicated as the reservoir of the Patuha geothermal system. In deeper part, the highest resistivity layer (> 100 ohm-m) which is indicated as a possible heat source/hot rock of the Patuha geothermal system. The shallowest BOC (Base of Conductor) layer (< 10 ohm-m) is found in the eastern part beneath the Ciwidey Crater at the elevation of about 1250 masl. On the other hand, the low resistivity layer gets thickened towards to western area until the deepest of about -1000 masl. The doming of resistive layer occurs below the Putih Crater and Mt North Patuha which might indicate an upflow zone. The high temperature solfatara occurs in this location. Besides that, the updome-shape also seen beneath Mt. South Patuha but there are no surface feature represents the direct discharge of the deep reservoir around this area as seen in Figure 7.
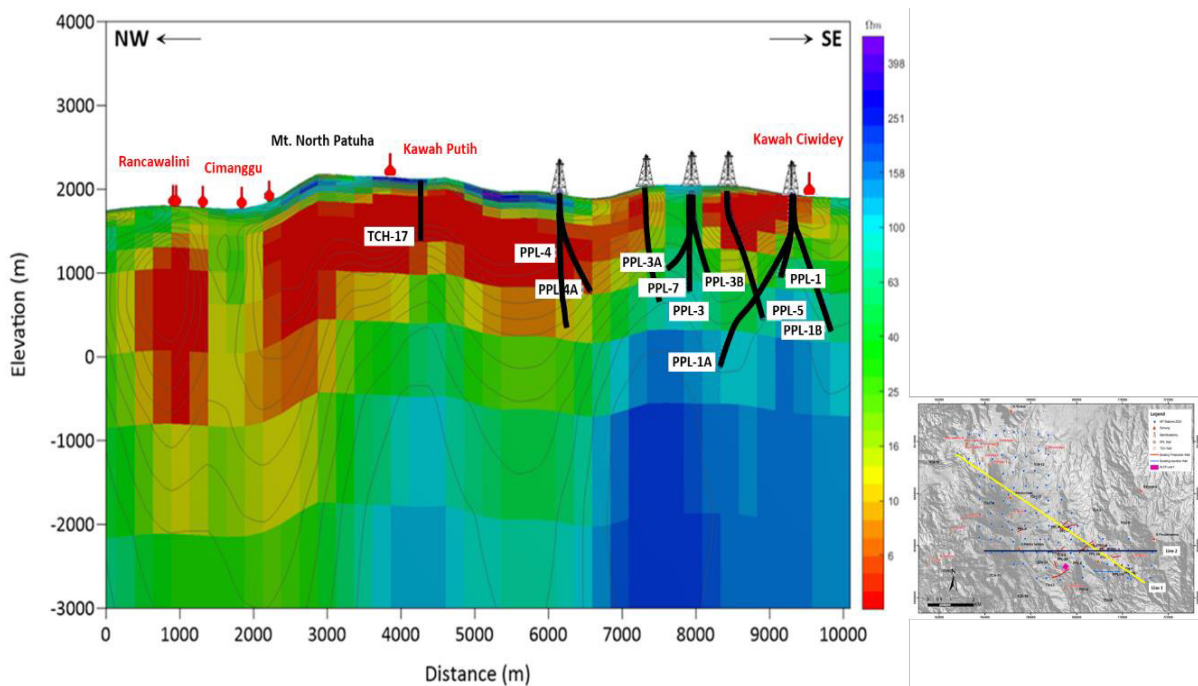

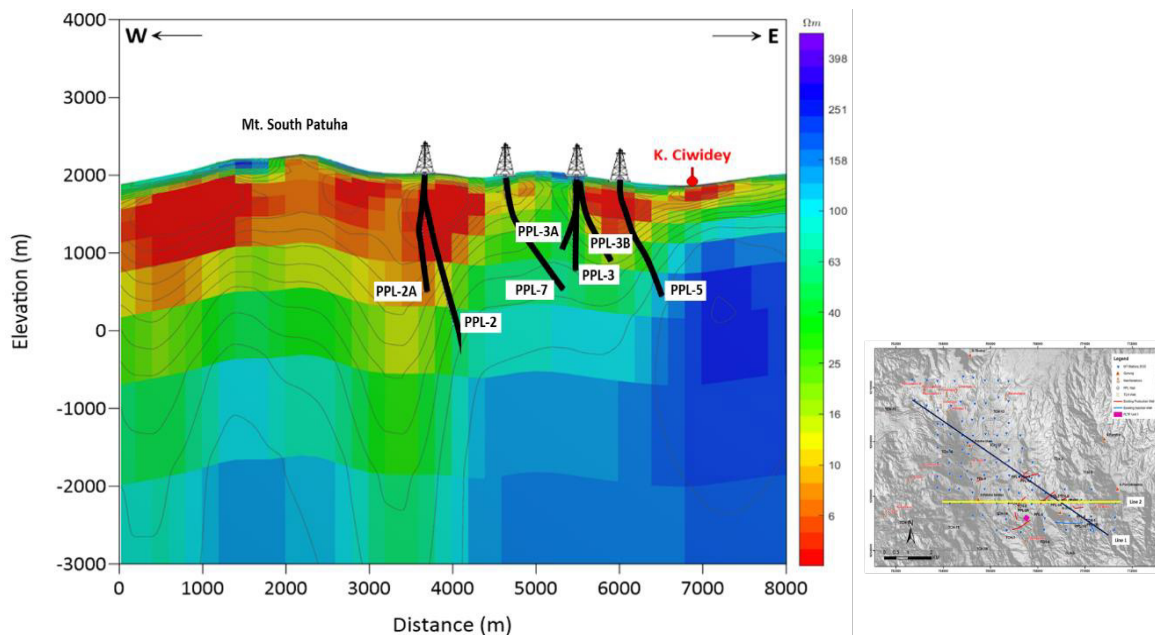**Figure 6**. Resistivity section of Line 1 with yellow solid line

Figure 7. Resistivity section of Line 2 with yellow solid line

B. Resistivity Distribution

The map of resistivity distribution at elevations: 1750, 1250, 750, 250, -1000 and -2000 meters are showed in Figure 8. At 1750 meters elevation, the low resistivity anomaly with resistivity of about 1 to 10 ohm-m, starting to emerge mostly in Patuha Concession Area. The low resistivity anomaly that appears in this area can be interpreted as altered rock. The rather higher resistivity layer (15 to 60 ohm-m) begins to occur at 1250 m elevation especially in the eastern part. Therefore, this elevation is estimated as the shallow top of reservoir (TOR) in the Patuha geothermal system compare than in western part. The highest resistivity zone in deeper part which indicates a possible hot rock/heat source of Patuha geothermal system extends around Mt. North Urug (near Ciwidey Crater), Mt. South Patuha and Mt. North Patuha (near Putih Crater).

DISCUSSIONS

The indication of high temperature system can be identified from the mineral presences that associated with temperature. The minerals that could be used to indicate the reservoir temperature are epidote and base of argillic or top of prophylitic. The geometry and depth are only used for guidance due to the epidote is more represent the liquid condition but the base of argillic may represent more to the current steam dominated condition. Figure 9 and Figure 10 shows a cross-section Line 1 and Line 2 that combine the 3-D inversion result of MT and drilling data (argillic-epidote zone and temperature profile from the wells). The presence of argillic zones that indicated as clay cap (with orange color in trajectory of well) have very good correlation with low resistivity value < 10 ohm-m. The base of argillic layer in the well has a trend going deeper from the eastern to western part. The continuous epidote zones (with green color in trajectory of well) also have very good correlation with moderate resistivity zone 15-60 ohm-m that indicate as reservoir zone. Generally, the resistivity distribution in MT model are almost correlated to delineate clay cap and reservoir zone in well data. However, this trend only used for guidance and the depth need to be compared with other data such as Top of Reservoir (TOR) from wells data since the mineral may indicate a relic condition.
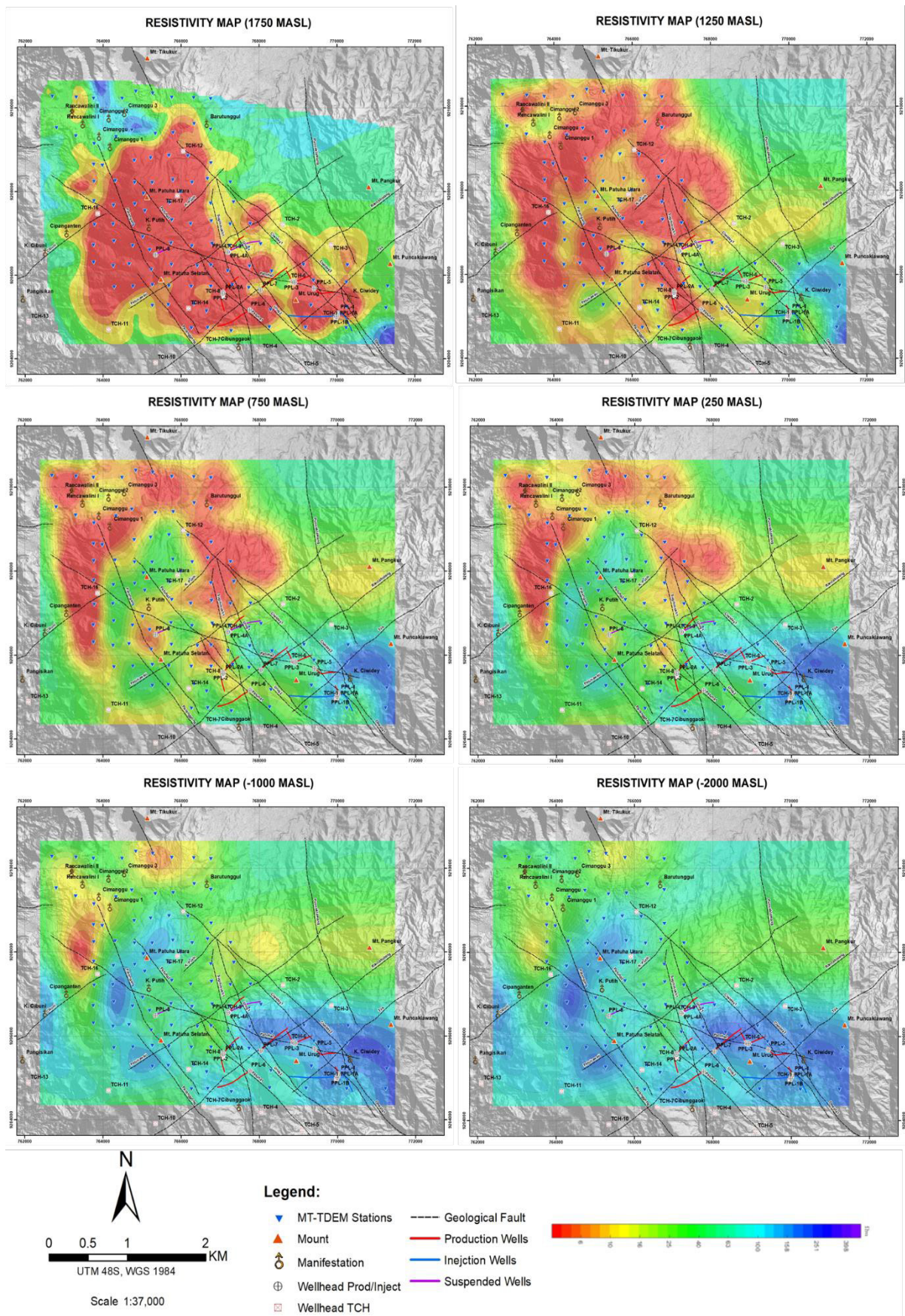
Figure 8. 3-D MT resistivity map distribution (in ohm-m) from 1750 to −2000 m elevation

Furthermore, the 3-D inversion model of MT data showed a good correlation also with well results especially in mapping the temperature distribution both vertically and horizontally. The initial of convective temperature in Patuha that indicated as reservoir temperature is about 217-238°C. The resistivity value around 15-20 ohm-m is correlated with Top of Reservoir of the production or injection well which is characterized by the presence of a convective temperature. The temperature of the well has same pattern with the distribution of Base of Conductor (BOC, < 10 ohm-m) as seen in Figure 9 and Figure 10. The solid line on the temperature contour is delineated by the well and 3-D MT and the dashed line on the temperature contour is guidance by BOC distribution map. The BOC from 3-D MT data is correlated with temperature around 200°C. In addition, high resistivity values >100 ohm-meters were also found in the area around the PPL-7 and PPL-3 wells that possibility correlated with the intrusion of diorite that found in the analysis of the cutting samples of those wells.
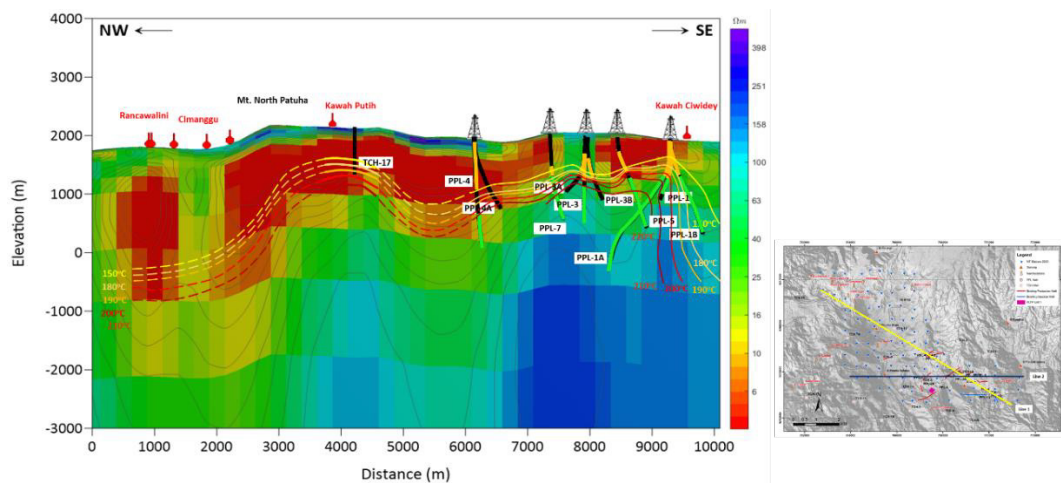

Figure 9. Resistivity section of Line 1 with temperature of well and mineral presence. Argillic zones with orange color in trajectory of well and continuous epidote zones with green color in trajectory of well
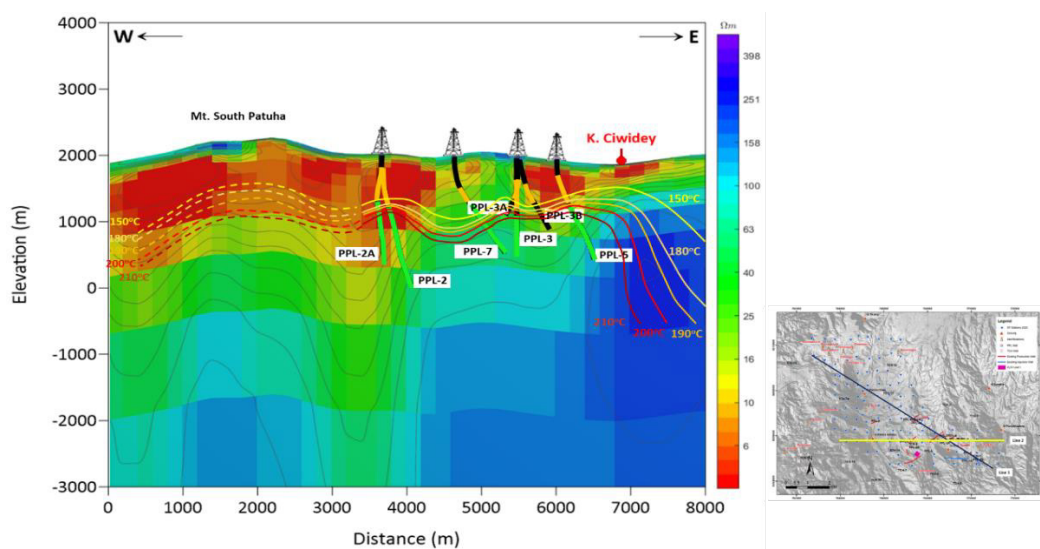

Figure 10. Resistivity section of Line 2 with temperature of well and mineral presence. Argillic zones with orange color in trajectory of well and continuous epidote zones with green color in trajectory of well
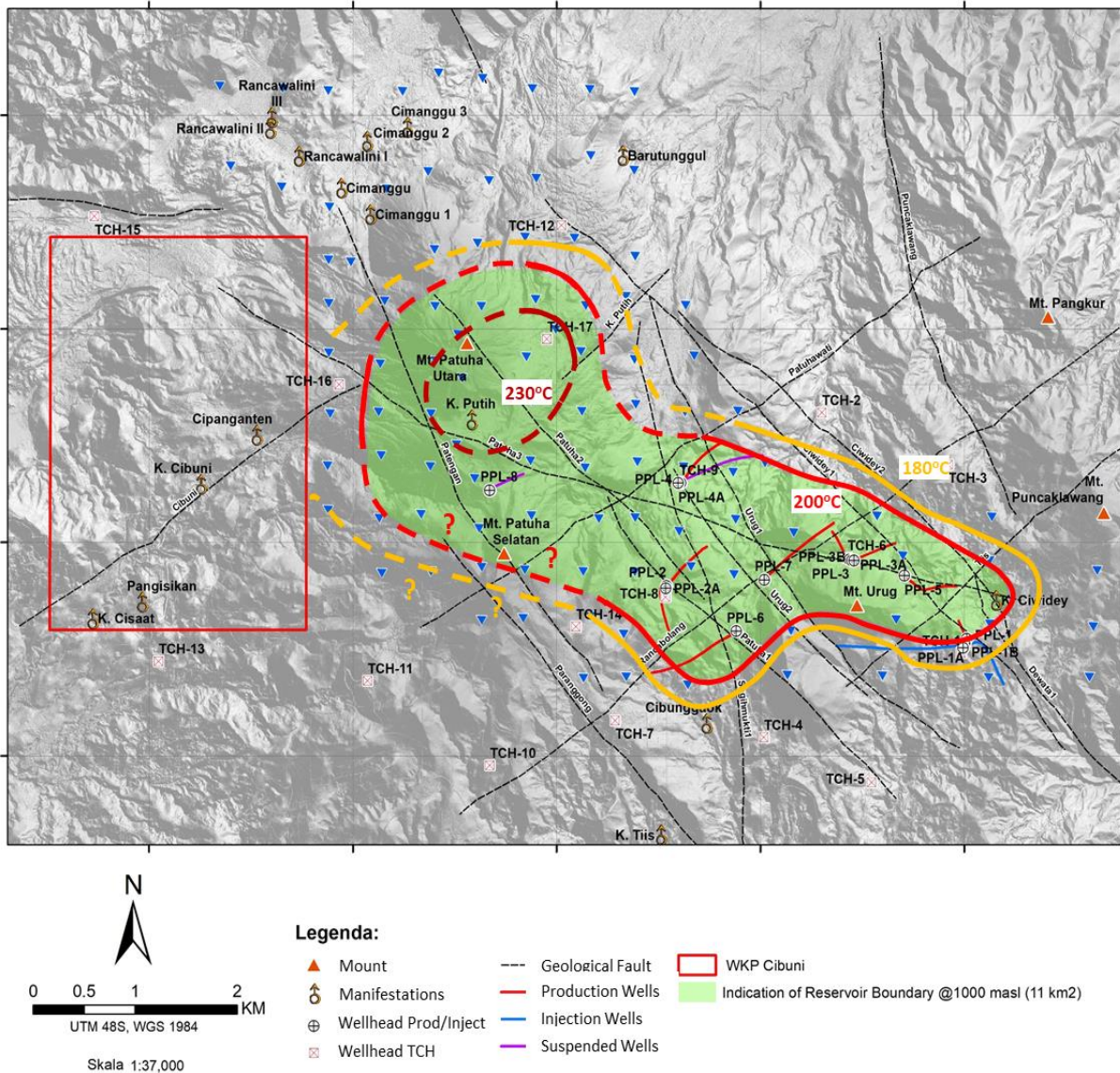
Figure 11. Distribution of Temperature (°C) in Patuha at 1000 masl after corrected with 3-D MT. The solid line on the temperature contour is delineated by the well and 3-D MT. The dashed line on the temperature contour is guidance by low resistivity distribution map

On the MT resistivity distribution map at elevations of 1750 m elevations (see Figure 8), it can be clear seen that the distribution of low resistivity anomaly (<10 ohm-m) that indicated as clay cap spreads to almost the entire of Patuha geothermal field area except in the area of total depth (TD) trajectory of the wells PPL-1B, PPL-1A and PPL-06. The distribution of low resistivity anomaly (<10 ohm-m) can indicate also as the boundary reservoir area in the Patuha Geothermal field. The PPL-1B has a well temperature that is not high enough compared to other wells, which is around 175°C. Consequently, PPL-1B is not commercial for production well and it is used for injection well. In addition, from the results of resistivity mapping there is a very good correlation also in determining of reservoir boundary which is characterized by the presence of reverse temperature from the well. There are two wells that have reverse temperature at deep depths, namely PPL-1A (injection well) and PPL-06 (production well) that can be seen in Figure 11.

If we compare Figure 5 and Figure 11, the distribution of Temperature in Patuha at

1000 masl has a significant difference, especially in areas that have a limited number of wells in the northwest area. Figure 11 shows a distribution of Temperature in Patuha at 1000 masl after corrected with 3-D MT results. The solid line on the temperature contour is delineated by the well and 3-D MT and the dashed line on the temperature contour is guidance by low resistivity distribution map. The guidance is carried out considering that MT data has a good correlation with well temperature in the existing wells for resistivity value <10 ohm-meter is correlated with temperature around 200°C.

In addition, from this result also obtained the estimated area of the reservoir boundary at 1000 masl is about 11 km^2. The reservoir boundary in the northwest and north of the Putih crater, it is obtained from the indication of clay cap thickening in the deeper part. Meanwhile, in the southern part of Mount South Patuha, there is no indication of clay cap thickening so this area still opening and has an option as a geothermal reservoir expansion in Patuha that can be confirmed by adding some MT stations in that area.

CONCLUSIONS

The 3-D MT inversion model shows a good agreement with drilling (well) results to delineate geothermal system in Patuha Geothermal Field. An obvious subsurface resistivity structure compares to drilling results can be seen from correlation with low resistivity value <10 ohm-m with the presence of argillic zones that indicated as clay cap. In addition, high resistivity values >100 ohm-meters were found in the area around the PPL-7 and PPL-3 wells are correlated with the intrusion of diorite that found in the analysis of the cutting samples of those wells. The 3-D inversion showed a good agreement also with well results especially in mapping the temperature distribution both vertically and horizontally. The resistivity value around 15-20 ohm-m is correlated with Top of Reservoir of the production or injection well which is characterized by the presence of a convective temperature. Furthermore,

reservoir boundary which is characterized by the presence of reverse temperature and low temperature from the well also can be detect by MT 3-D inversion model. The resistivity distribution map from 3-D MT results are also used to correct especially in areas that have a limited number of wells in the northwest area. The good correlation results between MT and drilling data can be used as a guidance for better development strategy in the northwest area and drilling prognosis for the next drilling campaign.

ACKNOWLEDGEMENTS

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