Discovering "Hidden" Geothermal Reservoir in Blawan-Ijen Geothermal Area (Indonesia) Using 3-D Inversion of MT Data

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Abstract. Blawan-Ijen Geothermal Area is located in the Banyuwangi and Bondowoso Districts in the east Java Province. The occurrence of geothermal system is probably related with Kendeng Caldera with diameter about 15 km. Unimpressive surface manifestations are found in the northern caldera margin within Blawan area, including bicarbonate springs with temperature between 35 – 50^{O}C. The only "rather impressive" manifestation is Ijen crater lake with abundant solfatara located in the eastern margin of the caldera. Unfortunately, the fluid has extremely low pH of less than 0.3. The rest of the caldera has no other surface manifestations. Accordingly, the crucial questions are: (1) Any geothermal reservoir exists within the caldera? (2) If yes, is the reservoir fluid: high temperature with neutral pH? (3) Where to find the promising zone (high temperature, high permeability and neutral fluid)? Those questions are challenging to answer within such "hidden" geothermal area. To answer the questions, MT data is optimized by employing careful and proper data processing before applying 3-D inversion. According to the reprocessing and 3-D inverse modeling of 67 MT data, the prospect zones is identified which are located at the central part of Blawan-Ijen geothermal prospect. In order to determine drilling location, additional MT survey were carried out which was focused at the prospect areas. A number of 30 MT points were surveyed. All the 97 MT data (including the additional data) were then inverted using 3-D inversion approach. The additional MT data give more detailed information of the subsurface condition, especially the promising zone in the central part of the Kendeng caldera. The promising zone is well correlated with the youngest volcanic activity, where indicated upflow (in the central part) and outflow zones (in the southern part) are controlled by geological structure in which the boundary could be clearly delineated. Drilling target was then recommended to test the indicated upflow zone. The slim hole drilling program, which the total depth reached 2000 m, finally discovered high temperature (283^{o}C) and neutral reservoir in Blawan-Ijen geothermal area. This is one example of the 3-D MT inversion role for discovering "hidden" geothermal reservoir.

INTRODUCTION

Exploring geothermal reservoir in several geothermal fields in Indonesia is very challenging. The challenges come from the geothermal system characterized by magmatic surface manifestation, some with unimpressive manifestations and some poor surface manifestations so called "hidden" geothermal system. Blawan-Ijen geothermal prospect, owned by PT Medco Cahaya Geothermal (MCG) is one of them. It is located in East Java Province, between two districts, Bondowoso and Banyuwangi. The occurrence of geothermal system is only indicated by extremely acidic fumarole in Ijen crater, located on the top of Mount Ijen, as well as bicarbonate-sulfate hot springs in the northern area (FIGURE 1). Hypothetically, the main upflow is possibly situated in the Mt Ijen summit, while the outflow is probably located toward the hot springs. However, locating exploration or production drilling close to Mt Ijen is very risky and dangerous, because of corrosion issue and volcanic hazards. Accordingly, discovering geothermal fluid whose characteristics of high temperature and neutral pH in particular area between Mt Ijen and Blawan hot springs is not easy. Moreover, the geological condition at the survey area is dominated by lava that possibly cover the geological structure. Accordingly, high permeable zone associated with geological structure could not also be determined clearly from Remote Sensing/geological mapping.

Based on this situation, geological and geochemical data could not give a conclusive guidance to define certain location to be drilled. Magnetotelluric (MT) technology, therefore, could be acted as hard data to reveal such "hidden" reservoir. Furthermore, to increase confidence level regarding the MT data, several steps for improving the quality of the MT data have been conducted. Started from reprocessing of the existing MT data (acquired on 2012), remote sensing data interpretation, acquiring additional "infill" MT data in the focused area and then re-modeling of the whole MT data using 3-D inversion. This paper presents the result of the study and then proceeds with well targeting. One slim hole has been drilled to confirm the result. It will be discussed also in the final part of this paper.

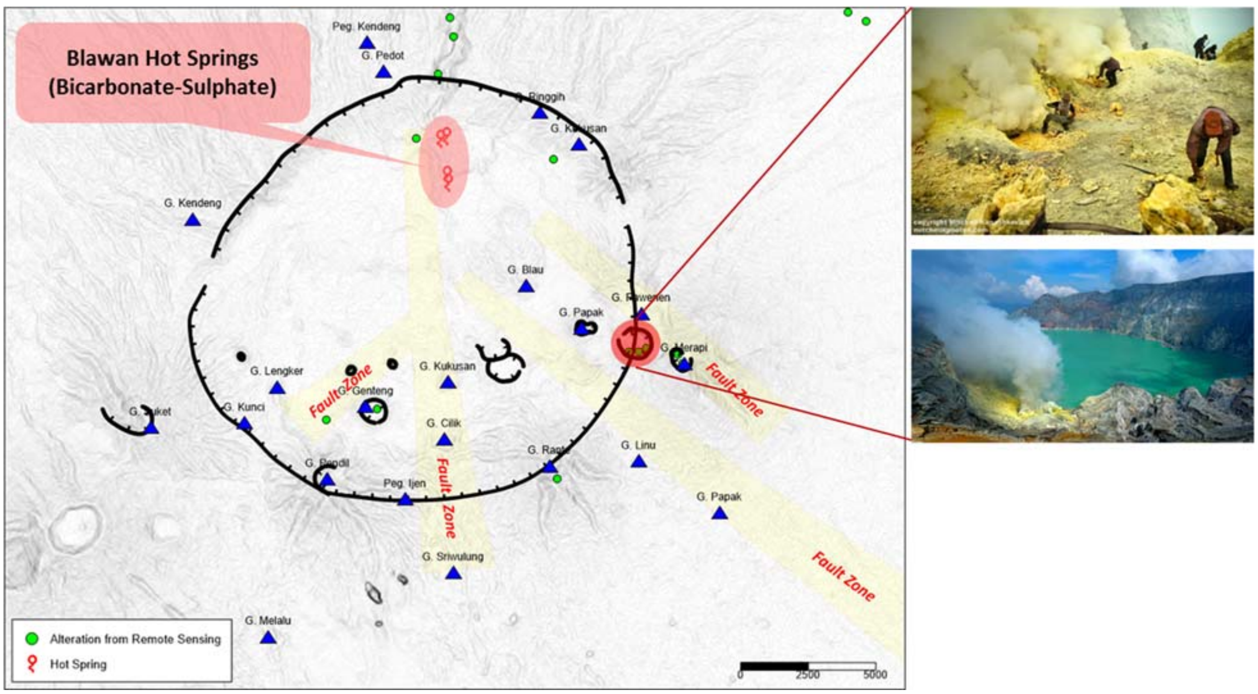

FIGURE 1. Field situation of Blawan-Ijen geothermal prospect (Daud, 2016)

FIELD REVIEW

The regional geology of the Blawan-Ijen is associated with Kendeng caldera structure triggered by big explosion of Old Ijen volcanic activity. Geological map of Blawan-Ijen geothermal prospect have been reconstructed by enhancing remote sensing data interpretation. The result of the interpretation was then cross-checked by field observation data (FIGURE 2). The lithology in the prospect area is dominated by volcanic rock such as andisitic lava, volcanic breccia, and pyroclastic. Volcanostratigraphy of Ijen and its surrounding area was formed by several eruptions that produce quaternary volcanic rock. The existence of heat source is indicated by distribution of lava as the youngest product. The lava is located at the uppermost part of the stratigraphy and could be one of the several indications of limited thermal manifestations exposed to the surface. In addition, the occurrence of the hot springs at the northern part and indication of altered rock in some places could be evidences of geothermal system in Blawan-Ijen area. The geological structures developed inside the caldera have N-S, relatively E-W, NE-SW, and NW-SE directions. The N-S structure located at the central of the prospect area, is interpreted as a normal fault. Volcanic structure, like circular feature, is also exist. The structure is mostly identified at the southern part at the area where the recent volcanic activity takes place.

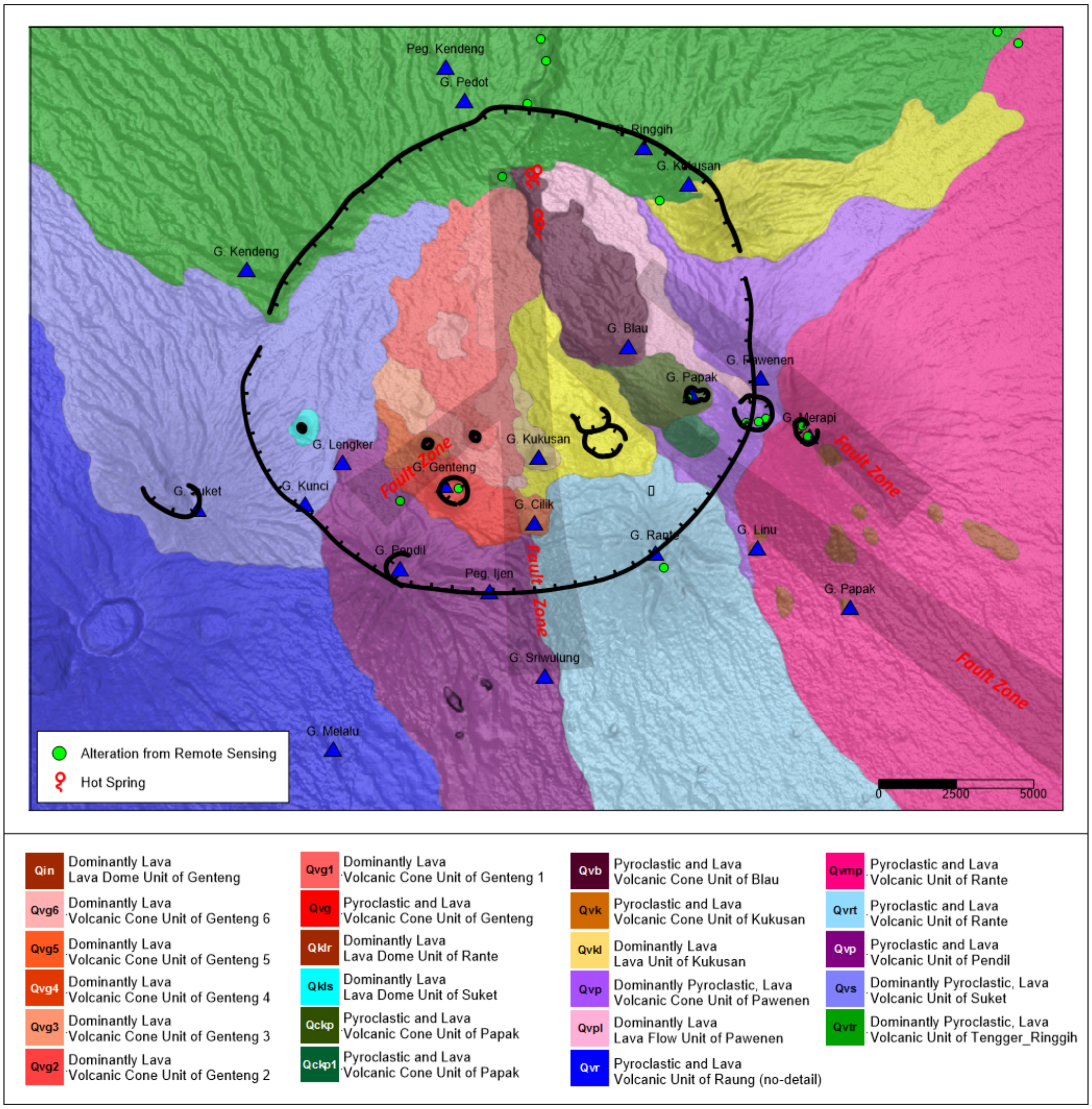

FIGURE 2. Geological map of Blawan-Ijen geothermal prospect

MAGNETOTELLURIC (MT) SURVEY

MT survey in Blawan-Ijen geothermal prospect was conducted in two periods. The first was accomplished in 2012 by ELC and the other was performed by PT Makara Mas - Universitas Indonesia in 2015 (Figure 3). The study was started by reprocessing of the 2012 MT data to improve the quality of MT data. The results show that 64 of 67 MT stations have good to excellent data quality, while the rest 3 data are fair quality. According to the reprocessing and initial 3-D inverse modelling, a promising zone were then identified in the center of the survey area. In order to increase the level of confidence of drilling targeting, additional MT survey were then carried out which was focused at the promising zone. A number of 30 MT measurement points were surveyed, including re-measurement of the previous fair quality data.

MT data processing was started by doing verification of time-series data and converting them into frequency domain by using Fourier transformation. Robust processing was done to eliminate the outlier data. The next step is selecting cross-power data to obtain better and smoother trend of the MT curve. The curve should be corrected from static shift effect before inversion modelling. Static effect in MT data possibly caused by near surface inhomogeneity, topography undulation, or vertical contact. This effect could be corrected by using TDEM data or geostatistical method (Daud, 2011). Available TDEM data in Ijen geothermal prospect was taken from 67 survey points (MT data of 2012). It means that no TDEM data for additional MT stations. To overcome this problem, the correction process of static shift for the remain data (MT Data of 2015) were done by using geostatistical method. The software being used is StaticShifter-X (Daud, 2011) developed by PT NewQuest Geotechnology in collaboration with Geothermal Laboratory of University of Indonesia. This method was done by using corrected MT data as the corrector. Those curves were then being averaged in each frequency to obtain corrector value. Then the uncorrected MT data were dragged toward that corrector value. This method has been verified by comparing the results of statistical method with those of the TDEM static correction for several MT data (Daud, 2011).

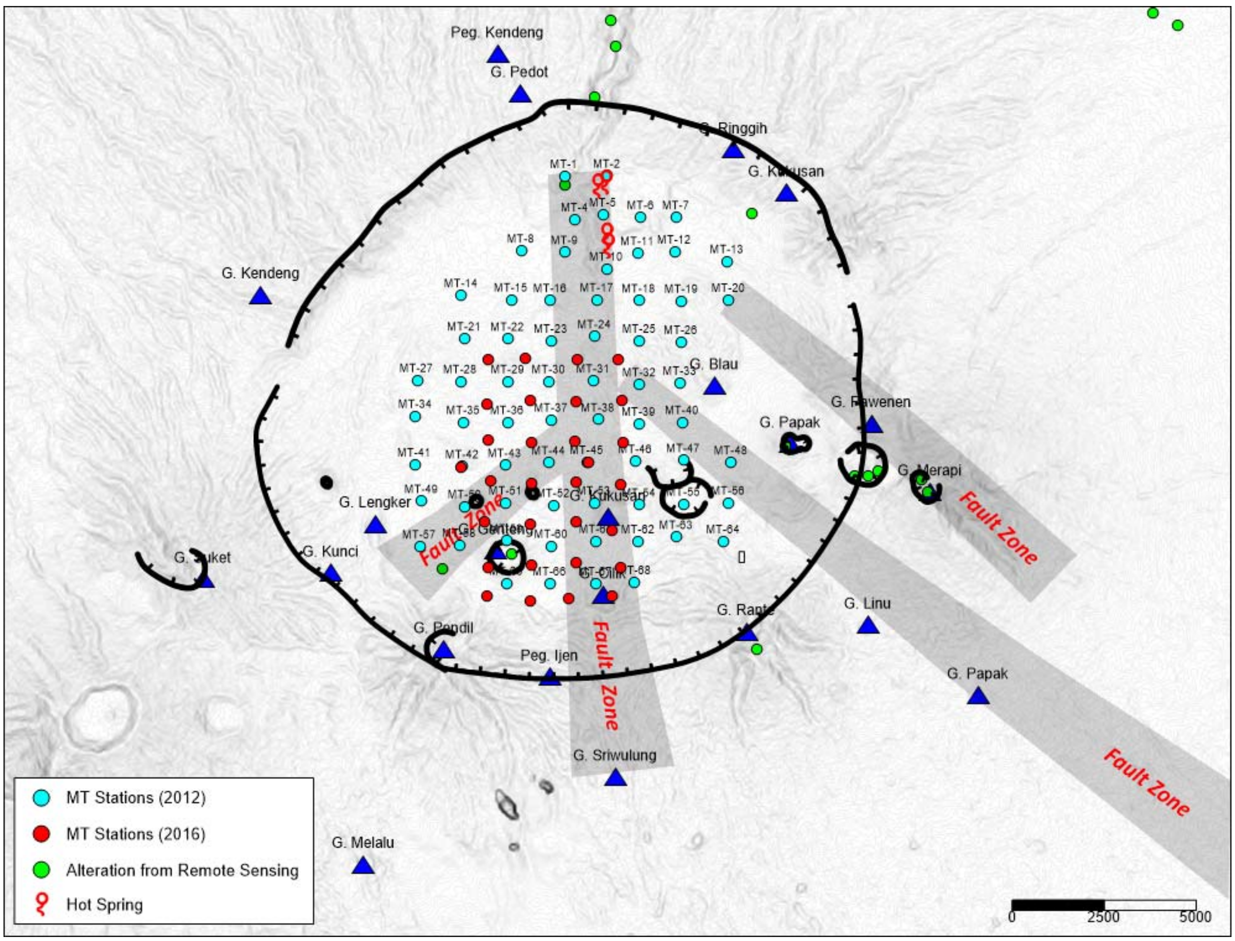

FIGURE 3. Map of MT stations distribution in Blawan-Ijen geothermal prospect

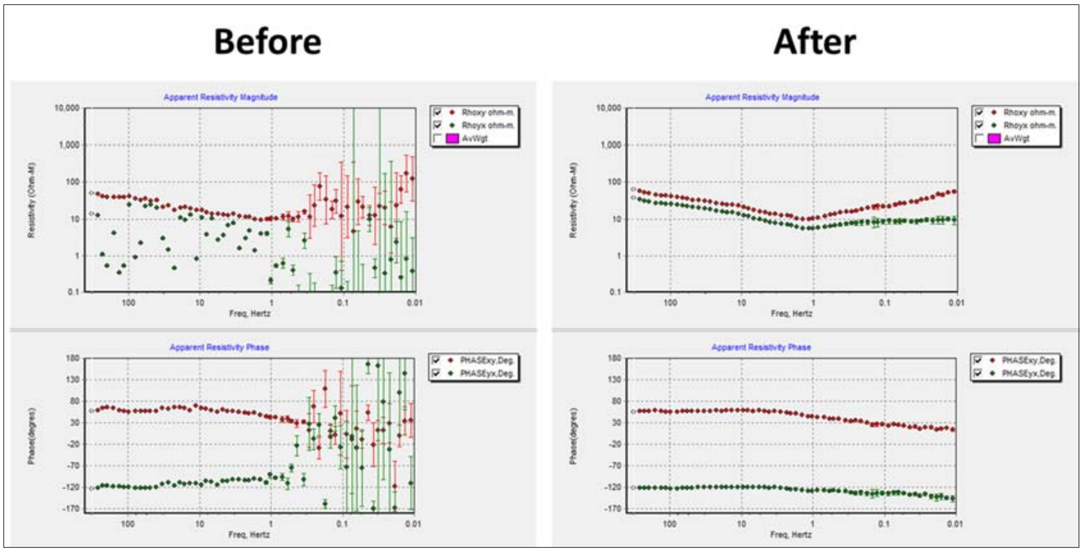

FIGURE 4. MT curve before and after cross-power selections

THREE-DIMENSIONAL INVERSION OF MT DATA

Three-dimensional inversion of the MT data is completed by using MT3Dinv-X software developed by PT. NewQuest Geotechnology in collaboration with Geothermal Laboratory of University of Indonesia (Daud, 2012), based on data space method (Siripunvaraporn, 2006). Mesh dimension of observation area was designed with 500 x 500 meters spacing in horizontal plane, with minimun spacing of 10 meters in vertical plane. Mesh was oriented in North-South direction for x-axis, with North as positive axis, and West-East for y-axis with East as positive axis. Initial model is made based on the homogeneous earth model with 100 ohm-m resistivity. Numbers of grid from South to North is 42, 34 for West to East and 22 for vertical direction. Thus, total numbers of mesh for 3-dimensional modeling is 42 x 34 x 22 = 31.416 blocks.

After setting the mesh parameter and dimension, the next step is input MT data and the associated parameter. Total numbers of data (N) is affected by numbers of survey station, frequency numbers and impedance element numbers. For Blawan-Ijen case, total numbers of MT station are 93 points, with 11 frequency and 8 impedance elements (real and imaginary components. Thus the total data is 8.184. Error floor parameter input is 5% to make sure that obtained model is match enough with observation curve. The best inversion result has RMS error of 10.1%. Static correction has also been done using TDEM data for existing MT data (67 stations) and geostatistical method (averaging) for 28 additional stations.

FIGURE 5 (A), FIGURE 5 (B) and FIGURE 5 (C) show distribution of true resistivity at elevation of 500 m, 0 m, and -500 m. Geological structure, distribution of alteration from remote sensing data and hot springs, as well as location of mountains around prospect area are also involved in the maps. By seeing the maps of 500 m elevation, we find that conductive layer mostly covers MT survey area. Indication of alteration from remote sensing has good correlation with this conductive layer (FIGURE 5 (A)). Generally, geological structure also play an important role in controlling conductive layer distribution.

Updome structure indicates the existence of upflow zone. It also shows good agreement with geological structure. The prospect area is concentrated at intersection zone of faults, which is located at the center of the survey area. It also extends toward the southeast direction, following the trend of the north-south structure up to Mt. Kukusan (FIGURE 5 (B) and FIGURE 5 (C)). The map of base of conductor (BOC) supports the indication by showing high elevation of BOC in the prospect area (FIGURE 5 (D)).

The prospect area also elongates to the southwest direction and is bounded by the northeast-southwest structure. The thickening of impermeable clay cap can be found at the eastern part of the prospect area, and could act as a barrier of acidic fluid originated from Ijen Crater (FIGURE 6). Drilling target was then recommended to test the indicated upflow zone.

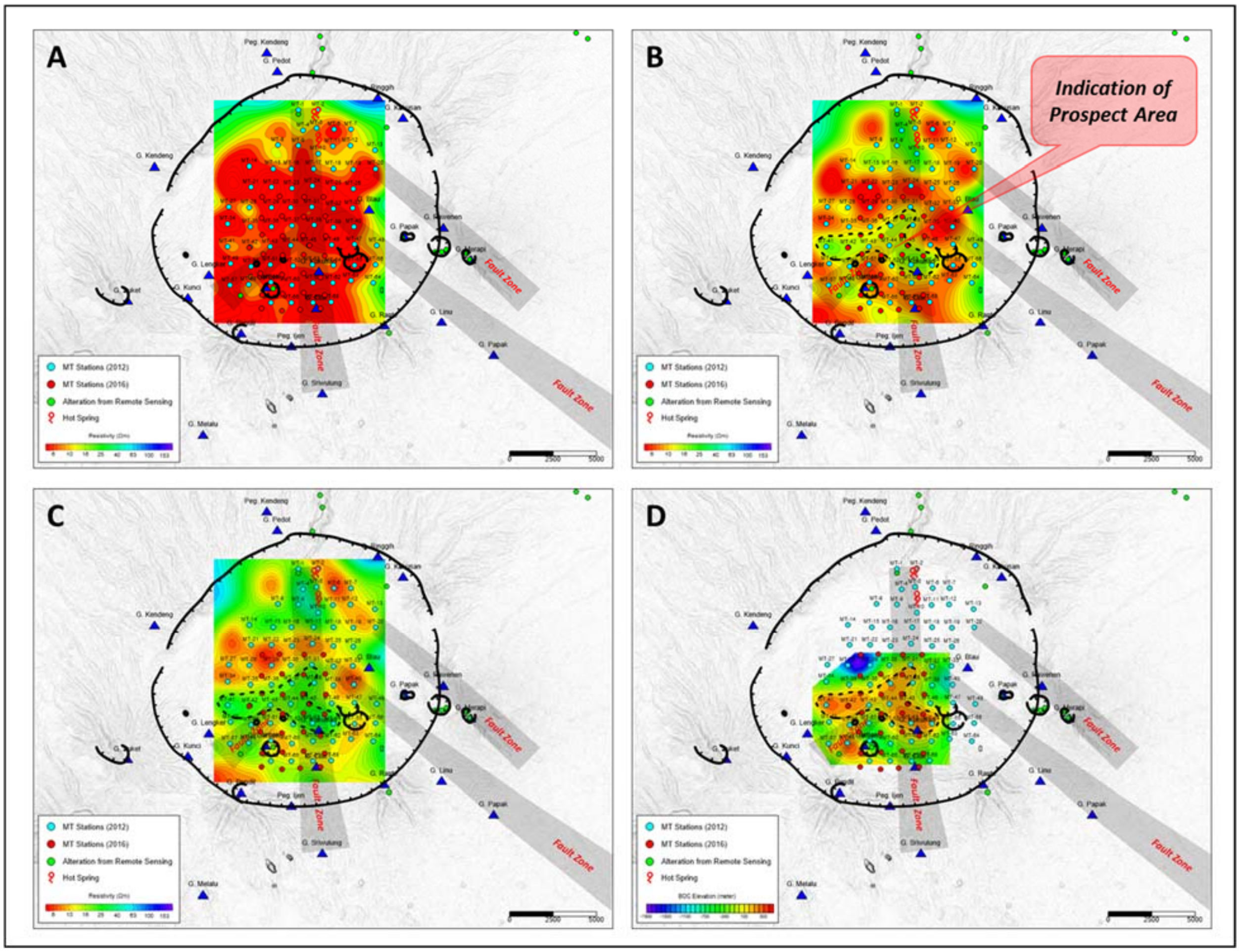

FIGURE 5. Map of resistivity distribution in 500 m elevation (A), 0 meter elevation (B), -500 m elevation (C) and base of conductor (BOC)

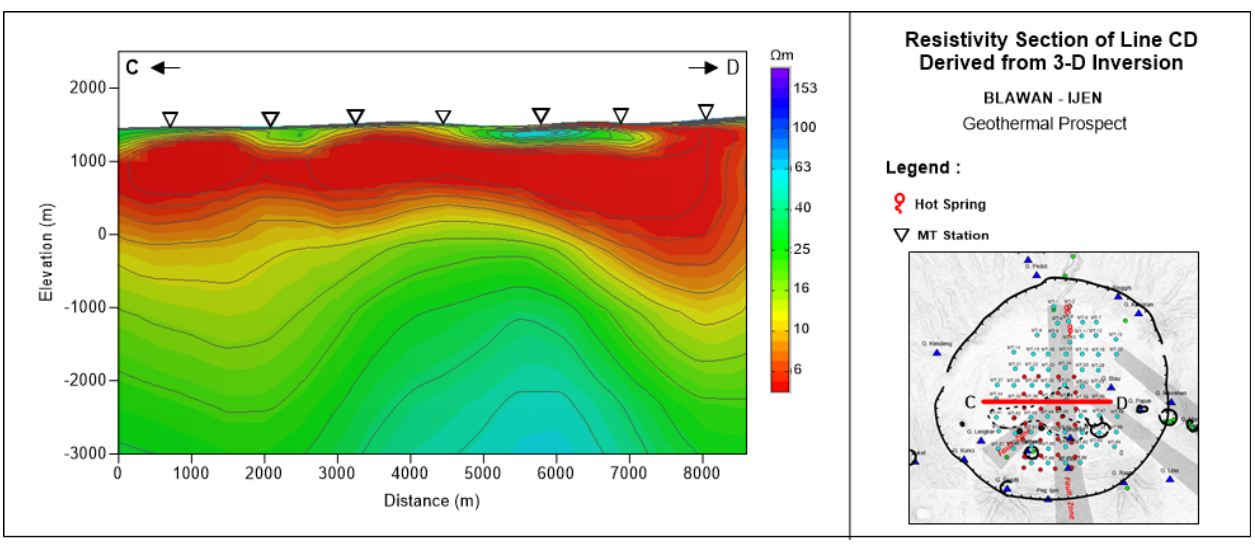

FIGURE 6. Cross section derived from 3-D inversion of MT data with west-east direction, crossing the indication of the prospect area in the central part of the Kendeng caldera

RESERVOIR DISCOVERY THROUGH SLIM HOLE DRILLING

The first slim hole has been drilled to find "hidden" reservoir indicated by 3-D inversion of MT data. The well was drilled vertically until 2000 m depth, and finally discovered high temperature (283ºC) and neutral fluid in Blawan-Ijen geothermal area. The 3-D inversion result also shows a good agreement with the subsurface temperature obtained from the temperature measurement along the well (FIGURE 7). The BOC that can be defined as the top of reservoir, is associated with temperature of 200ºC, found at the depth of 1400 m. High temperature associated mineral, such as epidote was also discovered at the depth of 1782 – 2000 m.

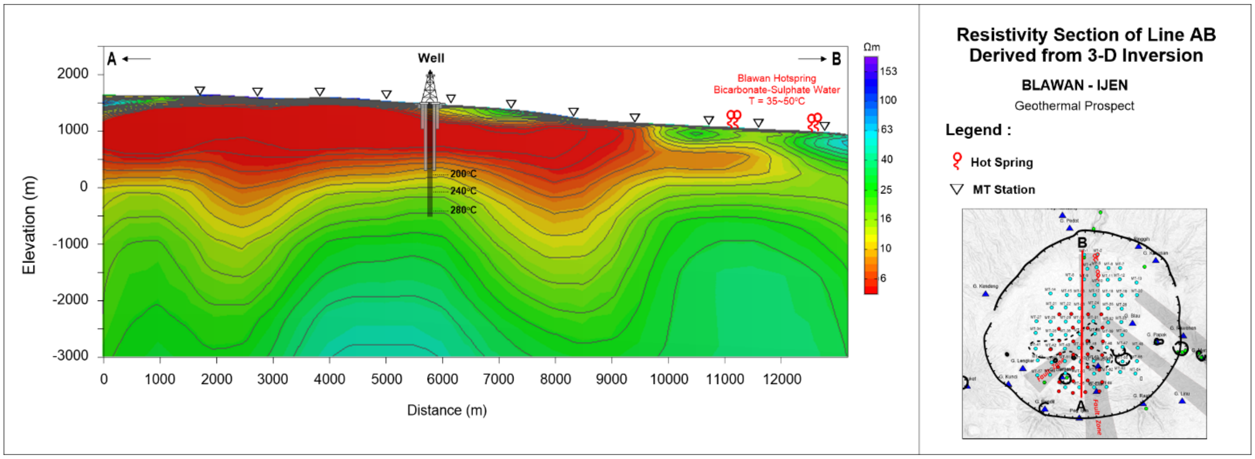

FIGURE 7. Well-correlation between MT and drilling result

DISCUSSION

MT technology could be the most powerful method to discover geothermal reservoir in "hidden" geothermal system, such as in the Blawan-Ijen geothermal prospect. Special case in Blawan-Ijen, when the geological and geochemical data could not give significant contribution, MT could act as a hard data to investigate the subsurface temperature in a geothermal system. Ussher et al (2000) gave correlation between observed resistivity and subsurface temperature based on several geothermal fields in the world. Generally, high resistivities are observed in the cool, upper part of geothermal systems where temperatures are less than about 70°C. Much lower resistivities of the order of 1 to 10 Ωm are found in the temperature range of 70 to 200 °C. At temperatures above 200 °C, resistivities increase markedly and are often greater than 100 Ωm, depending on the nature of the primary lithologies. Based on this findings and other authors' observations in many geothermal fields, determination of high temperature (upflow zone) in Blawan-Ijen geothermal area was pointed by using 3-D inversion of MT data.

MT technology is a powerful tool for guiding well targeting, however, with one condition, i.e. the MT data should be acquired, processed and modelled properly. The data quality should be controlled and assured before conducting 3-D inversion. This considerations should be focused, before giving recommendation for drilling location. In addition, since "hidden" geothermal resource has high risk (i.e. high uncertainty), slim hole drilling can be utilized for confirming the existence of reservoir.

In Blawan-Ijen geothermal area, slim hole drilling has been applied with diameter 2 3/4 inches at the total depth. The slim hole drilling program, which the total depth reached 2000 m, finally discovered neutral fluid in Blawan-Ijen geothermal area with high temperature of more than 280ºC. This is a good example of the important role of 3-D MT inversion for discovering "hidden" geothermal reservoir.

CONCLUSION

Blawan-Ijen Geothermal Area is located in the Banyuwangi and Bondowoso Districts in the east Java Province. The occurrence of geothermal system is probably associated with Kendeng Caldera with diameter about 15 km. Unimpressive surface manifestations are found in the northern caldera margin within Blawan area, including bicarbonate warm springs. The only “rather impressive” manifestation is Ijen crater lake with abundant solfatara located in the eastern margin of the caldera. Unfortunately, the fluid has characteristics of magmatic origin with extremely low pH of less than 0.3. The rest of the caldera has no other surface manifestations.

The only hard data in such difficult “hidden” geothermal area is MT data. The available MT data is optimized by employing careful and proper data processing before applying 3-D inversion. Reprocessing of the existing 67 MT data as well as conducting additional “infill” 30 MT data have accomplished to discover a concealed reservoir within the Kendeng caldera. Three-dimensional inversion was then selected to overcome complex geological structure in the survey area. The indication of upflow and outflow zones from 3-D inversion of MT data is also strengthened by geological structure in which the boundary could be clearly delineated. Drilling target was then recommended to the indicated promising zone.

The first slim hole drilling, which the total depth reached 2000 m, finally discovered high temperature (283^{o}C) and neutral reservoir in Blawan-Ijen geothermal area. Based on this finding, it can be considered that 3-D MT inversion can be utilized for discovering such similar “concealed” geothermal reservoir in other area.

ACKNOWLEDGMENTS

The authors wish to thank PT Medco Cahaya Geothermal, as the owner of Blawan-Ijen geothermal prospect, for the permission to publish this paper. We acknowledge PT NewQuest Geotechnology for providing MT related softwares and processing assistants.

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