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3-Dimensional Inversion of MT Data over the Arjuno-Welirang Volcanic Geothermal System, East Java (Indonesia)

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ABSTRACT

The Arjuno Welirang geothermal area is located about 60 km southwest of Surabaya, the capital city of East Java. Geologically, the prospect area is dominated by quaternary volcanic rocks, both lava and pyroclastic. Impressive surface thermal manifestations can be found in this area, which include solfataric-fumaroles with temperature of 137°C found in the summit of Mount (Mt) Welirang and bicarbonate hotsprings with a temperature range of 39 to 55°C found in the western and northwestern vicinities of Mt Welirang. The occurrence of solfataric-fumaroles with magmatic gases indicates the existence of a volcanic geothermal system in the subsurface. The surface manifestations are geologically controlled by the northeast-southwest fault structures. The CO_2 gas geothermometer indicates a high temperature reservoir of about 260°C. To delineate the subsurface resistivity structure associated with the geothermal system, a 3-D inversion was performed using the Occam Data Space algorithm. The 3-D inversion was applied to 34 MT soundings with a frequency range of 320 to 0.01 Hz. Overall, the quality of the MT data used varied from good to very good. The subsurface resistivity structure revealed by 3-D inversion showed a low resistivity (1-15 ohm-m) altered rock at the upper part overlying a reservoir zone with slightly higher resistivity (20-60 ohm-m). The lower part of the resistivity structure showed the highest resistivity value (> 80 ohm-m), which indicated a hot rock region. The geometry of the resistivity structure showed the updome structure of the base of the conductive layer (BOC) centered below the Mt Welirang summit. The updome structure indicated an upflow zone that was supported by the occurrence of solfataric-fumaroles on the summit of Mt Welirang. The depth of BOC at this position was about 1 km, while those at the surroundings were deeper, following the elevation of the vicinity of Mt Welirang. The 3-D resistivity inversion also revealed the subsurface fault structures as indicated by remote sensing data at the surface. The 3-D MT inversion result was then incorporated with geological and geochemical data to construct a conceptual model of the Arjuno-Welirang geothermal system.

1. INTRODUCTION

In recent time, the application of 3-D inversion for magnetotelluric field datasets has increased. There are some benefits for using 3-D inversion. Since it can solve ambiguity, there is no need to make an assumption for the strike direction. In addition, there is a high degree of freedom to overcome the 3-D effect and the data from spreading station positions can be inverted easily without data projection (Siripunvaraporn, 2012). In this research, an attempt was made to apply 3-D inversion for real magnetotelluric field datasets on the Arjuno-Welirang geothermal area in order to get representative earth resistivity structures in this area.

In 2010, the Center for Geological Resources of the Ministry of Energy and Mineral Resources (MEMR) carried out the MT acquisition in the Arjuno-Welirang geothermal prospect area. There were 34 stations arranged in a grid with a station spacing of about 1 to 2 km. Due to the limited budget and time in the first step of the MT survey, only the north and northwest vicinities of Mt Welirang were covered.

The 3-D inversion of the MT data was then performed to delineate the subsurface resistivity distribution of the Arjuno-Welirang geothermal prospect area. Moreover, the objectives of the 3-D inversion of MT data were to delineate the resistivity structures associated with the geothermal system and to construct the conceptual model of the Arjuno-Welirang geothermal prospect area by incorporating the MT data with geological and geochemical data.

This paper describes the Arjuno-Welirang geothermal prospect, the 3-D inversion of MT data, and the construction of a conceptual model of the Arjuno-Welirang geothermal prospect area. A brief review of the geological and geochemical data is also described in this paper.

2. FIELD REVIEW

The Arjuno-Welirang geothermal area is located about 60 km southwest of Surabaya, the capital city of East Java (Figure 1). The presence of a geothermal system in this area is related to the volcanic activity in the south of East Java. Geologically, the prospect area is dominated by Quaternary volcanic rocks, both lava and pyroclastic. Geological structures such as faults, the caldera rim structure, and other circular features are indicated by remote sensing data. The circular feature is correlated with the collapse zone that was formed as a result of Pre Arjuno-Welirang volcanic eruption (Figure 2).

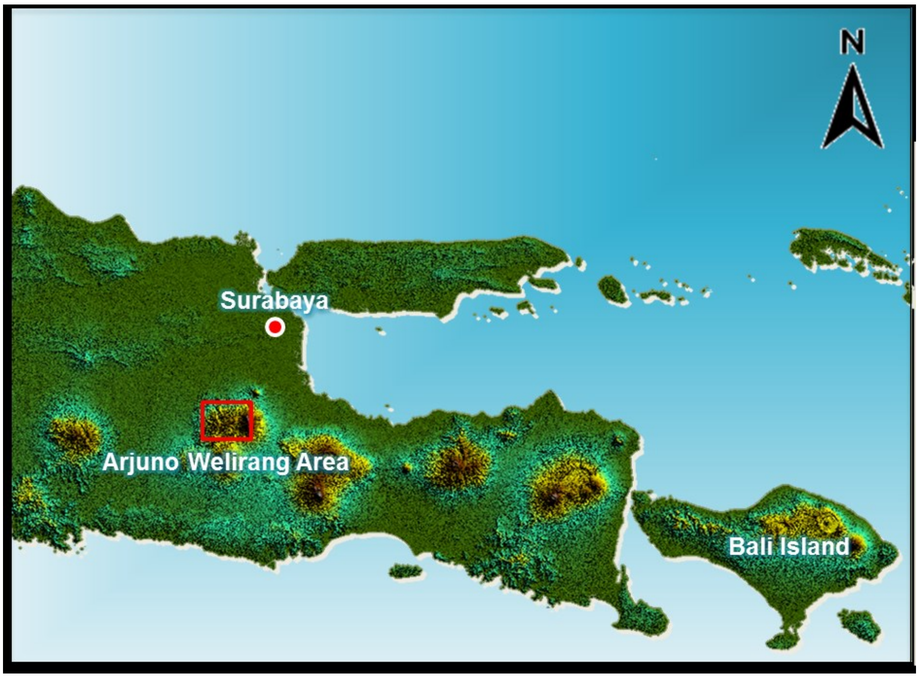

Figure 1: Location of Arjuno-Welirang Geothermal Area, East Java, Indonesia

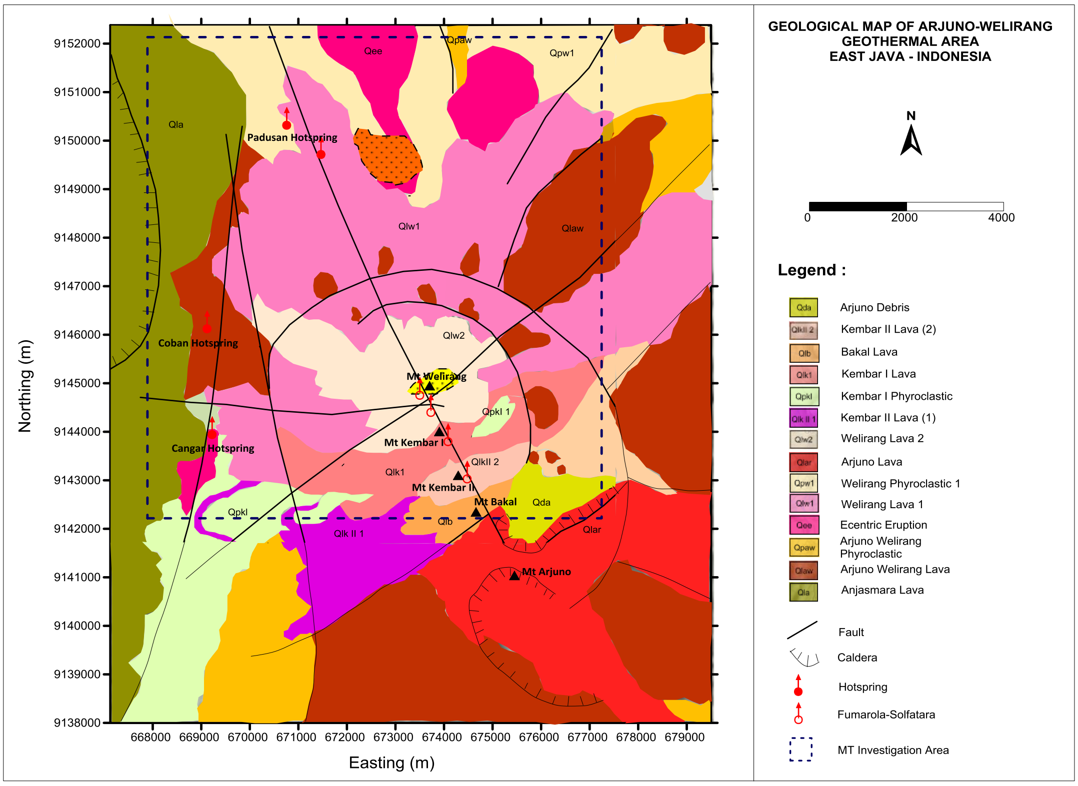

Figure 2: Geological Map of Arjuno-Welirang Geothermal Area, East Java, Indonesia

Impressive surface thermal manifestations found in this area included solfataric-fumaroles with a temperature of 137^{o}C found in the summit of Mt Welirang. In addition, bicarbonate hotsprings with temperature values ranging from 39 to 55^{o}C were found in the western and northwestern vicinities of Mt Welirang. In the Na-K-Mg diagram (Figure 3), all of the hotsprings were determined as immature water, indicating the mixing of thermal water and shallow ground water. The outcrop of advanced argilic alteration was found in the summit of Mt Welirang, whereas the outcrop of weak argilic alteration was found in the vicinites of Mt Pundak. The occurrence of solfataric-fumaroles with magmatic gases indicated the existence of a volcanic geothermal system in the subsurface. Cangar and Coban hotsprings were controlled by Cangar faults, whereas the Padusan hotsprings and solfatara-fumaroles were controlled by the Padusan faults. The temperature of the reservoir, assessed using gas geothermometers, was about 260^{o}C. Therefore, the Arjuno-Welirang geothermal system could be categorized as a high temperature geothermal system.

It can be seen in Figure 1 that the Arjuno-Welirang geothermal system is situated in the geological complex area. This increases the possibility that there is a 3-D effect on the MT data. To overcome this problem, a 3-D inversion of the MT data for the Arjuno-Welirang field should be carried out. In addition, 3-D inversion has the ability to resolve the 3-D effect by applying a 3-D earth model in the inversion process, such that all of the data stations can be run simultanously in their real positions without projection.

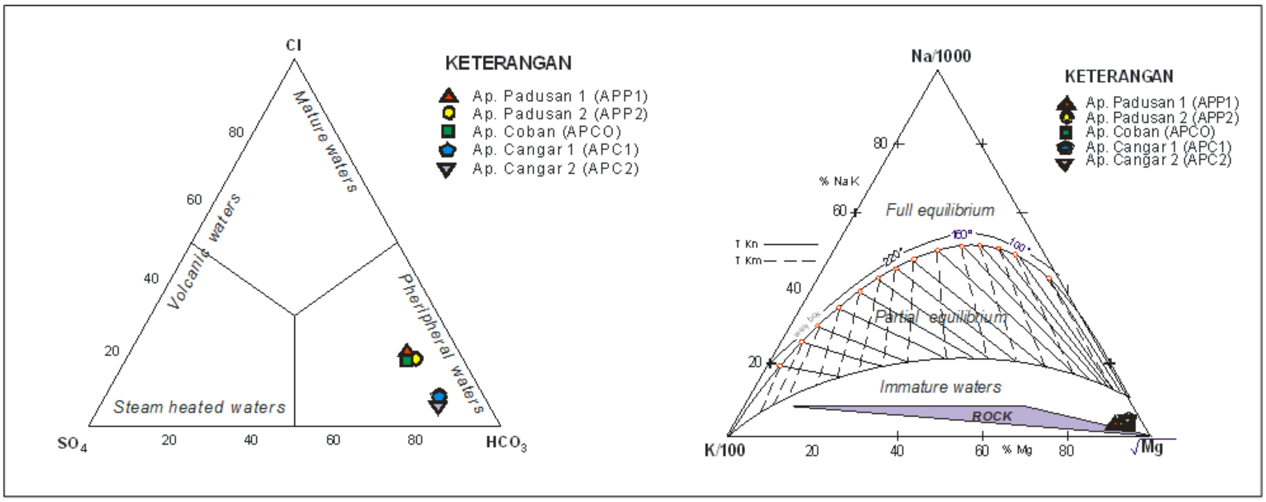

Figure 3: Ternary Diagram of Chemical Compositions of Hot Springs in the Arjuno-Welirang Geothermal Area

3. 3-D INVERSION OF MT DATA

The 3-D inversion method was applied for the 34 MT soundings with a frequency range of 100 to 0.01 Hz. The overall quality of the MT data used varied from good to very good. The 3-D MT inversion was carried out using the MT3DInv-X software program (Daud et al., 2012). It is a user-friendly software program that utilizes the Occam's inversion data space algorithm developed by Siripunvaraporn (2011). With this software program, the 3-D inversion process was performed more effectively. The result of the 3-D inversion in this software program was integrated with the GeoSlicer-X software program (Daud and Saputra, 2010). The output of the MT3DInv-X was exported into the (x, y, z) value data format, which was used as data input in the GeoSlicer-X software to visualize the data in three dimensions.

3.1 Mesh Grid Parameter

The 3-D model consisted of blocks in the 3-D mesh-grid in the dummy coordinate system. The center of the dummy coordinate system was situated in the center of the station distribution. In the MT3DInv-X software, the x-axis was oriented from north to south (with north as positive), the y-axis was oriented from east to west (with east positive), and the z-axis was positive downwards. The 3-D MT inversion process used a 100 ohm-m homogeneous half-space as the initial model. The number of blocks was 30 from north to south and 30 from west to east, with 22 vertical layers (without air layers). Thus, the total number of model blocks was M = 30 x 30 x 22 = 19,800.

3.2 Data Input

The data input for the 3-D MT inversion process were the real and imaginary parts of the impedance tensor (Zxx.real, Zxx.imag, Zxy.real, Zxy.imag, Zyx.real, Zyx.imag, Zyy.real, Zyy.imag). To constrain the data from high errors, the error floor of the impedance tensor was set as 5% to ensure that the model response fitted well with the observed data. The total number of data (N) depended on the number of stations, frequencies, and impedance tensor elements. The total number (N) for the 3-D inversion of the Arjuno-Welirang MT data was 34 stations, 9 periods with the frequency range of 100 to 0.01 Hz, and all eight impedance tensor elements. Thus, the total number of data (N) is 34 x 9 x 8 or 2,448.

3.3 3-D Inversion Process

The 3-D MT inversion process was run on a PC with specifications as follows: Intel Pentium core i7 with 16 GB of RAM. For one iteration, it took about 2 hours and the total time to reach the 34th iteration was about 68 hours. The 3-D inversion process using MT3Dinv-X was stable and convergent before finally reaching the best fit. Thus, it produced a good subsurface resistivity structure representing the real condition. The final RMS misfit achieved was 10.8%.

4. RESULTS AND INTERPRETATIONS

4.1 Resistivity structure of Arjuno-Welirang Geothermal System

The subsurface resistivity structure revealed by the 3-D inversion process indicated the presence of geothermal system in this area. The conductive layer was one of the characteristics of a geothermal system found in the resistivity model. This can be seen in the cross-section Line AB (Figure 4) and cross-section Line CD (Figure 5). This conductive layer has a resistivity between 1 to 15 ohm-m with various thickness values that range from 1 to 2 km. The slightly higher resistivity layer below the conductive layer has a resistivity of 20 to 60 ohm-m. The lower part of the resistivity structure shows the highest resistivity value that is greater than 80 ohm-m. The geometry of the resistivity structure shows an updome structure for the base of conductive layer (BOC) centered below Mt Welirang. The resistivity contrast in the cross section indicates the geological structures, such as faults, in this area.

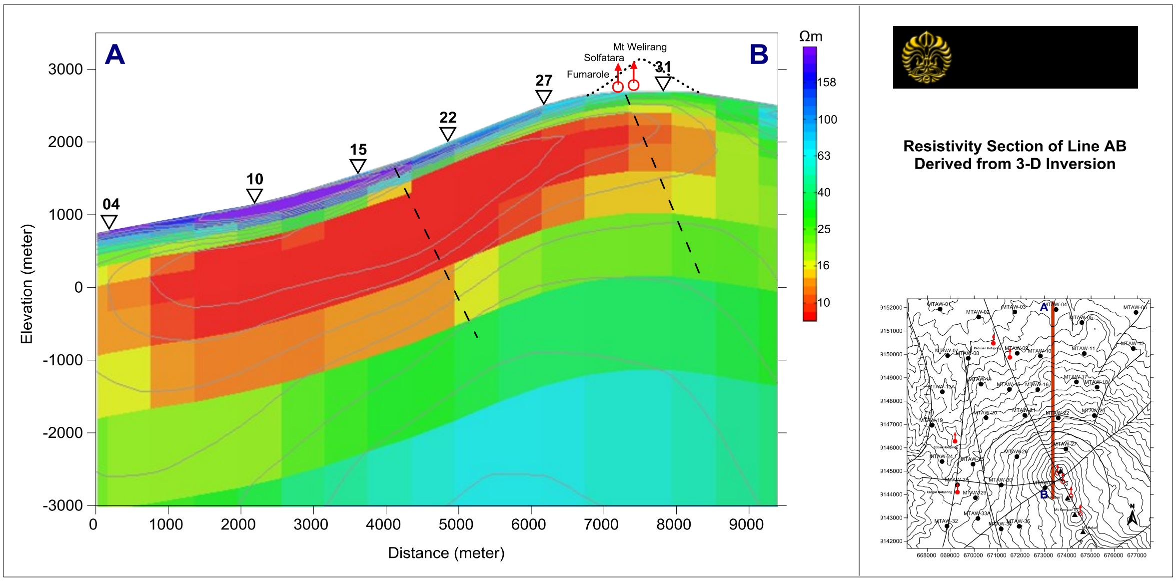

Figure 4: Resistivity Structure Derived from 3-D Inversion along Line AB of the Arjuno-Welirang Geothermal Area

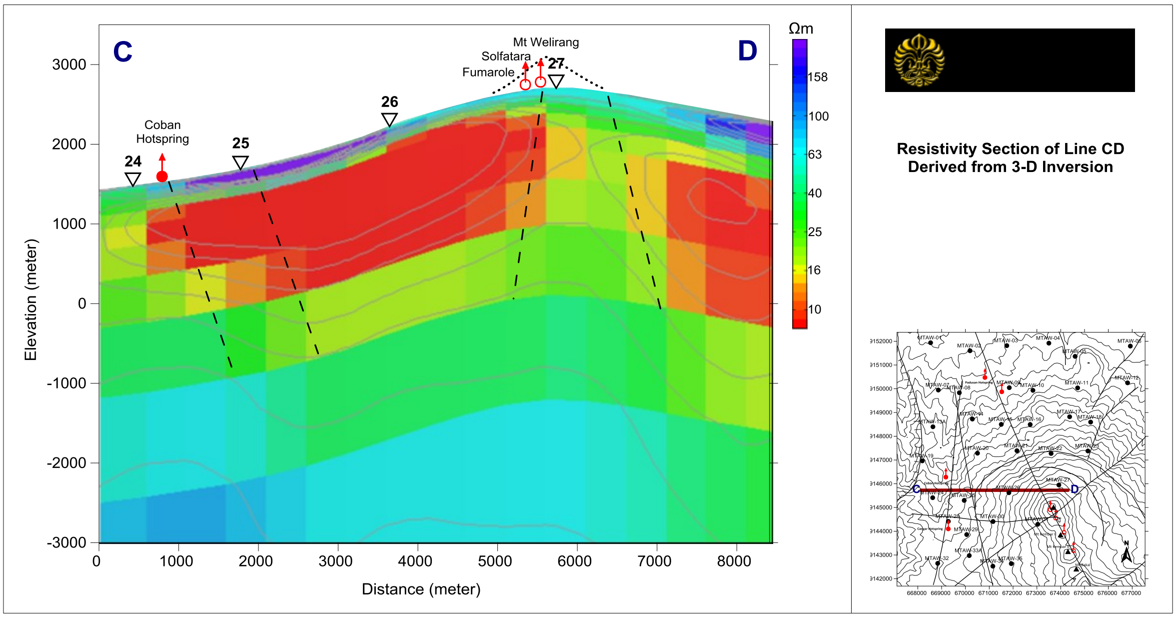

Figure 5: Resistivity Structure Derived from 3-D Inversion along Line CD of the Arjuno-Welirang Geothermal Area

4.2 Integrated Interpretation

Integrated interpretation was done to develop a conceptual model of Arjuno-Welirang geothermal system. The 3-D MT inversion result was then incorporated with the geological and geochemical data. Magnetotelluric investigation was necessary for identifying the existence of upflow and outflow zones, as well as the indicated geological structures. The upflow zone is clearly indicated by the updome resistivity structure of the Line AB and Line CD below Mt Welirang (Figure 4 and Figure 5). The presence of solfataric-fumaroles in the summit of Mt Welirang supports the interpretation of the upflow zone location. In addition, the occurrence of solfataric-fumaroles with magmatic gases indicates that the upflow zone originates from a volcanic geothermal system in the subsurface. The outflow structure is also indicated clearly by the elongation of the conductive layer in the resistivity sections of the Line AB and Line CD (Figure 4 and Figure 5), following the decrease in surface topography. Chemical compositions analysis results from the Cangar hotsprings, Coban hotsprings, and Padusan hotsprings supports the indicated outflow zones. Electrical discontinuities in the resistivity sections of Line AB and Line CD can be interpreted as faults represented by dashed lines (see Figure 4 and Figure 5). These fault structures might control the upflow and outflow zones in the Arjuno-Welirang hydrothermal system. Figure 6 summarizes the 3-D resistivity model and its interpretation for the Arjuno-Welirang geothermal system using the Geoslicer-X software (Daud et al, 2010).

5. CONCEPTUAL MODEL OF ARJUNO-WELIRANG GEOTHERMAL SYSTEM

On the basis of the integrated interpretation of the 3-D inversion of the MT data incorporated with geological and geochemical data, a conceptual model of Arjuno-Welirang geothermal system was then developed, as shown in Figure 7 and Figure 8. Figure 7 illustrates the conceptual model represented by the base of conductor (BOC) elevation contour and possible hydrogeology. In addition, Figure 8 shows the conceptual model represented by the subsurface distribution of altered rocks, reservoir rocks, fault structures, and possible hot rocks. The main upflow zone is situated below the Arjuno-Welirang volcanic complex, as indicated by the highest elevation of BOC (Figure 7) and updome shape of the conductive layer, as well as horst structure of the resistive basement interpreted as hot rock (Figure 8). The occurrence of solfataric-fumaroles with magmatic gases in the summit of Mt Welirang supports this model and indicates that the upflow zone originates from a volcanic geothermal system in the subsurface. The main reservoir below MT Welirang is located at a depth of about 1,500 meters. Furthermore, the subsurface temperature at this depth, estimated from gas geothermometry, is about 260^{o}C. The conceptual model also suggests that the outflow zones are situated in three locations: Padusan, Cangar and Coban area as indicated by the occurrence of hot springs in the areas. The existence of the outflow zones are controlled by the northwest-southeast and west-east fault structures (Figure 7 and Figure 8).

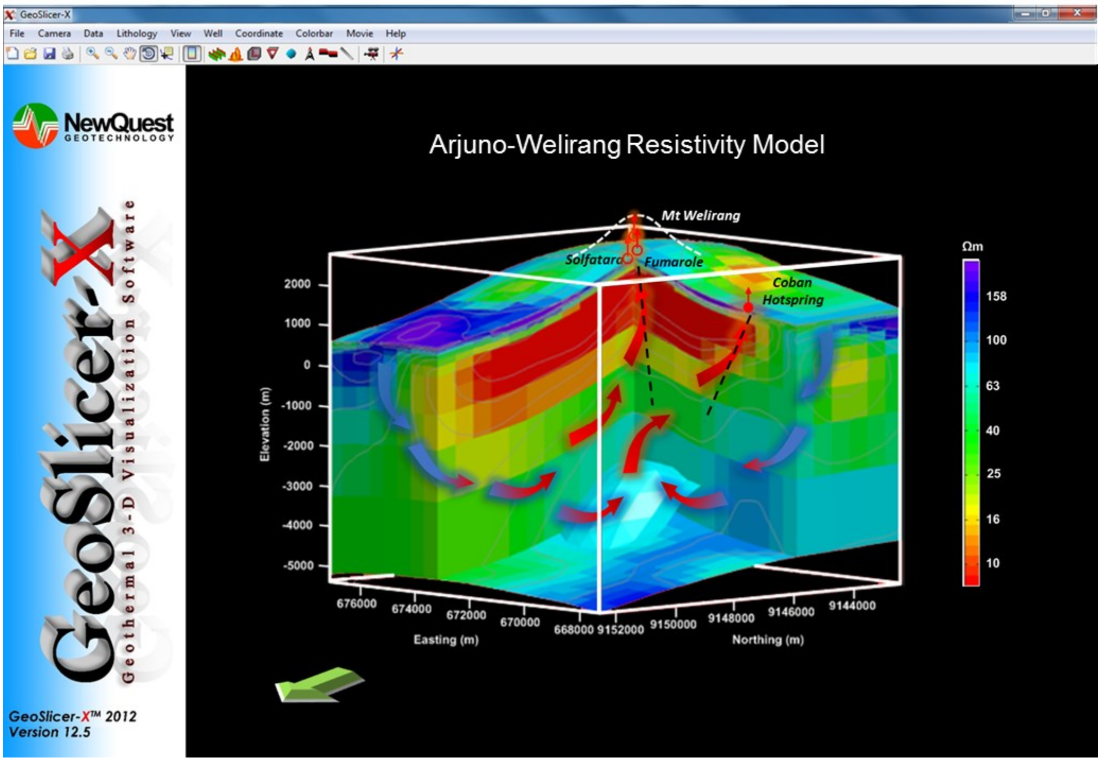

Figure 6: 3-D Resistivity Model Using GeoSlicer-X Software of the Arjuno-Welirang Geothermal Area

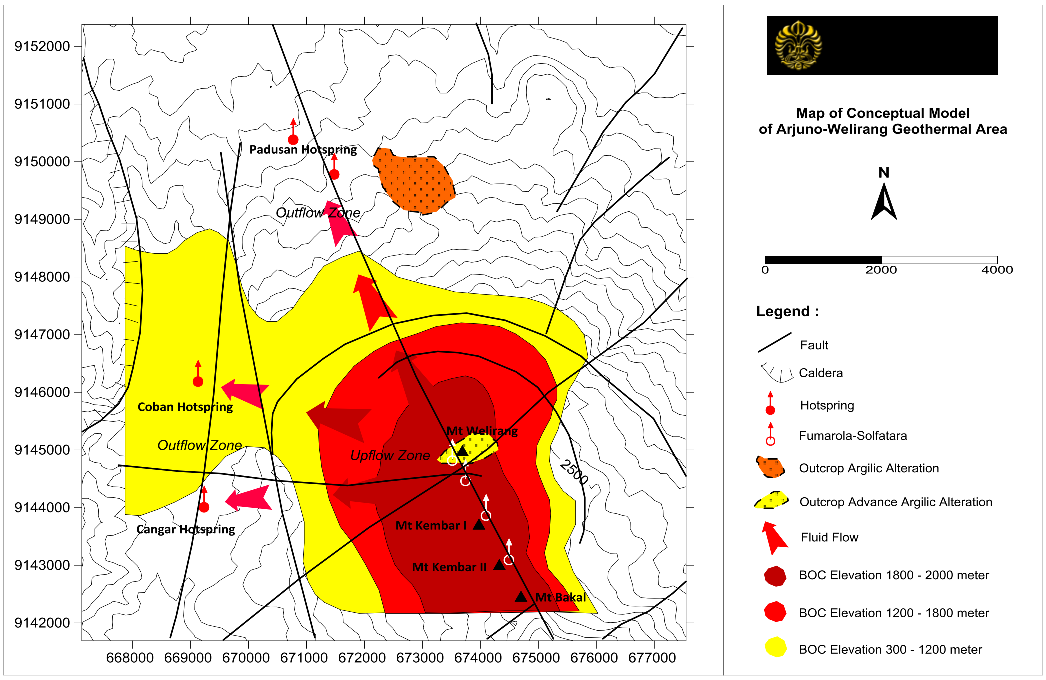

Figure 7: Conceptual Model Represented by BOC Elevation Contour and Hydrogeology Map of the Arjuno-Welirang Geothermal Area

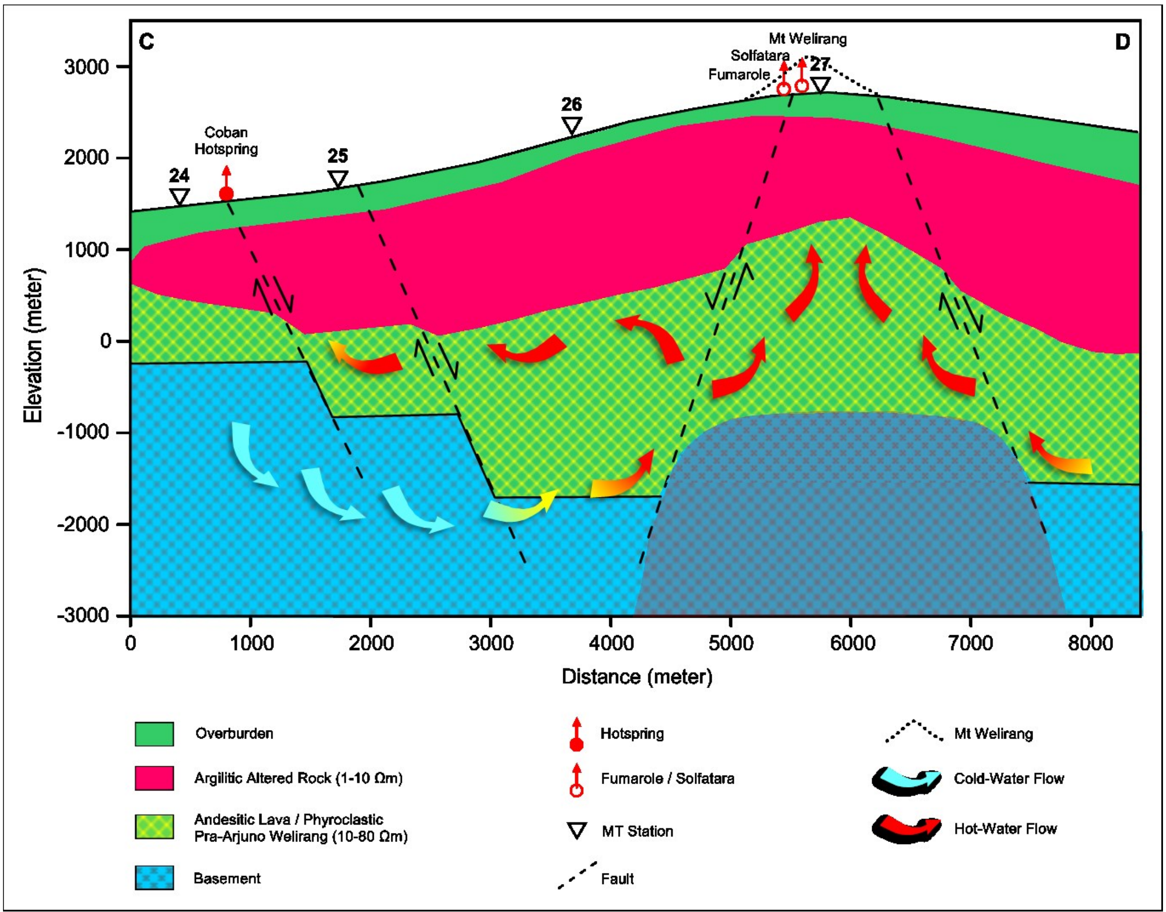

Figure 8: Conceptual Model of the Arjuno-Welirang Geothermal System

6. CONCLUSIONS

The three-dimensional inversion of the MT data in the Arjuno-Welirang geothermal prospect area shows a good agreement with surface geological features, as well as geochemical data. On the basis of this study, a conceptual model of the Arjuno-Welirang geothermal prospect area is presented. The upflow zone is situated below the Mt Welirang volcanic complex, as shown by an updome shaped resistivity structure. The base of conductive (BOC) layer is located at a depth of about 1,500 meters, which is the minimum depth of the main reservoir. The occurrence of solfataric-fumaroles with magmatic gasses found on the top of Mt Welirang suggests that the Arjuno-Welirang geothermal prospect is a volcanic geothermal system. Outflow zones are indicated by the elongation of the conductive layer, following the elevation of the vicinity of Mt Welirang towards the west and northwest, as indicated by the occurrence of bicarbonate hotsprings at the Cangar and Coban in the west and at the Padusan in northwest.

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