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New Interpretation of DC Resistivity Data in the Sibayak Geothermal Field, Indonesia

Supriyanto Suparno, Yunus Daud, Syamsu Rosid, Dede Djuhana and Yayan Sofyan

Department of Physics, University of Indonesia, Kampus Depok 16424, INDONESIA

supri@fisika.ui.ac.id

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ABSTRACT

DC Resistivity analysis was carried out in the Sibayak geothermal using Schlumberger Vertical Electrical Sounding (VES) during a preliminary study in 1990. The resistivity data has been processed conventionally using one-dimensional (1-D) inversion to estimate vertical variation of resistivity related to hydrothermal activity at shallow depths of less than 1 km. Subsequently, the inversion results were correlated to develop a 2-D resistivity section; afterwards, it was combined with the MT data processing result. However, the results of 1-D inversion of DC resistivity are not fully satisfactory for actual 3-D structures such as geothermal systems. Therefore, we have re-processed the same Schlumberger VES data set by performing a 2-D inversion based on ABIC least squares method. The 2-D inversion result shows a more realistic feature in terms of geological structure. Caldera boundaries and a dome-like structure of the low resistivity are clearly determined, indicating an up-flow zone around fractures in the southeast direction of the Sibayak Mountain. By tuning and improving the interpretation method, we accomplished descriptions of the shallow subsurface conditions in the Sibayak geothermal field. These results can be used to improve the understanding of the shallow subsurface conditions in the Sibayak geothermal field.

1. INTRODUCTION

In many cases, high temperature zones of geothermal reservoirs are located in regions of anomalously low apparent resistivity. It is acceptable that apparent resistivity anomalies can be used as an indicator of a geothermal targets. However, in geothermal prospects located in steep terrain, like the Sibayak geothermal field, the apparent resistivity anomalies often identify cooler outflow zones, rather than the centers of the geothermal systems (Anderson et al., 2000).

Some results of resistivity studies in the Sibayak geothermal field, which mainly focused on deep resistivity structure, have been published by several geophysicists. Mulyadi (2000) analyzed MT data in 1-D from each MT station and correlated all the results to develop 2-D deep resistivity sections. The following year, Daud et al. performed 2-D inversion of the same MT data to construct a 2-D resistivity model. The combination of shallow and deep resistivity models were studied by Suparno in 2005 using 3-D inversion of Misse-a-la-mase data and 2-D inversion of MT data. Even though the MT method can image deeper resistivity structures than other resistivity methods, its resolution is too low to identify a geological structure, especially near the surface. Therefore, an effort is required to improve the data to provide detailed resistivity structures with respect to the shallow and deeper zones.

In the Sibayak geothermal field, the shallow subsurface resistivity distribution in vertical directions was achieved conventionally by processing a 1-D inversion of DC-resistivity VES data. The results were not fully satisfactory for imaging complex geologic structures of geothermal fields. Therefore, the same data set has been reprocessed using a 2-D inversion technique based on the ABIC (Akaike Bayesian Information Criteria) least squares method to improve the shallow resistivity model for better interpretation. The interpretation results clearly indicate the caldera boundaries in the northeast and the northwest of Mt. Sibayak. Interestingly, the interpretation results exhibit good correspondence with an up-flow zone and lateral flow-direction that were inferred based on previous MT methods.

2. SIBAYAK FIELD OVERVIEW

The Sibayak geothermal field is a liquid-dominated geothermal system which in the North Sumatra province of Sumatra Island, Indonesia, as shown in Figure 1. The field lies inside the Singkut caldera at elevations between 1400 and 2200 m. There are three active volcanoes: Mt. Pintau (2212 m), Mt. Sibayak (2090 m) and Mt. Pratektekan (1844 m). The geologic conditions of Sibayak geothermal field are illustrated in Figure 2.

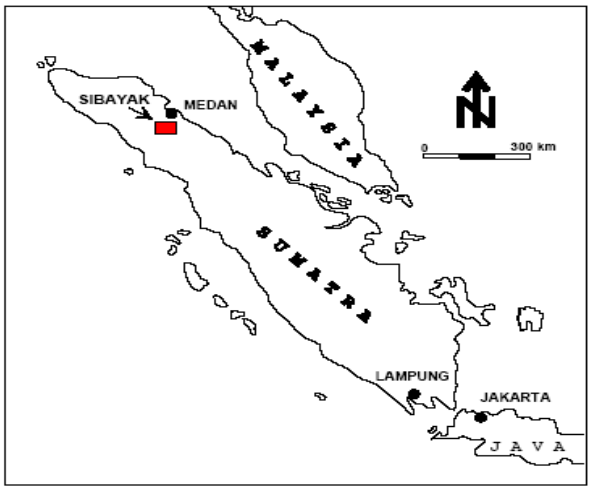

Figure 1: Location map of Sibayak geothermal field.

In the area of the Singkut caldera, the Quaternary volcanic rock formation is divided into pre and post caldera units. The former includes Singkut dacite-andesite and Singkut laharic breccia, and the latter includes Simpulanangin pyroxene andesite, Pratektekan hornblende andesite, Pintau pyroxene andesite and Sibayak hornblende andesite. The volcanic rock formation is composed of andesite, andesite breccia and tuff breccia. Relatively moderate clay and chloritic hydrothermal alteration are found within this formation.

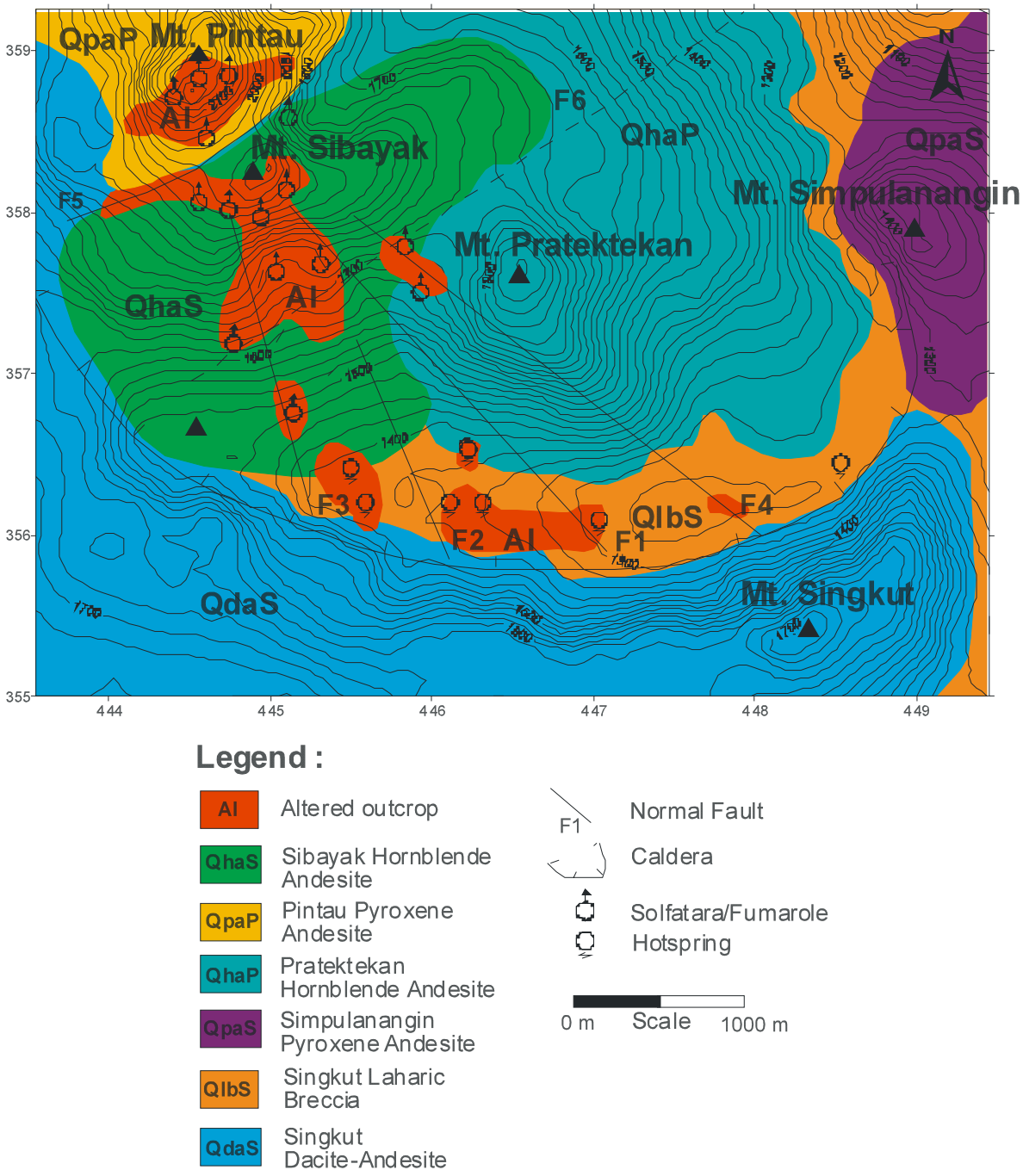

Figure 2: Geological map of Sibayak geothermal field.

The caldera structure is elongated to NW-SE, and it was developed after the Mt. Singkut volcanic eruption (0.1 Ma). Some fault structures (F1 to F4) within the caldera have orientations to NW-SE and extend to the center of Mt. Sibayak and Mt. Pintau, where they are intersected by the NE-SW fault structures (F5). The NW-SE fault structures are also intersected by the NE-SW lineament (F6) encountered between Mt. Sibayak and Mt. Pratektekan.

Many geothermal manifestations consisting of solfataras and fumaroles are found at high elevations in the area between Mt. Sibayak and Mt. Pratektekan. The largest fumaroles that indicated an up-flow zone was observed on the eastern flank of Mt. Sibayak around the center of the fracture zone. Chloride springs with silica sinter exist at lower elevations in the southern and southeastern parts of Mt. Pratektekan around the Singkut caldera rim.

3. RESISTIVITY MEASUREMENT

The DC resistivity sounding with a Schlumberger array was carried out on 26 VES stations using electrode spacing ranging from AB/2= 2 up to 1000 m in successive steps, as shown in Figure 3. The field sites were chosen on the basis of the accessibility and applicability of the Schlumberger geoelectrical method.

The AOB and AOC profiles, with sounding station SBY-D16 as a center, were chosen as the appropriate ones for investigating subsurface thermal activity and geological structure. The sounding station SBY-D16, which is located around the center of three fractures extension between Mt. Sibayak and Mt. Pratektekan, is very close to the largest fumaroles indicated as up-flow zones. The area is the most interesting area for further investigation and development.

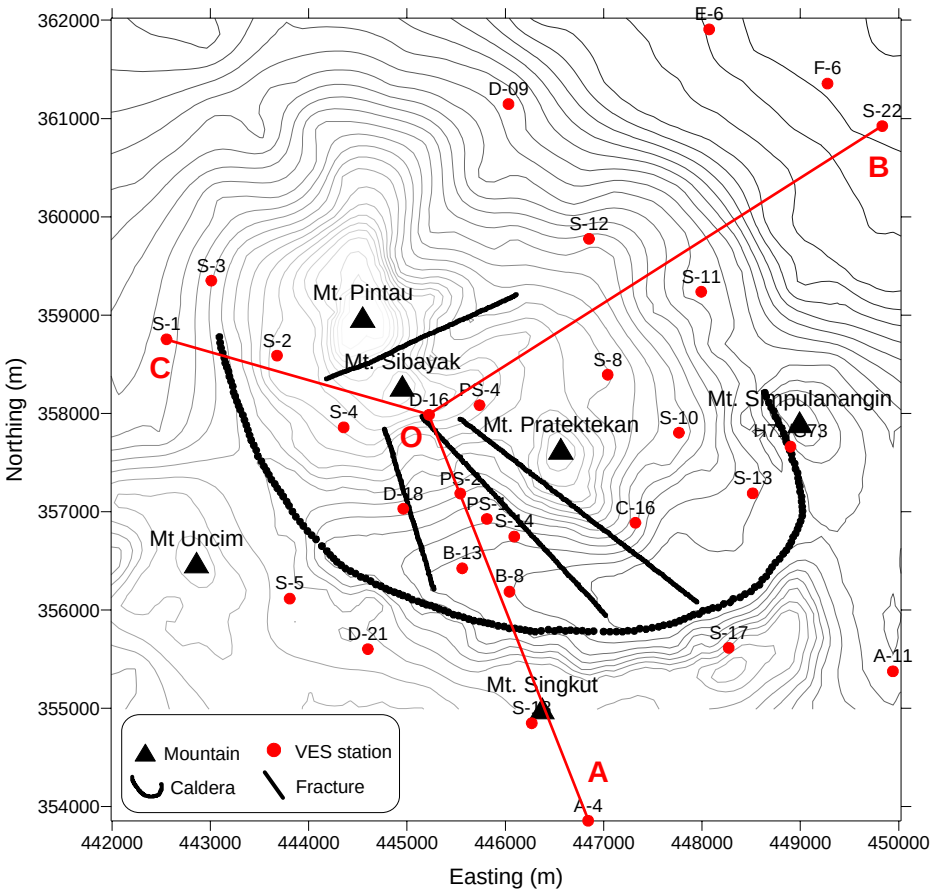

Figure 3: Schlumberger VES sounding stations and three line profiles for interpretation.

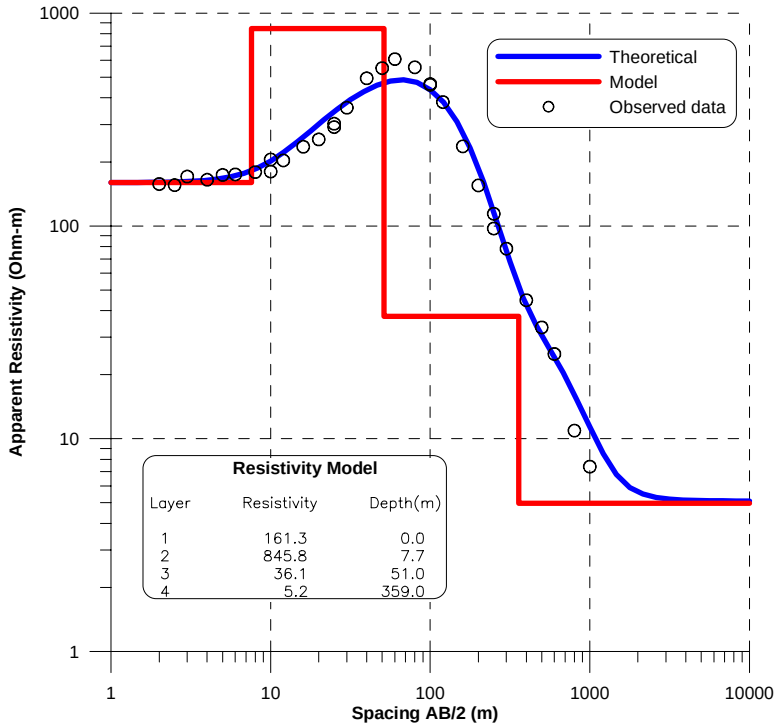

Figure 4: 1-D inversion of apparent resistivity data from sounding station SBY-D16.

4. DATA PROCESSING AND INTERPRETATION

The VES resistivity data were initially processed in an iterative 1-D modeling technique proposed by Zohdy (1989). The final model derived by Zohdy program was then obtained, in combination with a simple resistivity-depth transformation of the observed data as an initial model for 1-D inversion (Meju, 1994). A selective example of this process, sounding station SBY-D16, is shown in Figure 4. The layering model and theoretical apparent resistivity sounding results are closely similar to the observed values.

Inspection of the theoretical VES's curves of the best fitted model reveals that the number of the interpreted layers is four layers, and the true resistivity of these layers varies from 5 to 830 ohm-m.

The lowest resistivity, 5 ohm-m, starts from 359 m depths. This result is used as a reference depth for processing results of 2-D inversion.

The 2-D inversion algorithm applied to the same DC-resistivity data set was made by Uchida (1991). The algorithm is based on ABIC (Akaike Bayesian Information Criterion, Akaike, 1980), and is based on the convergence of the optimum smoothness using a finite element calculation mesh. The theoretical basis of the 2-D scheme is extensively discussed by different authors (e.g. Sasaki, 1981, Uchida, 1991 and El-Qady et al., 1999).

Two profile section lines (AOB and AOC) were selected crossing the indicated up-flow area and fracture extension to the NE and SE directions between Mt. Sibayak and Mt. Pratektekan. The integrated resistivity cross section, which varies from 2 to 1000 ohm-m, is shown in Figure 5 and Figure 6. The depth scale of the profiles refers to 1-D inversion results from sounding station SBY-D16 (Figure 4). It is clearly shown that the 1-D inversion resistivity layer beneath station SBY-D16 has quite similar form to the result of 2-D inversion.

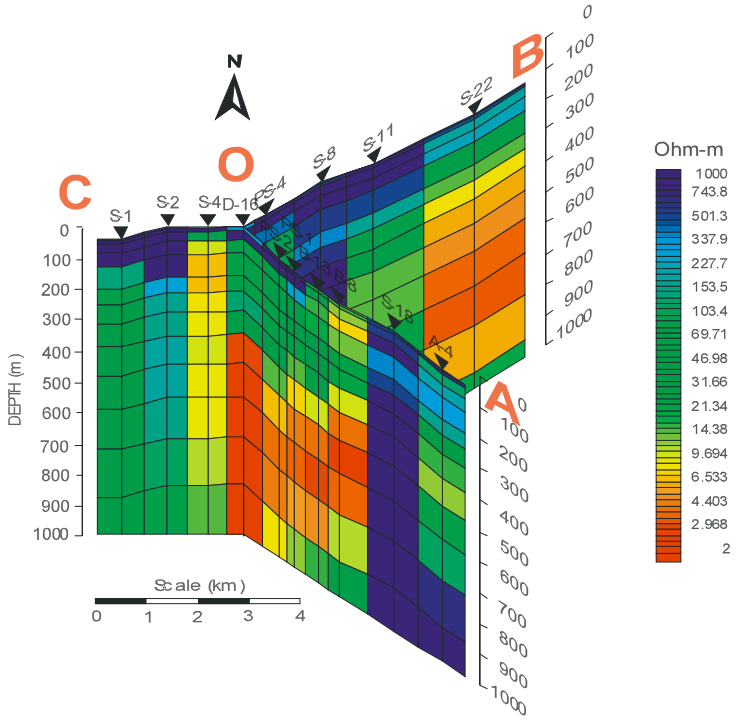

Figure 5: Integrated cross section 2-D resistivity inversion from AOC profile side.

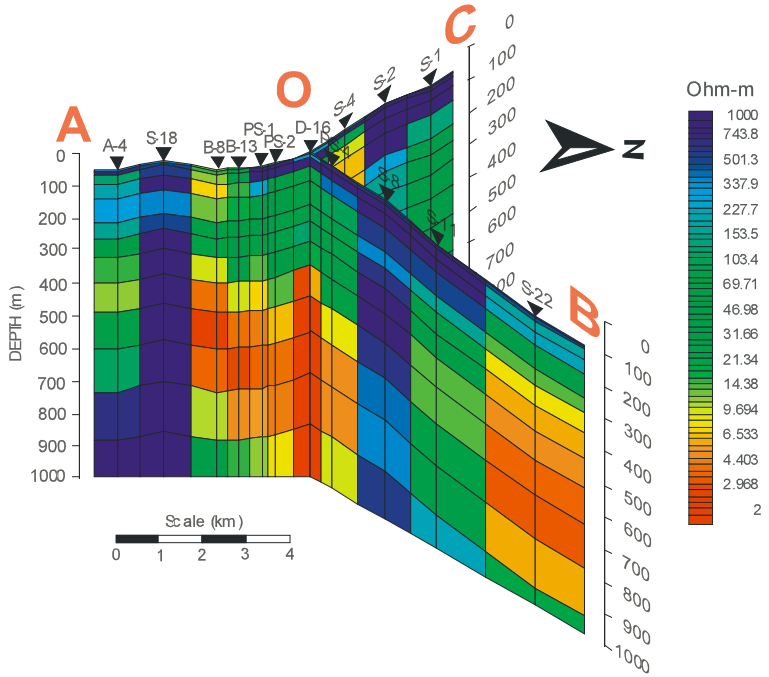

Figure 6: Integrated cross section 2-D resistivity inversion from AOB profile side.

The lowest vertical resistivity below the station D-16 could be associated with hydrothermal activity within a rock-altered zone, and it produces a conductive smectite layer (a clay mineral that has resistivity less than 10 Ohm-m). According to Anderson et al. (2000), the lowest resistivity zone below steep terrain topography could be interpreted as a good indicator of an up-flow zone. Moreover, the existence of fumaroles close to station D-16 and fracture extension to station D-16 may support the interpretation.

Other low resistivity anomalies that are closer to the surface, were found between stations PS-2 and B-8 along the profile OA (Figure 5); and between stations PS-4 and S-8 in the profile OB (Figure 6). In this zone, the low resistivity may be caused by lateral flowing of hydrothermal fluid through fractures in the southeast direction of Mt. Sibayak inside the Singkut caldera rim. By considering the steep terrain topography in the study area, where a significant hydrological gradient is present in the sub-surface, it is common that the conductive smectite layer may be much closer to the surface in cooler outflow areas (Anderson et. al., 2000). Moreover, this interpretation has good agreement with the interpretation of MT-data suggested by the indicated out-flow zone to the SE direction (B direction) from the central area, as shown by the extension of the low resistivity zone (Daud et al, 2001).

The cross section in Figure 6 also clearly shows high contrast of resistivity between stations S-18 and B-8. It can be inferred as a vertical contact between two formations. Based on the geological map (Figure 1), the vertical lithology boundary between Sibayak hornblende andesite and Singkut laharic breccia is located around the same position as the vertical contrast of resistivity between S-18 and B-8. In fact, according to the sounding station distribution map (Figure 3), the two stations are separated by the caldera rim. Accordingly, high contrast of resistivity in this area has verified the existence of a caldera rim. The same subsurface interpretation can also be made between stations PS-4 and S-8, as well as between S-2 and S-4. Based on these interpretation results, a boundary of the geothermal reservoir area is proposed, as shown in Figure 7.

Even though the more resistive layer underlaying the low resistivity zone, which is usually associated with the reservoir zone, could not be modeled due to a limited depth penetration of the Schlumberger sounding, the model has provided useful guidance for deeper subsurface geophysical investigation mainly inside the boundary of the geothermal reservoir.

5. CONCLUSION

The interpretation technique has imaged a detailed shallow resistivity structure in the Sibayak geothermal field. The trend of low resistivity distribution in the vertical direction interpreted as the geothermal reservoir is located inside the Singkut caldera rim. The low resistivity zone indicates an up-flow zone located on the southeast direction of Mt. Sibayak in the center of fracture extensions. Accordingly, by considering the low resistivity distribution (below 10 ohm-m) and steep terrain situation, the most interesting area covers about 16 km^2 located between Mt. Sibayak and Mt. Pratektekan. This conclusion is supported by the previous MT-data.

6. ACKNOWLEDGEMENTS

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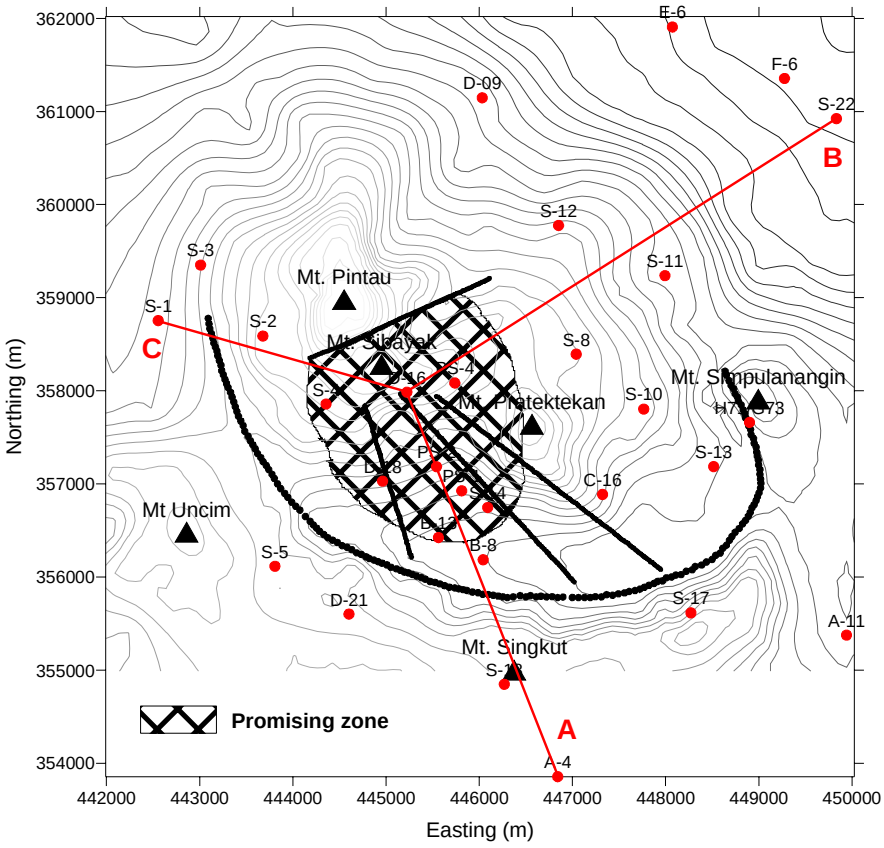

Figure 7: Boundary of geothermal reservoir interpreted based on 2-D inversion of DC resistivity data.

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