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# An Update on the Resistivity Model of the Mt. Apo Geothermal Project, Philippines

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## ABSTRACT

The 2017 magnetotelluric study of the Mt. Apo Geothermal Project confirmed several resistivity features from the 2006 resistivity model of previous studies including the NW-trending high resistivity anomaly associated with the high temperature resource, the major outflow towards the northwest, and the postulated minor outflows towards the southwest and southeast. Moreover, the recent survey also identified a new feature characterized as a NE-trending moderately resistive anomaly that appears to cut through the supposedly continuous conductive layer of the reservoir. With an additional 102 MT soundings from stations surrounding the 2017 study area, the 2019 model updated and expanded the resistivity model, explored the extent of the postulated outflows and further characterized the NE-trending anomaly.

## 1. INTRODUCTION

### 1.1 Location

The Mt. Apo Geothermal Project is located within the Mt. Apo National Park in South Central Mindanao, Philippines. The project harnesses the geothermal energy associated with the Philippines' highest peak, Mt. Apo. Its 701 hectare development block lies on the mountain's northwest flank with a total output of 105 MW. Immediately to the south of Mt. Apo geothermal area is the Mt. Zion geothermal prospect, one of EDC's frontier areas in Mindanao. The prospect encloses a total area of 90 km2.


**Figure 1: Mt. Apo Geothermal Area is located in South Central Mindanao and immediately to its south is the Zion Geothermal Prospect**

### 1.2 Previous Works

Several resistivity surveys have already been conducted in the area since 1984 identifying various resistivity anomalies of interest. In 1984 SRT and VES Surveys were conducted in the area and results identified and characterized four low resistivity anomalies in and surrounding the Mt. Apo which are the Marbel, Kapatagan, Bulatukan and Tico Anomalies (Delfin et al., 1989) as shown in Figure 2.

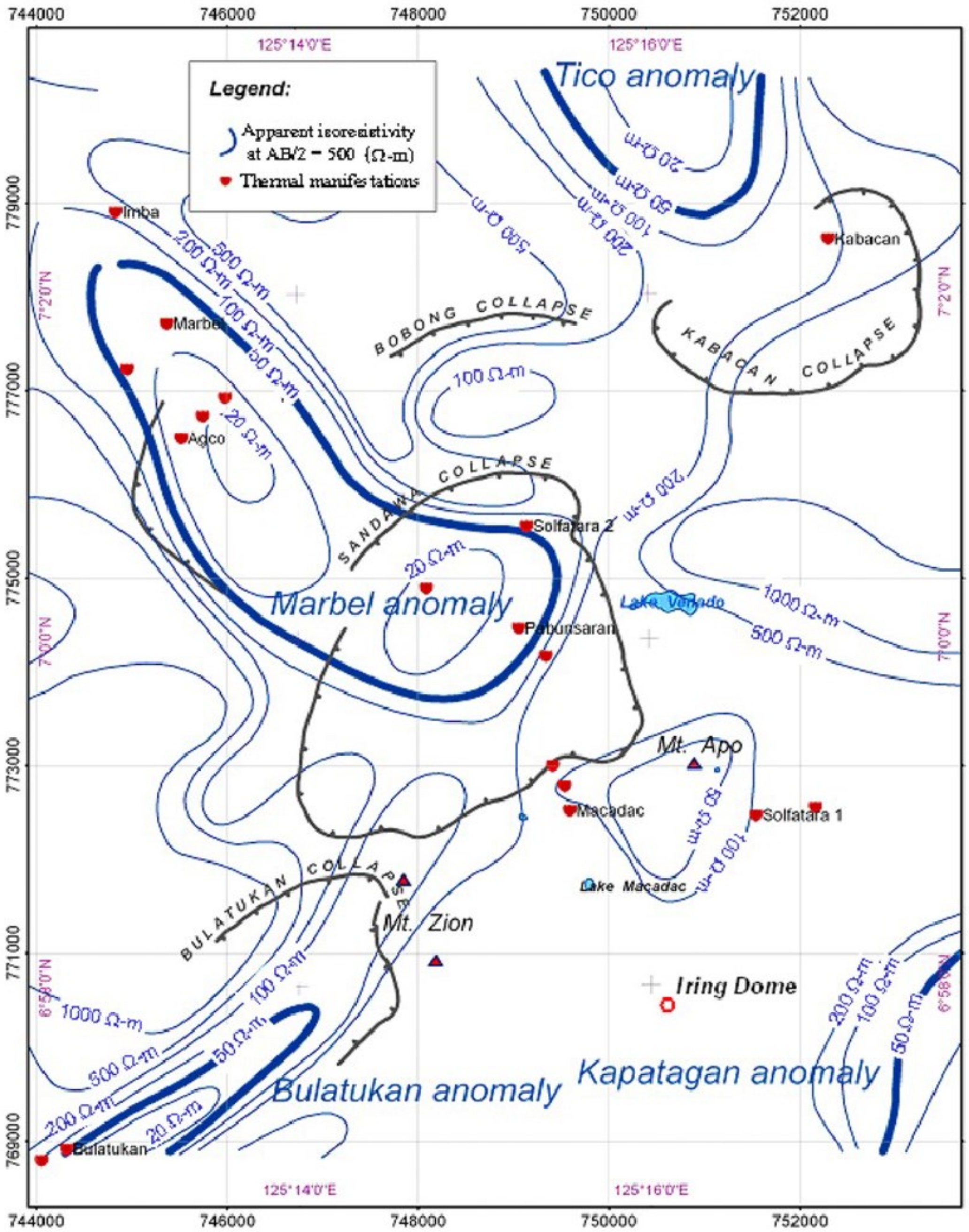


**Figure 2: Results of the 1984 SRT and VES Survey (taken from Los Baños et. al., 2010)**

The most notable of these anomalies is the Marbel anomaly which was characterized as a NW-trending anomaly associated with the prominent thermal features in the area. Its elongate shape is evidently controlled by the flow of hydrothermal fluids along a major NW-trending structure. Two postulated outflows were also identified which are the Bulatukan anomaly towards SW and towards SE is the Kapatagan Anomaly. The large low resistivity anomaly to the north is interpreted to be related to the broad cold altered grounds of Tico and therefore named as the Tico Anomaly (Delfin et al., 1989).

In 2006, the first MT Survey was conducted in the Mt. Apo Geothermal Area. This was the first deep penetrating resistivity survey conducted at the Mt. Apo geothermal area. It installed a total of 146 stations covering roughly 100 km2 as shown in Figure 2**.**

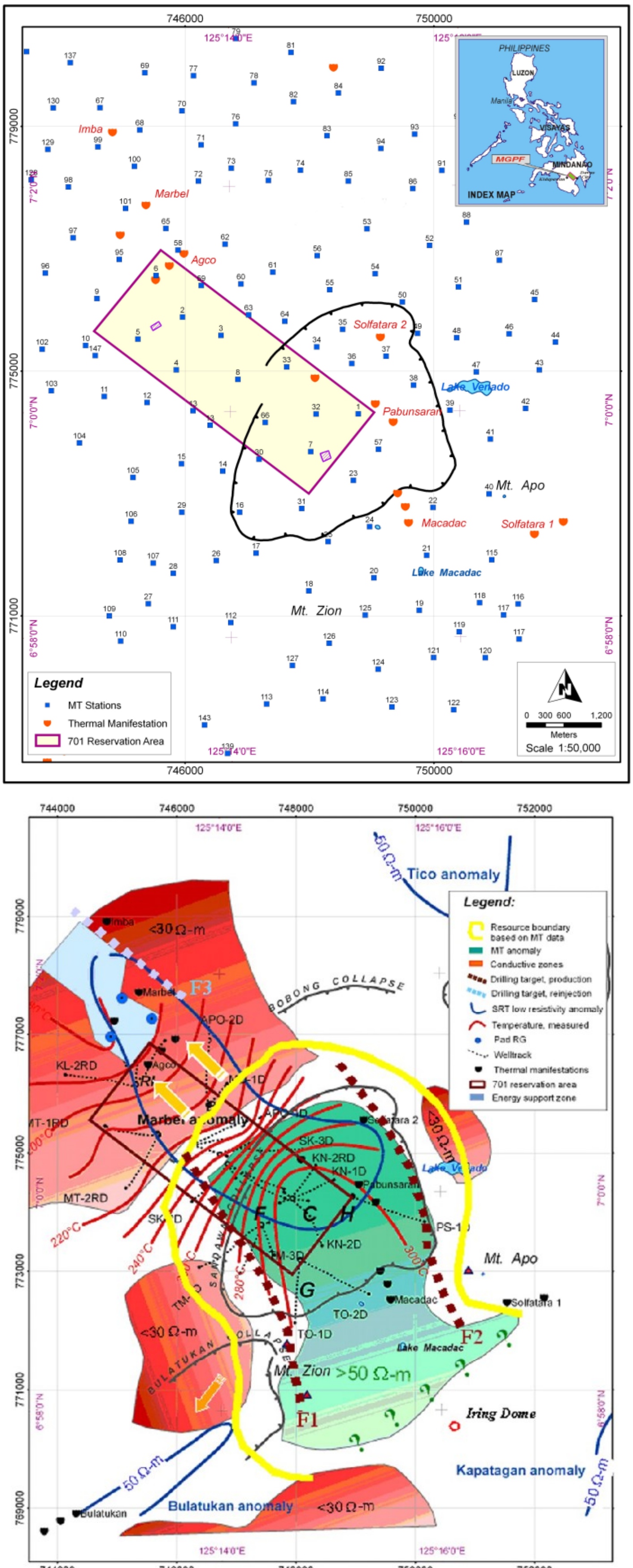


**Figure 3: The 2006 MT Survey installed 146 stations and the results identified the high resistivity anomaly interpreted to signify the high temperature resource of Mt. Apo Geothermal Area (Los Baños et. al., 2010)**

Results of this survey outlined a NW-trending MT anomaly with a possible extension of the resource towards Mt Zion area in the southeast. The NW-trending MT anomaly has been established to most likely approximate the extent of the high temperature region of the reservoir (Figure 3). The northern half of the anomaly coincides with the zone of elevated temperatures exceeding 300̊C . The southern end of the anomaly is delineated beneath Mt. Zion and Lake Macadac. This includes the southern flanks of the peak. (Rigor et al., 2006)

The prominent conductive zones located around the MT anomaly signify the most likely outer margins of the resource. The widespread low resistivity region mapped in the NW characterizes the major outflow of the resource. The conductive zones towards south of Mt. Zion and East of Macadac are indications of possible minor outflows towards the SW and towards the SE which supports the anomalies delineated by SRT and VES. (Rigor et al., 2006)

## 2. METHODOLOGY

The magnetotelluric (MT) method is a passive electromagnetic technique which involves measuring variations in the natural electric field, E, and magnetic field, B, in orthogonal directions at the surface of the Earth. It is a means of determining the resistivity structure of the earth at depths ranging from a few tens of meters to several hundreds of kilometers (Simpson and Bahr, 2005). The electric response of the Earth's subsurface could be obtained from large depths by extending the measuring (or sounding) period during a magnetotelluric survey. This principle is described in the electromagnetic skin depth relation, which is in a simplified form:

$$p(T) \approx 500\sqrt{(T\rho\ a\ )}\ m$$

Here p(T ) is the electromagnetic skin depth in meters (m), T is the magnetotelluric sounding period in seconds (s) and a is the apparent resistivity in ohm-meter (Ω-m). The variations of the Earth's electromagnetic fields measured during a magnetotelluric sounding are initiated by lightning discharges or interactions between solar wind and the ionosphere and magnetosphere. Here the former is causing high frequency (>10 Hz) time variations and the latter is causing low frequency (<10 Hz) time variations. Both these electromagnetic fields are the sources of MT signals being measured. An induced electric field by a time-varying magnetic field generates an electric current in the ground (Simpson and Bahr, 2005).

Magnetotellurics has a long track record in the exploration of convection-dominated play type geothermal systems. This is especially the case for volcanic type geothermal systems, which have a clear resistivity pattern. The electrical resistivity of the subsurface of a geothermal system depends on its temperature, porosity and permeability, fluid salinity, and alteration mineralogy.

### 2.1 Data Acquisition

The 2017 survey occupied 41 stations while the Mt. Zion survey added 102 stations totaling to 143 stations occupied using four sets of Phoenix MTU-5A data loggers. This is in addition to the 129 stations occupied by the MT survey in 2006. The Hx, Hy, Hz, Ex, and Ey, were measured using MTC-80C magnetic coils. Each sounding was measured for one overnight with about 16-18 hours of continuous recording. A typical MT station layout is illustrated in Figure 4.

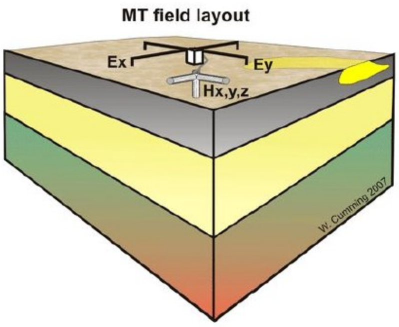


**Figure 4: MT Station layout that is followed by the 2017 and 2019 Magnetotelluric (MT) survey campaigns in Mt. Apo geothermal area and Mt. Zion geothermal area respectively.**

Each raw MT data from the 143 MT stations consists of time series (TS) files which were reprocessed using discrete Fourier transform (DFT) and robust crosspower implementation which resulted to two interdependent curves such as the resistivity and phase curves, both in the frequency domain (Phoenix Geophysics, 2005). Both DFT and robust crosspower implementation were executed. Analysis of the dimensionality of the magnetotelluric data (i.e. induction arrows, phase tensors, rotational invariants) determined the three dimensional nature of the subsurface beneath the area.

Data modeling included static shift correction for transverse electric (TE) and transverse magnetic (TM) modes, and station data rotation. The 1-D smooth inversion was calculated from the TE mode. Mode choice and static correction was based mainly on geological plausibility, consistency with adjacent stations and polarization. The inversion was extended only to the minimum depth which fits the data. Iso-resistivity plan maps at various elevations were generated to show lateral resistivity distribution across the study area. This demonstrates more accurate spatial characterization of the resistivity structures.

## 3. RESULTS

The updated resistivity model of Mt. Apo confirms several features identified by the previous resistivity surveys. Comparison of the first MT model of Mt. Apo and the updated model is shown in Figure 5.

Iso-resistivity maps shows of the 2006 and 2019 model both show the anomalous highly resistive body characterized as the high temperature resource located beneath the Sandawa collapse. The recent model also recognizes the postulated anomaly extensions towards the SW and towards the SE first identified in the 2006 model. The broad conductive zone in the NW correlated with the established major outflow of the resource can also be observed in both models.

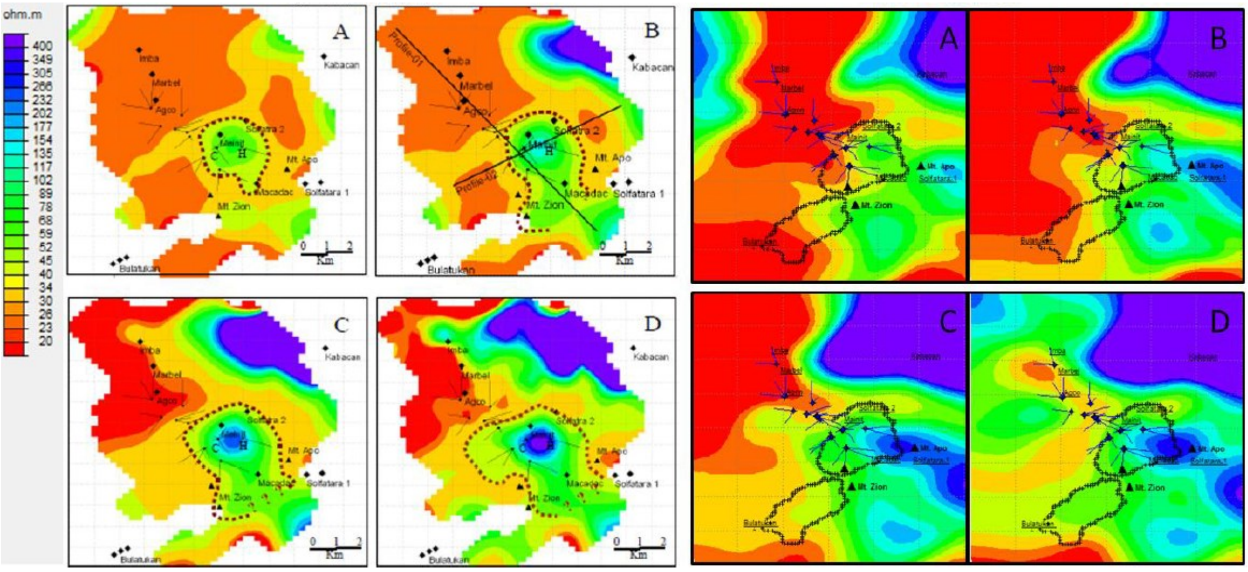

**Figure 5: Resistivity maps at different elevations: A) 500M, B) SEA LEVEL, C) -500M, D) -1000M. LEFT- 2006 model, RIGHT- 2019 model. (Modified from Mendoza and Tugawin, 2017)**

### 3.1 Characerization of Resistivity Anomalies

A total of four anomalies of interest have been characterized further in size and extent with the additional stations. The anomalies are namely the Macadac/Maag anomaly, Mount Apo Anomaly, Venado Anomaly, and Sandawa Anomaly (Figure 6).

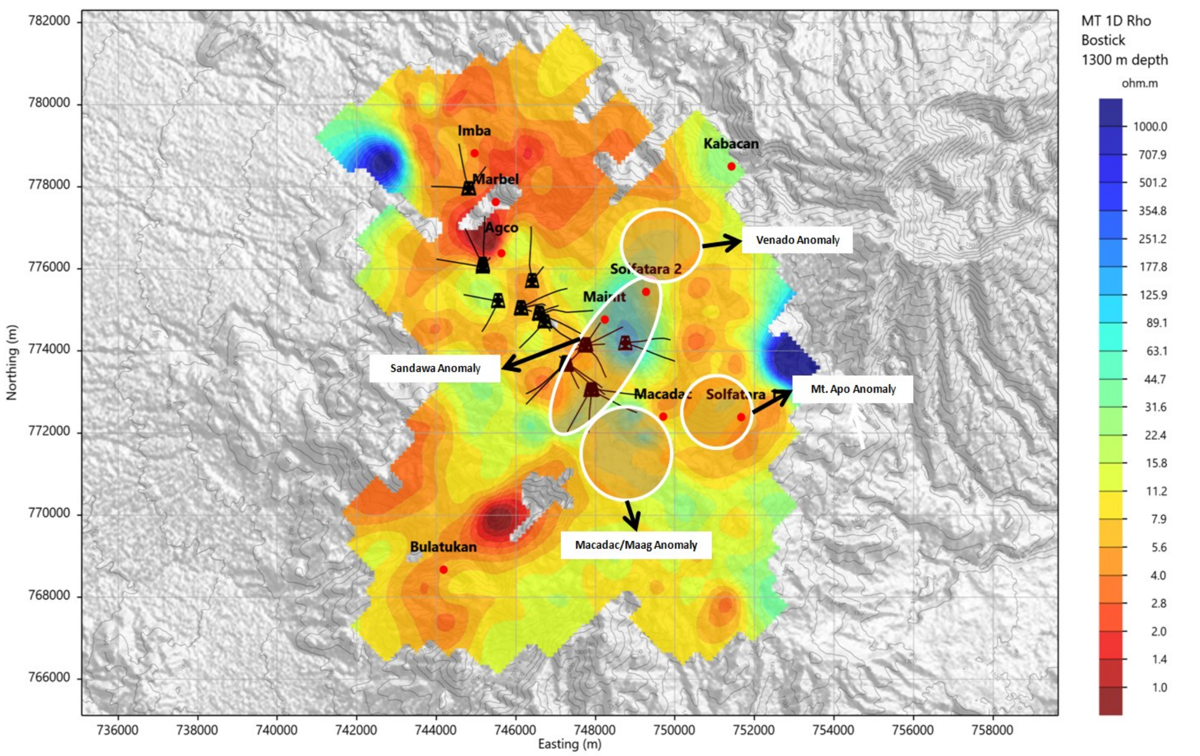


**Figure 6: Four anomalies have been identified in the Mt. Apo Geothermal Area (Modified from Morillo and Pastor, 2019)**

The resistivity structure towards the Zion geothermal area can be characterized as two resistivity anomalies. One is an up-doming beneath Mount Apo which will be refered to as the Mount Apo anomaly in this report and the other, an intermediate to high resistivity anomaly beneath Macadac/Maag area on the southwest flank of Mount Apo which we referred to as the Macadac/Maag anomaly in this report.

Mount Apo Anomaly

The Mount Apo anomaly can be characterized as an up-doming beneath Mount Apo, which can be interpreted as an upflowing beneath Apo. This is overlain by a continuous conductive cap thickening and spreading downflank from the peak towards the southeast.

Macadac/Maag Anomaly

The resistivity anomaly beneath Macadac/Maag is similar to the Sandawa collapse anomaly in such a way that it also has a gap in the conductive layer (Figure 7). The gap which has resistivities of 10-20 ohm-m can be due to a geologic structure or simply the thinning of the conductive cap due to upflowing geothermal fluids. A very thin conductor might not be resolved in the inversions of the MT data. The thickening of the conductive layer downflank from Macadac/Maag can be interpreted to be due to outflowing geothermal fluids towards Bulatukan area.

Sandawa Anomaly

The Sandawa Anomaly is a NE-trending feature observed within the Sandawa collapse. The feature appears as a gap in the conductive layer. It is an elongate feature that extends from Bulatukan collapse in the SW towards the northern edge of the Sandawa collapse in the NE. It is characterized as a moderately resistive zone (10Ωm- 30Ωm) that is cutting through the conductive layer.

Venado Anomaly

Aside from the already established anomaly related to the MAGP geothermal resource beneath Sandawa collapse, an extension towards Venado area is observed. This is manifested as an up-doming resistive feature overlain by a conductive cap beneath the Venado solfara. The anomaly is bounded by a thickening of the conductive layer to the northwest, southeast and northeast, thus separating this anomaly from the up-doming beneath Apo.

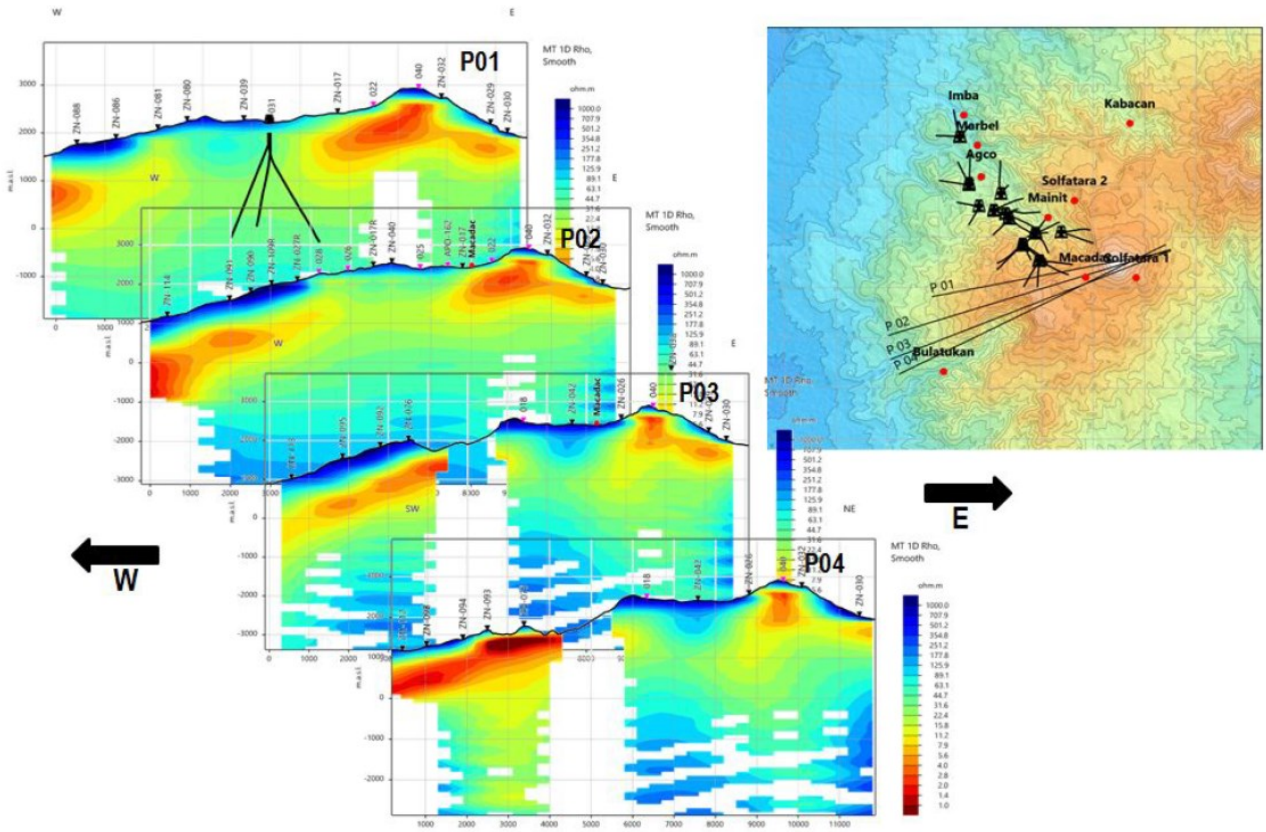


**Figure 7: Resistivity profiles 1 to 4 showing the subsurface resistivity structure beneath Apo and Bulatukan. (Morillo and Pastor, 2019)**

## 4. DISCUSSION AND CONCLUSION

The updated MT model of the Mt. Apo and Mt. Zion geothermal areas have identified and characterized four resistivity anomalies characterized by the thinning of the conductive layer.

Similarly, the Mt. Apo and Macadac/Maag anomalies are interpreted as upflowing fluids. The postulated upflow beneath Mt. Apo peak is interpreted to have possible outflow path towards the W-SW direction. Whereas the postulated upflow beneath Macadac/Maag area has an interpreted outflow towards Bulatukan hot springs in the southwest. These outflows indicate possible extension of the resource which merits further investigation and correlation with Geology and Geochemistry.

The Venado anomaly, on the other hand is believed to be an extension of the resource towards Venado area in the northeast. The resource extension manifests as an up-doming resistive feature overlain by a conductive cap beneath the Venado solfara.

The gap in the resistive layer found beneath Sandawa collapse is aptly called the Sandawa Anomaly. This moderately resistive feature is inferred to be possibly structural or lithological as interpreted in a 2017 study correlating the anomaly with various reservoir data. Well data correlation showed geographical overlap with the end points of known acidic wells suggesting a possible relationship between the anomaly and the acid source. Correlation with new structures showed newly identified structures and fracture patterns in the same area that trend similarly with the anomaly which concurs with the possible interpretation of a fault. This is also supported by a regional perspective on structural geology which lead to a correlation of the anomaly with the features of the nearby Tampakan Mineral District. Correlation showed similarities between the Sandawa anaomaly and the NE structures of Tampakan that are characterized as dilational fractures (Mendoza et. al., 2017). Further investigation is recommended for a more conclusive interpretation of this anomaly.

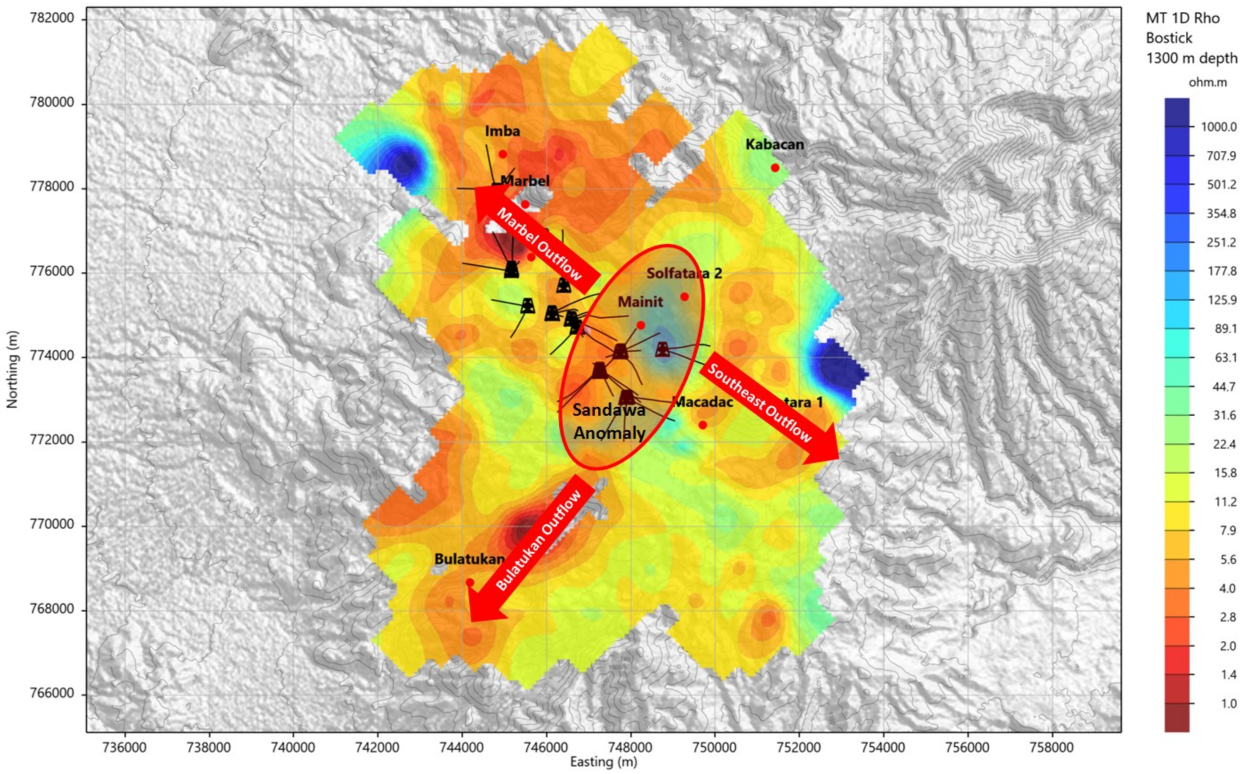


**Figure 8: Updated Resistivity Model of Mt. Apo Geothermal Area**

The results of this survey also updated the geophysical model of Mount Apo to include new inferred upflows and outflows. The Marbel outflow has already been established by reservoir data but new identified possible outflows towards the southwest and southeast that are interpreted as possible resource extensions have been incorporated in the new model. A 3-D inversion of the MT data is recommended to refine the resistivity model due to the inherent 3-D characteristic of the data. A 3-D model is likely to illustrate better the anomalies particularly those inferred to be related to structural features.

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