

## Resistivity Structure of the Mt. Labo Geothermal Project based on Magnetotelluric (MT) Sounding Measurements, Southern Luzon, Philippines

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### ABSTRACT

Results from inversion modeling derived from MT sounding data collected in 1995 and the more recent 2012-2013 surveys in the Mt. Labo Geothermal Project (MLGP) generally show a thin high resistivity layer ( $>30$  ohm-m) overlying most of MLGP. Beneath this thin high resistivity layer is a conductive layer associated with the smectite and illite-smectite clays of the altered andesite and dacite rocks from the Mt. Labo central cone. Beneath the base of the conductive layer is a dome-like resistive feature, postulated to be the top of the reservoir. This resistive feature is bounded by thick conductive layers on both sides. An isoresistivity map at 1500 m below sea level shows a  $\sim 15$ -30 ohm-m resistivity anomaly and is postulated to be part of the geothermal reservoir. Isotherms from drilled wells indicate higher temperatures towards this intermediate resistivity anomaly and lower temperatures towards the conductive zones located in the margins. The postulated upflow in Mt. Labo is beneath the resistive dome-like feature where the highest temperatures were encountered by the drilled wells. Outflow of hot fluids is probably towards the southwest feeding the thermal springs of Kilbay and Alawihaw.

### 1. INTRODUCTION

The Mt. Labo Geothermal Project (MLGP) is located in the southwestern flank of the Mt. Labo Volcano which straddles the Bicol and Calabarzon regions of Luzon, Philippines. MLGP has been the subject of geothermal interest since 1982. Surface exploration surveys by the then PNOC-EDC were first conducted in 1985. Since then a total of 8 wells were drilled in Mt. Labo from 1990 to 1997. In 1995, after drilling the 6<sup>th</sup> exploration well, the first MT survey was conducted jointly by West Japan Engineering Consultants (WEST JEC) Inc., Phoenix Geophysics, Sigma Energy Technologies, Inc. and the Philippine National Oil Company - Energy Development Corporation (PNOC-EDC) to assess the deeper subsurface resistivity structure of MLGP. After drilling two more wells the project was put on hold and has since been put on a low priority due to problems in acidity and poor permeability in some of the wells. Interest in the project still remained and was subsequently revisited in 2012-2013 due to technological advancements in utilization of acid wells. A more detailed MT survey consisting of 120 stations was conducted from December 2012 to February 2013 to supplement the 31 stations from the original 1995 MT survey and to be able to produce an updated resistivity model of MLGP.

### 2. GEOLOGIC SETTING

Mt. Labo is the northern tip of a chain of volcanoes known as the Southeast Luzon Volcanic Arc or Bicol Volcanic Belt (Figure 1). It includes major volcanic systems from the south such as Mt. Bulusan, Pocdol Mountains (Bacman), Mt. Mayon, Mt. Malinao, Tiwi, Mt. Iriga and Mt. Isarog. A branch of the Philippine Fault, namely the San Miguel Fault cuts across the Mt. Labo Geothermal Project in a northwest-southeast direction (Figure 1). The Mt. Labo Geothermal Project is underlain mainly by two formations, the Labo volcanics and the Susung Dalaga formation (Sdf) (Figure 2). The Labo volcanics is further characterized into three subdivisions, namely the Labo basal unit (Lbu), the Labo central cone (Lcc) and the youngest Labo pyroclastic flow (Lpf). Table 1: Generalized stratigraphy of Mt. Labo Geothermal Project (Delfin and Alincastre, 1988) and ages based on thermoluminescence dating (Ramos et al., 2000).

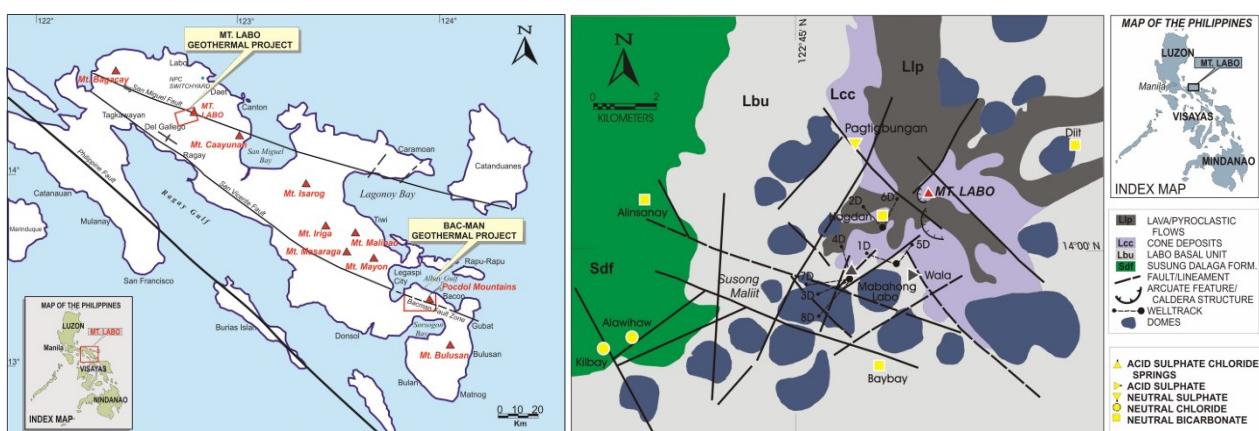


Figure 1: Volcano-Tectonic Map of the Southeast Luzon Volcanic Arc (left).

Figure 2: Geologic Map of Mt. Labo Geothermal Project (Panem, 1995) (right).

Formation	Subdivisions	Description	Age
Labo volcanics	Labo basal unit (Lbu)	Weathered and variably altered andesite, dacite and basalt lavas and lahar.	580 Ka
	Labo central cone (Lcc)	Andesitic to dacitic lavas.	129-88 Ka
	Labo pyroclastic flow (Lpf)	Non-bedded, poorly consolidated to well-compacted andesite-dacite block and ash.	27 Ka
Susung Dalaga formation (Sdf)		Volcanics exposed west of Mt. Labo. Consists of andesitic to dacitic lava flows, agglomerates and tuffs. Wells encountered this formation with a sedimentary suite which includes fossiliferous, carbonaceous, fine-grained clastics, conglomerates and limestones.	Late Miocene (~4 to 5 Ma)

**Table 1: Generalized stratigraphy of Mt. Labo Geothermal Project (Delfin and Alincastre, 1988) and ages based on thermoluminescence dating (Ramos et al., 2000).**

### 3. PREVIOUS GEOPHYSICAL SURVEYS

#### Schlumberger Resistivity Traverse (SRT) and Vertical Electrical Sounding (VES)

Direct current (DC) Schlumberger resistivity traversing (SRT) with half current electrode spacing at AB/2 of 250 m and 500 m and vertical electrical sounding (VES) with AB/2 of up to 1000 m were conducted by Layugan et al, (1988) from 1986-1987 at MLGP. A total of 337 SRT stations and 39 VES sites were occupied. Results of the SRT survey showed a 10 ohm-m low resistivity anomaly extending at high elevation near the western margin of Mt. Labo. Inside the western part of this anomaly lies a 5 ohm-m contour (Layugan et al, 1988). Results of the SRT and VES surveys postulated an upflow of geothermal fluids near the Mabahong Labo thermal area within the low resistivity anomaly and a southwest outflow direction which feed the neutral chloride springs of Kilbay and Alawihaw (Layugan et al, 1988).

#### Magnetotelluric Survey

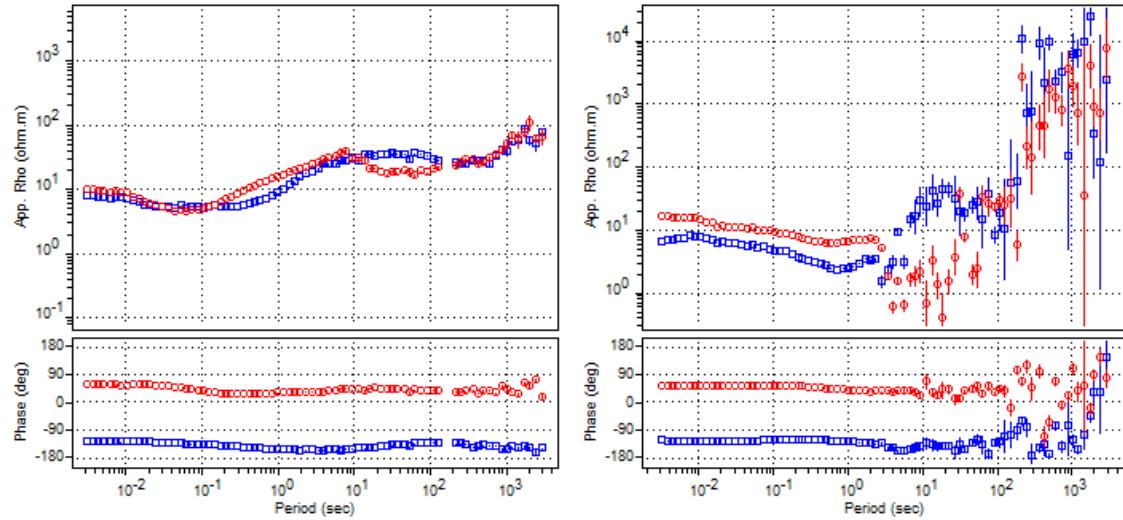
A total of 31 MT stations were measured in 1995. The data was initially processed and modeled using the Bostick inversion method by Ushijima and Mizunaga of Kyushu University, Tagomori et al. of WEST JEC and Yamashita of Phoenix Geophysics (West Japan Engineering Consultants Inc., 1995). The results delineated two low resistivity (<10 ohm-m) resistivity anomalies, the Susung Malit and Banga-banga conductive zones. These two low resistivity anomalies were then separated by a central resistive zone postulated to be the geothermal reservoir. The MT sounding data were later reprocessed and remodeled by Los Baños et al (2008) using 1-D Occam modeling for the isoresistivity maps and 2-D Occam modeling for the resistivity cross-sections. These results were included in the 2008 reassessment of the Mt. Labo Geothermal Project (Los Baños et al, 2008).

#### Gravity Survey

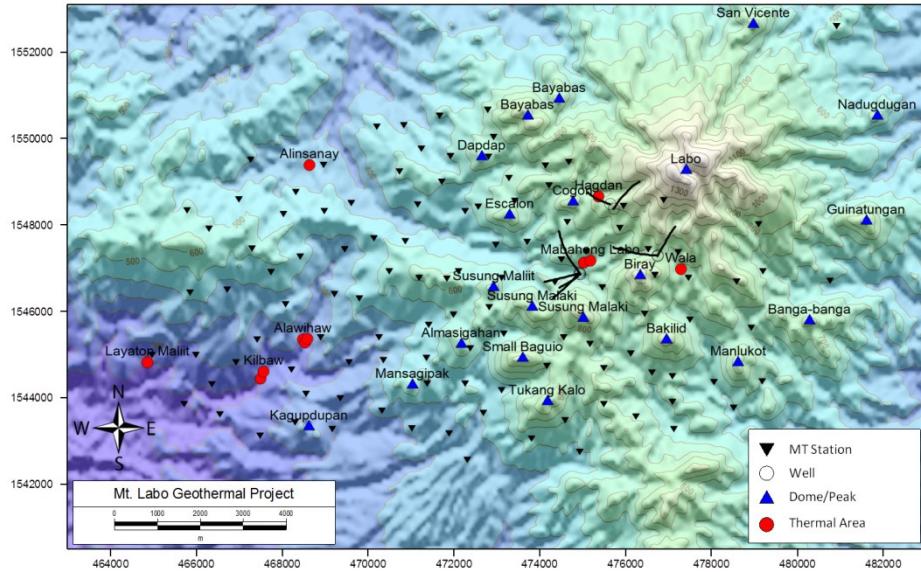
A regional Bouguer gravity survey was also conducted in MLGP by Los Baños and Maneja (1996) in 1995. It covered a total of 169 stations within and around MLGP. The results of the gravity survey delineated a broad negative gravity anomaly west of Mt. Labo. This was correlated with the thick sedimentary rocks of the Susung Dalaga Formation. Two separate positive gravity anomalies were also mapped beneath Mt. Labo in the east and Kilbay-Alawihaw area in the west. These were interpreted to be diorite intrusives. The positive gravity anomaly beneath Mt. Labo is postulated to be a diorite intrusive serving as the heat source for the present hydrothermal system (Los Baños and Maneja, 1996).

#### Magnetotelluric Survey

A total of 120 roving MT stations (Figure 4) were occupied using sets of Phoenix MTU-5A system. Each sounding was measured for two nights with about 40 hours of continuous recording. Each raw MT data from the 120 roving MT stations consists of time series (TS) files which were reprocessed using discrete Fourier transform (DFT) and robust cross-power implementations using Phoenix's SSMT2000™ software (Phoenix Geophysics Limited, 2005). Cross-power components per frequency of each curve were manually edited and converted to a standard MT file format called an Electronic Data Interchange (EDI) file (Wight, 1988). The EDI files were then imported to WinGLink® Integrated Geophysical Processing software for post-processing such as post-editing, inversion and modeling (Geosystem SRL, 2008). A remote reference MT station was measured simultaneously with these roving stations. MT data quality was primarily affected by inclement weather conditions such as continuous heavy rains, strong winds and lightning storms at times during the survey. Out of the 120 occupied MT stations, 102 stations yielded good and acceptable data quality while 18 stations had poor data quality. 25 stations were retested wherein 14 stations had noticeable improvement.



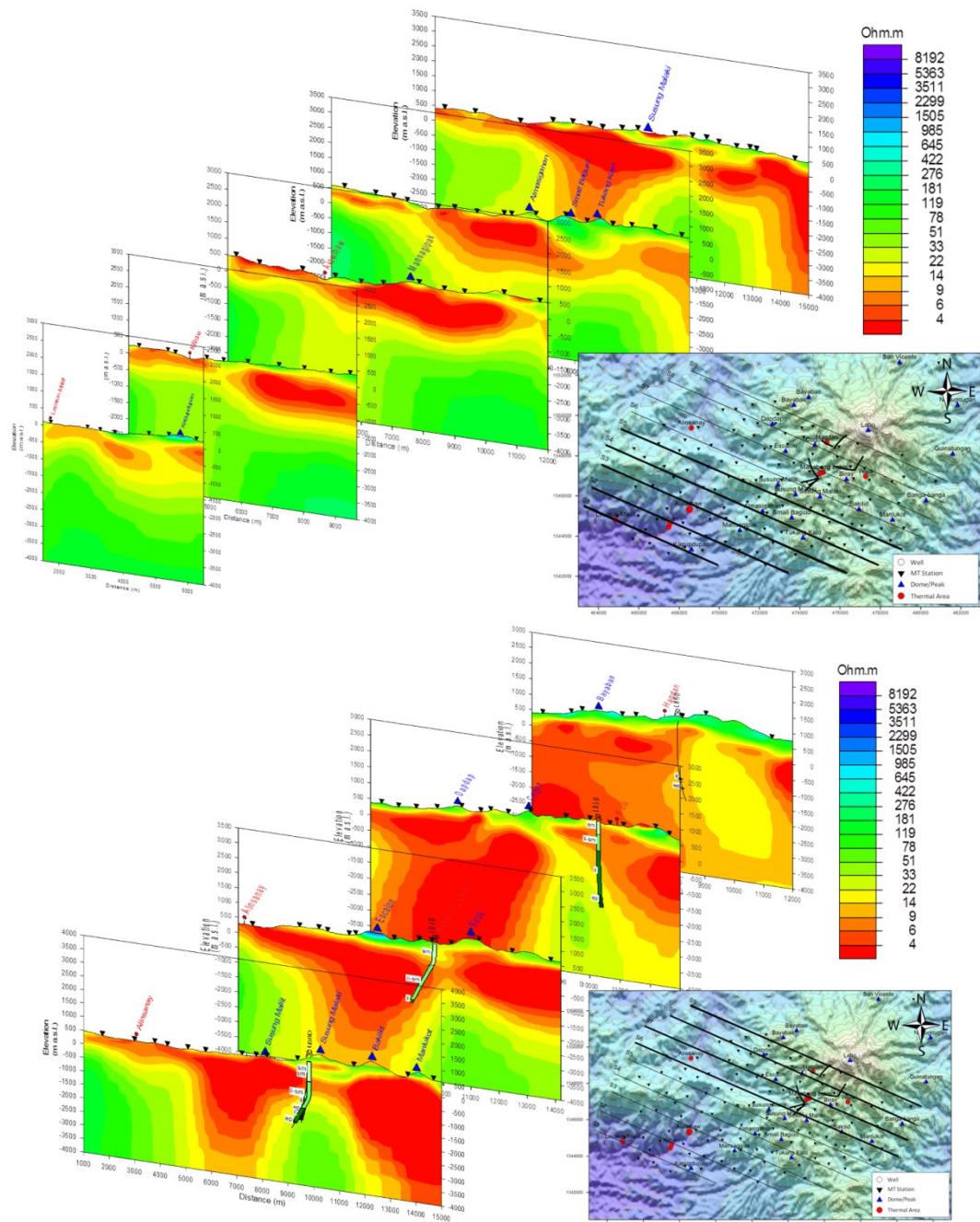
**Figure 3: Example of resistivity and phase curve of an MT station having a good quality data (left) as opposed to an MT station having a bad quality data (right).**



**Figure 4: Location of MT stations across the Mt. Labo Geothermal Project.**

### Resistivity Profiles

The 2D resistivity models in MLGP (Figure 5) generally show a three-layer high-low-high resistivity trend. The topmost  $>30$  ohm-m resistivity layer coincides with the unaltered andesite and dacite lava flows from Susung Dalaga formation in the west while in the east this layer correlates with the relatively fresh and unaltered andesite and dacite lavas from the Labo volcanics and the cluster of volcanic domes in the area. Beneath this thin high resistivity layer is a conductive  $<15$  ohm-m layer coinciding with the low to medium temperature smectite and illite-smectite clay alterations. This low resistivity layer forms the conductive clay cap of the geothermal system. Beneath the base of this conductor is a resistive  $>15-50$  ohm-m dome-like feature which is associated with the high temperature secondary minerals such as epidote, chlorite and biotite present in the reservoir. Bounding this dome-like feature on both sides are thick low resistivity layers which are correlated to the smectite and illite clay alterations at the near surface while at depth these layers are associated to the sedimentary suite of the Susung Dalaga Formation which are composed of fossiliferous, carbonaceous, fine-grained clastics, conglomerates and limestones (Panem and Bien, 1994).



**Figure 5: 2D models along nine resistivity profiles across the Mt. Labo Geothermal Project.**

## Isoresistivity Maps

At 500 m elevation (Figure 6), a broad  $<15$  ohm-m conductive zone is generally seen overlying most of the MLGP which is correlated with the smectite and illite-smectite clay cap overlying the geothermal system as well as the thick Susung Dalaga sedimentary formation. The western portion of the area, shows a broad  $>15-120$  ohm-m resistivity zone postulated to be part of the intrusive body modeled in the gravity survey. An intermediate resistivity zone of  $\sim 15-30$  ohm-m appears at 1500 m elevation (Figure 6) beneath the Susung Malaki and Biray Dome which is interpreted to be part of the top of the geothermal reservoir. This intermediate resistivity anomaly is bounded to the north, east and west by broad conductive zones, which are associated with the Susung Dalaga sedimentary formation.

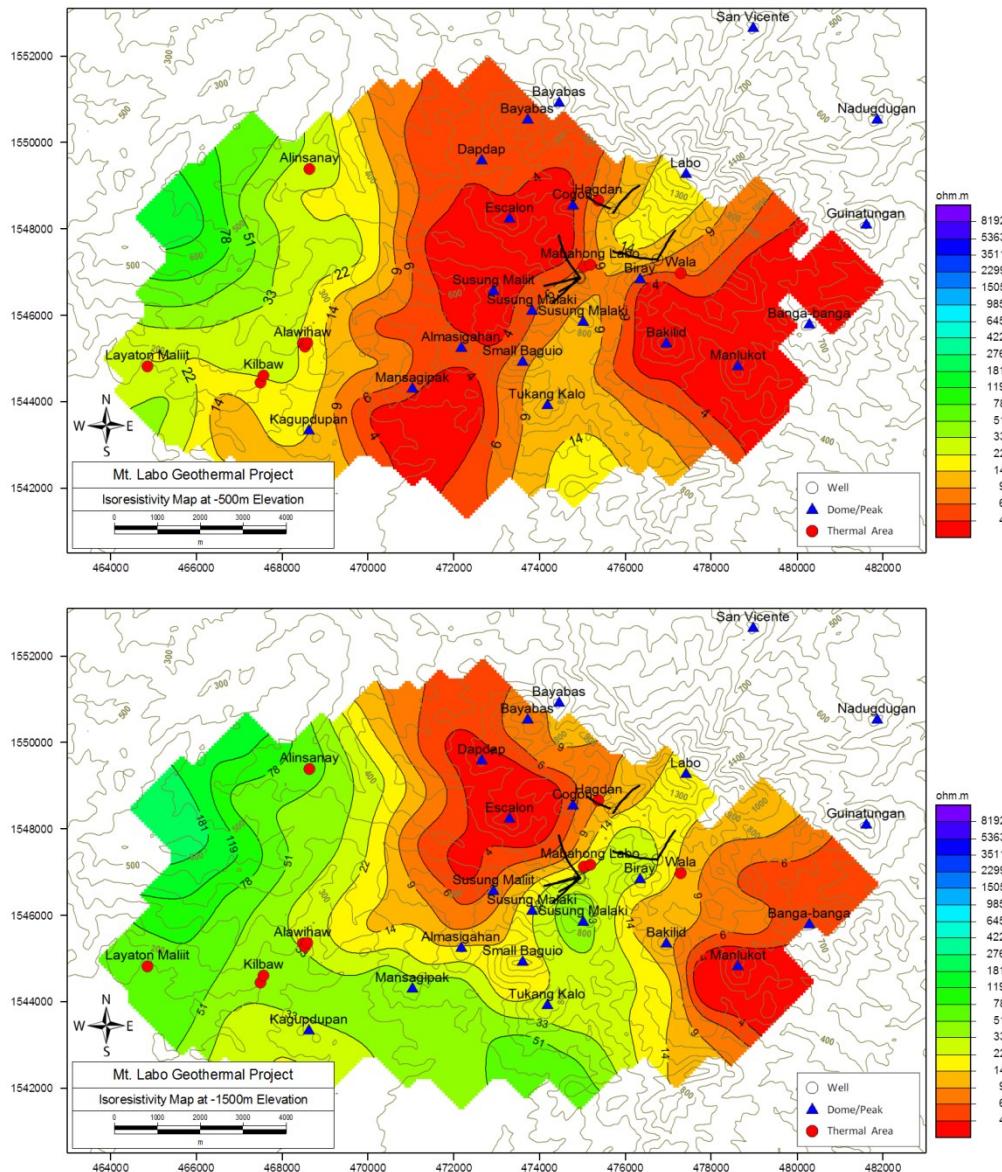


Figure 6: Isoresistivity maps at -500 m elevation (top) and -1500 m elevation (bottom).

## DISCUSSION

The  $<15$  ohm-m conductive zones surrounding the anomaly most likely defines the immediate outer margins of the hydrothermal system as indicated by the  $<220^{\circ}\text{C}$  temperatures encountered by the wells which intersected these zones (Profiles 7 and 9 in Figure 5 and Figure 7). The  $\sim 15\text{--}30$  ohm-m resistivity anomaly delineated in MLGP coincides where  $>250^{\circ}\text{C}$  temperatures were encountered by the wells which intersected this resistivity anomaly beneath Susung Malaki and Biray Domes (Figure 7 and 8). Resistivity profile A-A' (Figure 8) shows the resistivity structure of Mt. Labo, based on the results of the MT survey, and temperature contours from the wells. This resistivity structure agrees well with typical models of most geothermal systems where the low resistivities are correlated with the conductive clay alteration minerals such smectite and illite-smectite which form at temperatures above  $70^{\circ}\text{C}$  (Anderson et al., 2000). At temperatures above  $180^{\circ}\text{C}$ , observed resistivity values of 20 to 100 ohm-m are associated to the high-temperature alteration minerals such epidote, chlorite and biotite (Anderson et al., 2000).

The results of the MT survey coincides with the results of the previous gravity survey which indicates a positive gravity anomaly roughly corresponding with the intermediate resistivity anomaly associated with the Mt. Labo geothermal system (Figure 9). This positive gravity anomaly is interpreted to be a diorite intrusive serving as the probable heat source for the Mt. Labo geothermal system (Figure 10) (Los Baños and Manjea, 1996). A separate dome-like resistive feature can be observed in the west (Figure 8). This is interpreted to be another diorite intrusive which intruded the Susung Dalaga formation at about 3.5 Ma (Batalbatol and Austria, 2013). This is supported by results of the previous gravity survey which also indicates a positive gravity anomaly beneath this area (Figure 10). This dome-like feature is overlain by a conductive layer which is exposed at the surface. The resistive layer which would have originally overlain this low resistivity layer might have already been uplifted, eroded, weathered and/or altered to form this low-high resistivity trend as opposed to the high-low-high resistivity trend commonly observed in most Philippine geothermal fields. This may be an indication that this is an older system which have already cooled considerably compared to the Mt. Labo high-temperature system.

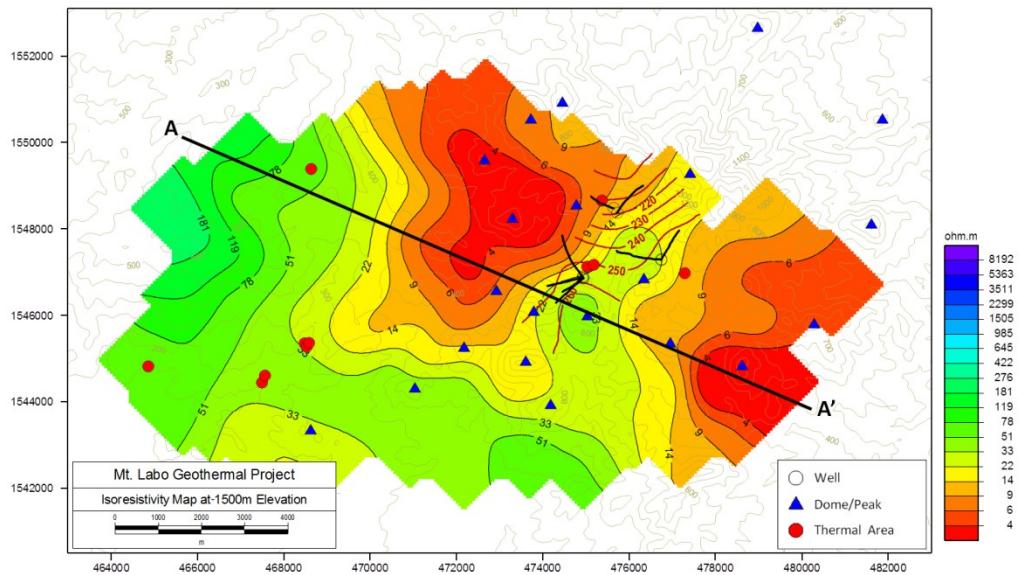
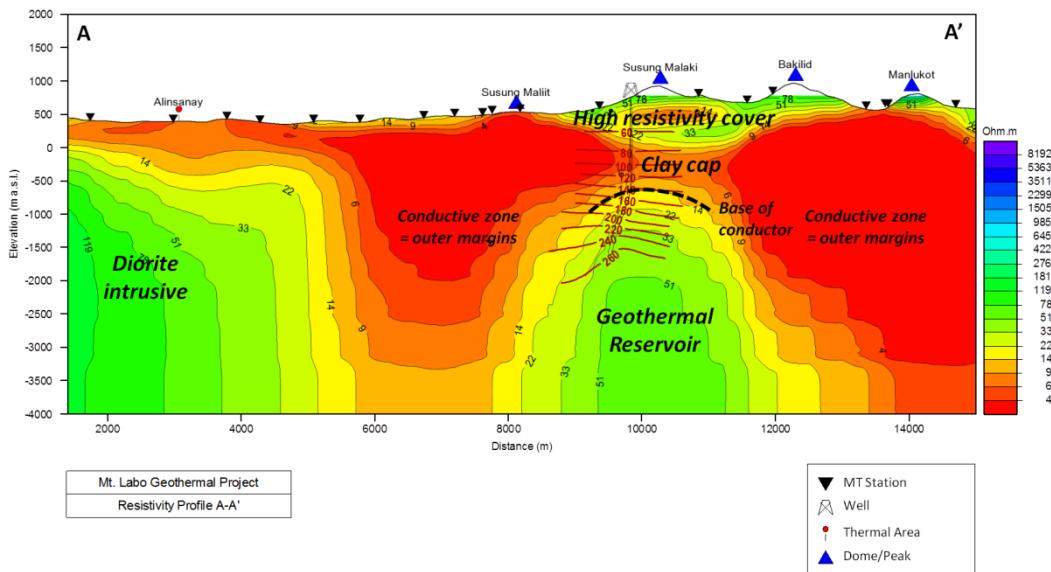


Figure 7: Isoresistivity map at -1500 m elevation overlain with isotherms from the wells.



## CONCLUSION

The resistivity structure observed in MLGP is consistent with the typical resistivity signature of a well-developed high temperature geothermal system. The low-resistivity <15 ohm-m layer corresponds to the conductive clay cap where hydrothermal fluids interact with the surrounding rock to form low temperature alteration mineral assemblages such as smectite and illite-smectite. The resistive >15-50 ohm-m core corresponds to the high temperature alteration mineral assemblage such as illite, epidote, biotite and actinolite. The postulated upflow in Mt. Labo is beneath the resistive dome-like feature where the highest temperatures were encountered by the wells. Outflow path is probably to the southwest feeding the thermal manifestations such as Kilbay and Alawihaw. Based on the interpretations of the MT survey results and subsurface data, drilling is recommended within the intermediate resistivity anomaly of the Mt. Labo geothermal system where high temperatures are expected.

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