Proceedings World Geothermal Congress 2005
Antalya, Turkey, 24-29 April 2005

Magnetotelluric (MT) Resistivity Surveys in Various Geothermal Systems in Central Philippines

Domingo B. Layugan, David M. Rigor, Jr., N. A. Apuada, C. F. Los Baños, and R. E. R. Olivar

Philippine National Oil Co.–Energy Development Corp. (PNOC-EDC) Fort Bonifacio, Makati City, Philippines

layugan@energy.com.ph

Keywords: MT, Magnetotelluric, Mahanagdong, Northern Negros, Southern Leyte, Mahagnao, Lobi, Philippines, Central Philippines

ABSTRACT

Since PNOC-EDC adapted magnetotelluric (MT) resistivty surveys in 1995, hundreds of MT data have been obtained in various Philippine geothermal areas. Interpretation of these data yielded a generally similar MT model for Philippine geothermal systems. The MT data provided a clearer and coherent resistivity structure and can better determine the actual size of the resource than the Schlumberger data.

The MT-derived resistivity model of Philippine geothermal systems is generally a three-layer structure. The surface cover is usually composed of approximately <100-300 m thick resistive layer of <100-500 ohm-m which coincides with the young, less altered volcanics. Immediately below the surface layer lies the highly conductive horizon with values of <10-15 ohm-m of varying thickness. This conductor represents the hydrothermal system's clay cap composed mainly of smectite. The base of this conductive second layer coincides with the transition from smectite to smectite-illite dominated argillic alteration. In the central part, the underlying third layer is a higher resistivity zone of <20-100 ohm-m. This relatively high resistive substratum is attributed to the decreasing amount of clays and to secondary assemblage dominated by higher temperature but less conductive minerals such as illite, chlorite, epidote, biotite and actinolite. This third layer corresponds with the hottest part of the geothermal system. It is then bounded by materials of varrying resistivity depending on the country rocks surrounding the area. The configuration and depth of the third layer point to the most probable location of the center of the resource.

1. INTRODUCTION

The Philippine National Oil Company Energy Development Corporation (PNOC-EDC) started employing the magnetotelluric (MT) resistivity technique beginning in 1995 to explore new geothermal areas and to delineate resource extension of producing fields for power expansion. This technique was specifically applied where the conventional D. C. Schlumberger resistivity traversing (SRT) and vertical electrical sounding (VES) measurements, whose penetration capabilities are hobbled by limitations imposed by cable lengths, high elevation and topography, were not able to penetrate thick volcanic cover and deeper reservoirs.

All MT soundings in these areas were obtained using a Phoenix V5-16 system, employing a remote-reference technique when necessary. Sounding was recorded for 10 hours overnight at each station at frequencies ranging from 0.00055 Hz to 384 Hz; eight hours were devoted for low-frequency signals (0.00055-6 Hz) and two hours for higher frequencies (9-384 Hz). After downloading the time-series data collected on each station, robust processing was performed between the remote and roving stations. Further pre-processing were made to generate resistivity vs. frequency curves. These resistivity curves were generally of good quality. One-D Occam or Marquardt modeling were then conducted using a WinGlink software.

The geothermal areas in the Philippines are generally of andesitic volcano-sedimentary systems. Most of these hydrothermal systems, particularly in Leyte, are developed along the Philippine Fault (Fig. 1), a major active left-lateral transcurrent fault that strikes southeastward through Luzon, Visayas and Mindanao. This fault and its major splays control the emplacement of high-level plutons, and the generation of substantial fracture permeability.

2. RESULTS

This paper presents the results and interpretation of MT surveys in geothermal areas undergoing exploration and development, and steam production in Central Philippines. These are the Southern Leyte geothermal prospect, Northern Negros geothermal project, Mahanagdong in the Leyte geothermal production field and Mahagnao and Lobi prospects in Central Leyte (Fig. 1). One of these areas, Mt. Lobi, showed similar MT signature as that of active geothermal systems. However, after exploratory drilling was completed it was found out that this prospect is non-geothermal. All these areas are characterized by the presence of various thermal manifestations such as warm to hot springs, hydrothermally altered grounds and sometimes solfataras.

2.1 Southern Leyte

The Southern Leyte geothermal prospect is found in the southeastern tip of Leyte island in central Philippines. The area which lies adjacent to the Philippine Fault is dominated by Mts. Cabalian and Cantoyocdoc, two Quaternary volcanic centers (Fig. 1).

D. C. Schlumberger resistivity surveys which included SRT and VES conducted in 1989 outlined two zones of low resistivity (10-20 ohm-m). These are the Mainit-Mahalo and the Nava-Magcasa anomalies located east and west of Mts. Cantoyocdoc and Cabalian, respectively (Fig. 2). Both anomalies are associated with thermal manifestations. A high resistivity block within the central region of the two volcanic centers separate these conductive zones. One exploratory well (SL-1D) was drilled in 1997 based on the earlier geoscientific surveys. After the completion of second MT measurements in 2000 (Rigor et al., 2001), another well was drilled (SL-2D) in the same year.

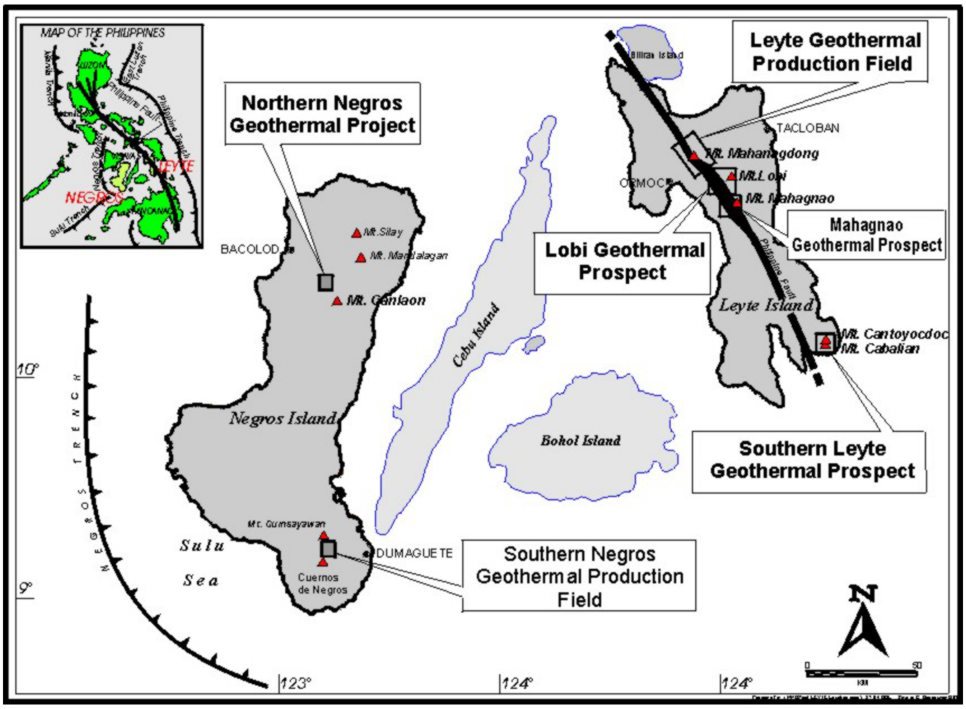

Figure 1: Location map of Mahanagdong, Lobi, Mahagnao, Southern Leyte and Northern Negros geothermal areas.

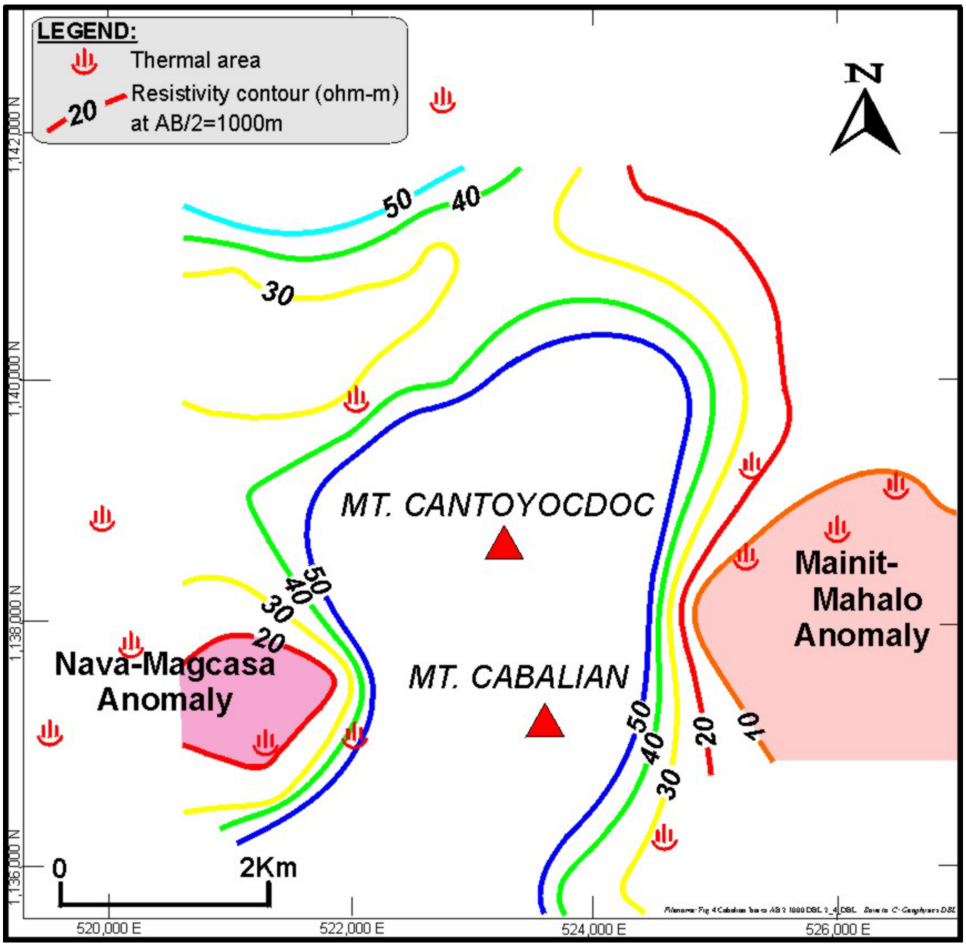

Figure 2: Apparent iso-resistivity map at AB/2 = 1000 m of Southern Leyte geothermal prospect based on Schlumberger VES.

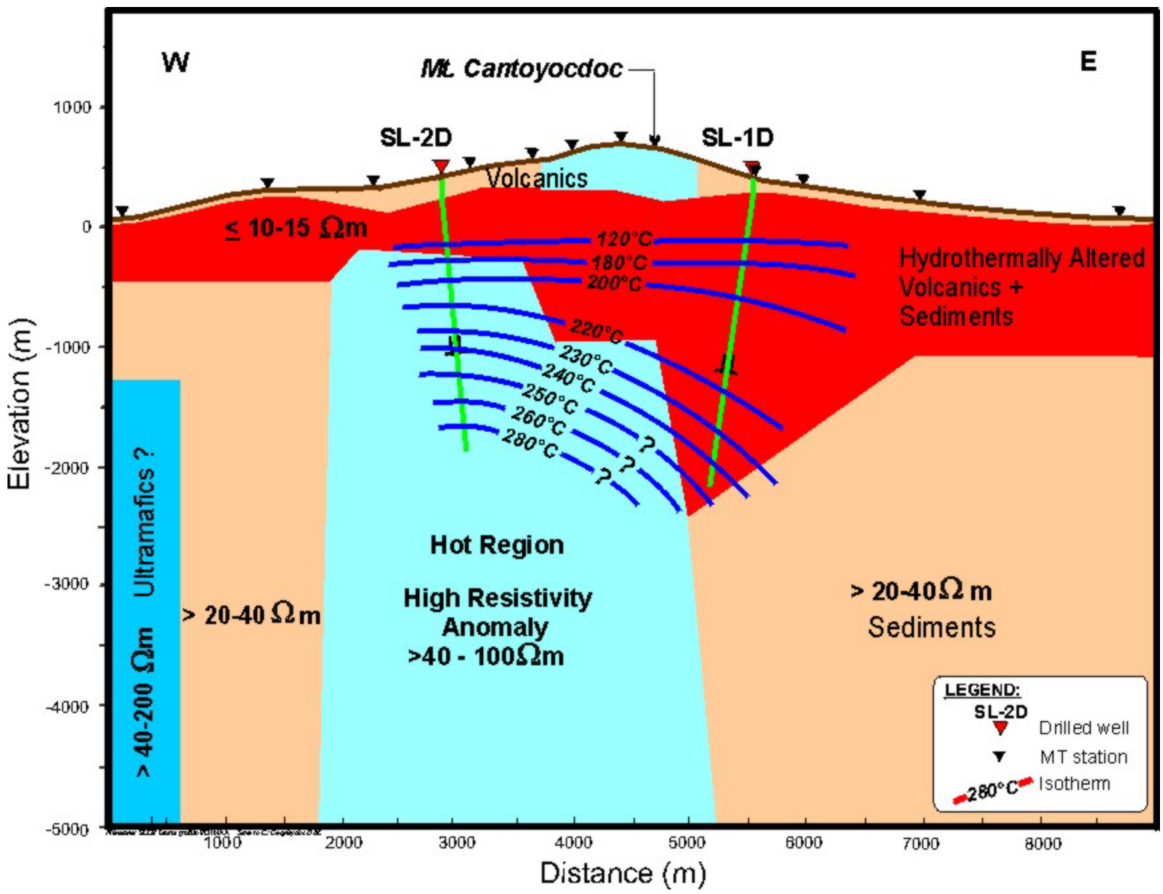

Figure 3: MT resistivity structure correlated with lithology and temperature at Southern Leyte.

A total of 69 soundings were gathered in 1997 and 2000 MT surveys. Figure 3 shows an interpreted resistivity model across the Southern Leyte geothermal field. The thin moderately to high resistivity cover (>20-100 ohm-m) represents the surface volcanics and some outcropping sediments. Beneath this is the relatively low resistivity layer of ≤10-15 ohm-m with variable thickness of 300-3000m. This layer is attributed to hydrothermally altered volcanics and sediments. The most important feature of the model is the high resistivity body (>40-100 ohm-m) beneath west of Mt. Cantoyocdoc. This intrusion-like resistive body is interpreted to represent the hottest region of the geothermal system. The higher resistivity values are believed to be caused by high-temperature but less conductive minerals such as illite, epidote, actinolite and garnet (Rossel and Zaide-Delfin, 2004) developed within the sediments. This high resistivity body is bounded by moderate resistivity values of >20-40 ohm-m that most likely reflect the sedimentary rock situated away from the center of the resource, where geothermal activity is absent.

On plan map (Fig. 4) the high resistivity body is clearly defined by the resistivity contours at –1500 m elevation. This high resistivity anomaly delineates a probable resource size of about 7-12 km^2 located west of Mt. Cantoyocdoc. Results of the two exploratory wells drilled in the area showed that well SL-2D, sited inside the high resistivity anomaly, yielded bottom hole temperature of 280°C and intersected permeable zones. On the other hand, well SL-1D, encountered subsurface temperature of 240°C and poor permeability outside and east of the proposed geophysical resource boundary (Fig. 4).

2.2 Northern Negros

The Northern Negros geothermal project, located in the island of Negros, Visayas , central Philippines is about 100 km north of the 200 MWe-producing Southern Negros steam field (Fig. 1). It is situated within the Canlaon Volcanic Complex which includes the active Mt. Canlaon Volcano, about 8 km southeast of the drilled area (Fig. 5a). The volcano along with Mts. Silay and Mandalagan in north and Mts. Guinsayawan and Cuernos de Negros in the south constitiute the Negros Arc. The latter is a N-S-trending chain of Quaternary andesitic volcanoes related to the eastward subduction of Sulu Sea along the Negros Trench (Fig. 1).

Geothermal exploration by PNOC-EDC started in 1970s including the drilling of two intermediate-depth wells (MC-1 and MC-2) near Mambucal which encountered sub-commercial temperature of ≤190°C and calcite-supersaturated fluids (Figs. 5a and 5b). Additional surface exploration studies in the 1990s led to the drilling of deep exploration wells which confirmed the presence of high-temperature (250°C) neutral-pH chloride beneath Pataan. Further drilling is now underway for the development of a 40 MWe steam field for commissioning by 2006.

D. C. Schlumberger traverses (SRT) conducted in 1978 delineated three <50 ohm-m low resistivity anomalies at half-current electrode spacing (AB/2) of 500 m. These anomalies were located in Mambucal, Saray and Hagdan as shown in the apparent iso-resistivity map in Figure 5a. Subsequent Schlumberger VES in 1982 with maximum half-current electrode spacing of AB/2=1000 m suggested that all three anomalies are connected at depth and extend

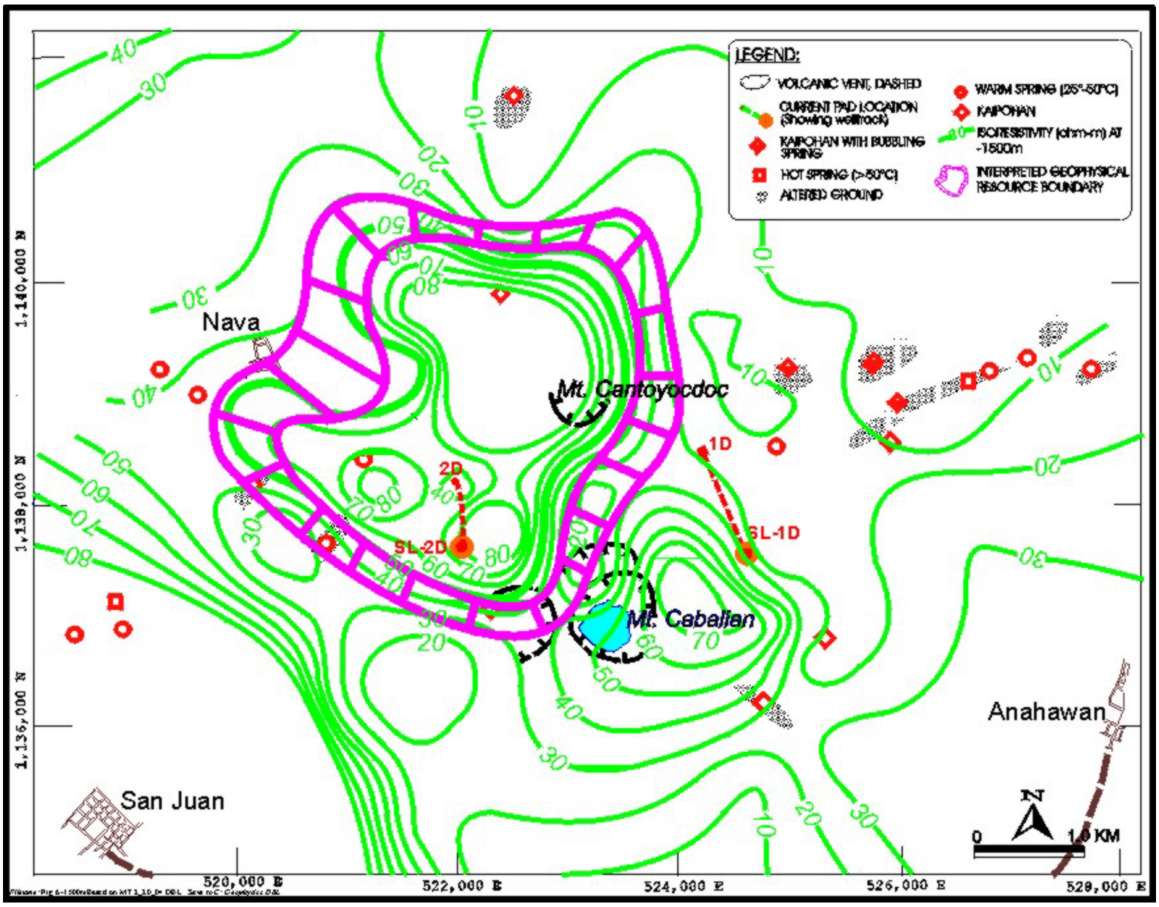

Figure 4: Iso-resistivity map at -1500 m elevation and the interpreted geophysical resource boundary of Southern Leyte based on MT.

north near Pataan (Fig. 5b). Interpretation of these Schlumberger data indicated that the geothermal upwelling zone lies upstream between the three areas (Layugan and Apuada, 1992). This led to the drilling of deep exploratory wells at Pataan in 1994 with a corresponding increase in subsurface temperature southeast of Mambucal.

In 1995, PNOC-EDC undertook magnetotelluric (MT) survey in 34 stations to aid in the drilling program (Rigor et al., 1999). Fifty-eight (58) MT stations were added in 2000 to provide detail of the field's resistivity structure (Maneja et al., 2001). Figure 6 is an apparent iso-resistivity map at sounding frequency of 3.03 Hz (0.33 sec). Depth of penetration at this frequency reaches up to about 1.5 km. The most prominent feature in this map is the 1.5-2-km wide, northwest-trending low resistivity (≤10 ohm-m) zone extending from Sumaguan and Pataan in the southeastern highlands to Mambucal in the northwestern foothills.

The vertical distribution of resistivity layers along the strike of the anomaly is shown in Figure 7. A resistive (30-100 ohm-m) surface layer blanketing the area from Mambucal to Sumaguan is underlain by the highly conductive (<10 ohm-m) second layer about 500 to 1000 m thick. The third layer consistently has higher resistivity values compared with the overlying second layer. The resistive first layer coincides very well with the young and less altered lavas and pyroclastics of the Canlaon Volcanics. Clay alteration marked by the top of the smectite (Sm) zone begins at depth equivalent to the top of the highly conductive layer. Where well data exist, the base of this second layer falls within the transition of the argillic alteration from illite-smectite (I-Sm) zone to illite (I) zone. In other words, the highly conductive second layer corresponds to an extensive hydrothermal clay cap. The hydrothermal nature of the third layer varies from place to place. Beneath Mambucal where the third layer is resistive, measured temperatures at corresponding depths are relatively low (<220°C). This results to deeper occurrence of higher grade alterations manifested by the steep plunge in the top of I-Sm and I zones (Fig. 7). In Pataan, the top of the moderately resistive third layer coincides with the onset of the I zone where temperature is at least 220°C. In this zone, the secondary minerals are dominated by illite, epidote, and biotite which are less conductive than the clays that pervade the overlying argillic (Sm and I-Sm) zones. The lack of drillhole information beneath Sumaguan precludes a definitive assessment of the nature of the third layer in this area. But if the trends observed in Pataan applies to adjoining Sumaguan, then the latter's moderately conductive third layer likely reflects transition to higher temperature and less clay–dominated alteration in the overlying second layer. Hence, in Pataan and Sumaguan, the top of the third layer corresponds to the surface of the geothermal reservoir (Maneja et al., 2001).

2.3 Mahanagdong

Mahanagdong is one of the three producing fields in the Leyte Geothermal Production Field (Fig. 1) with an installed capacity of 80 MWe. Early Schlumberger SRT and VES surveys mapped a low resistivity anomaly in Mahanagdong and Bao (Fig. 8). However, east-southeast of Mt. Mahanagdong, VES soundings were not able to penetrate deeper due to high elevations and relatively thick volcanic cover (Layugan et al., 1990). This and the increase of subsurface temperatures towards the east-southeast of Mt. Mahanagdong prompted the conduct of MT

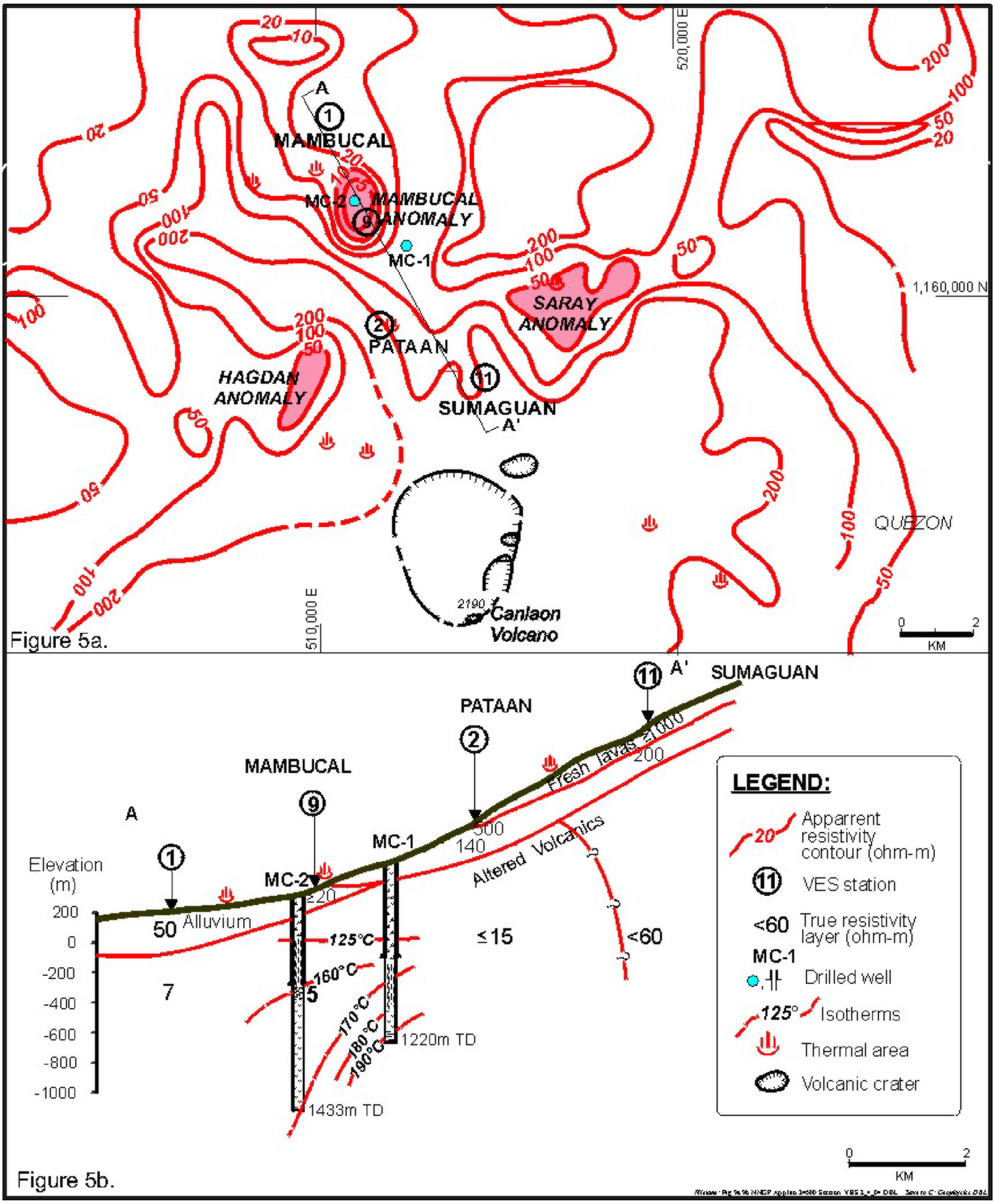

Figure 5: a) Apparent iso-resistivity map at AB/2 = 500 m based on SRT and b) resistivity model based on VES of the Northern Negros geothermal field (after Layugan and Apuada, 1992).

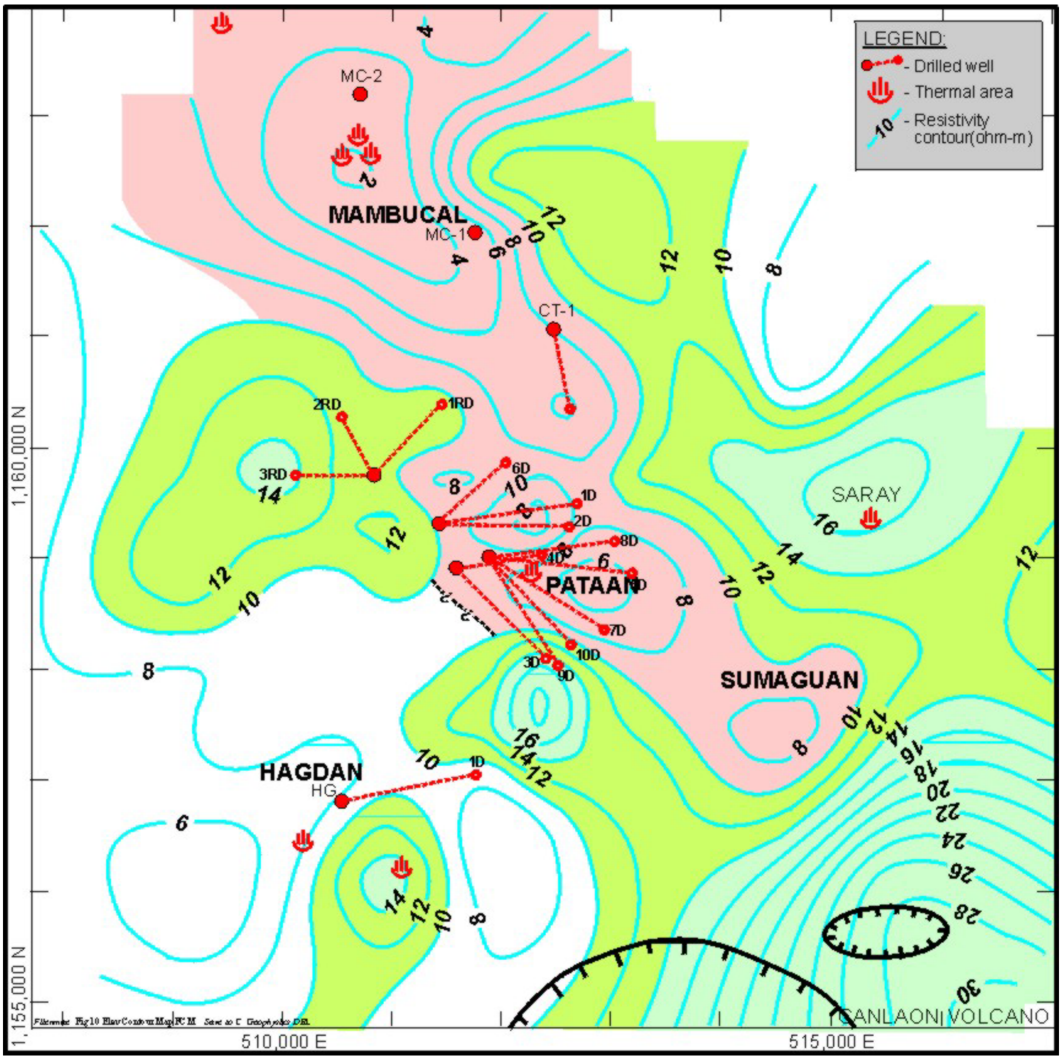

Figure 6: Apparent iso-resistivity map at f = 3.03 Hz of Northern Negros based on MT (after Maneja et al., 2001).

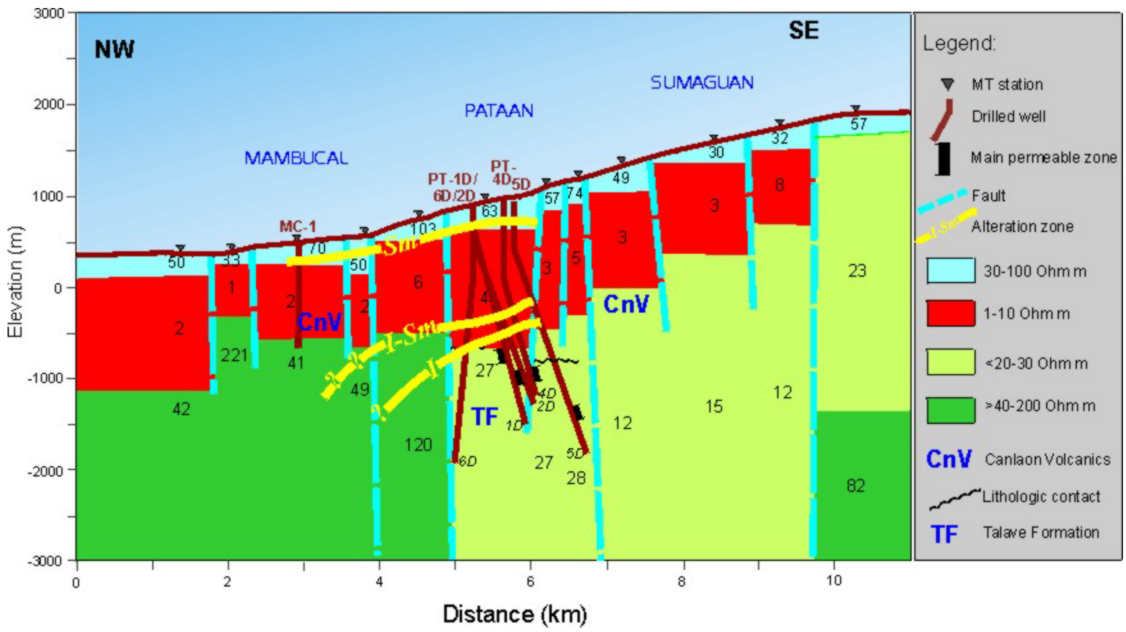

Figure 7: MT resistivity structure correlated with alteration across the Northern Negros field (modified after Maneja et al., 2001).

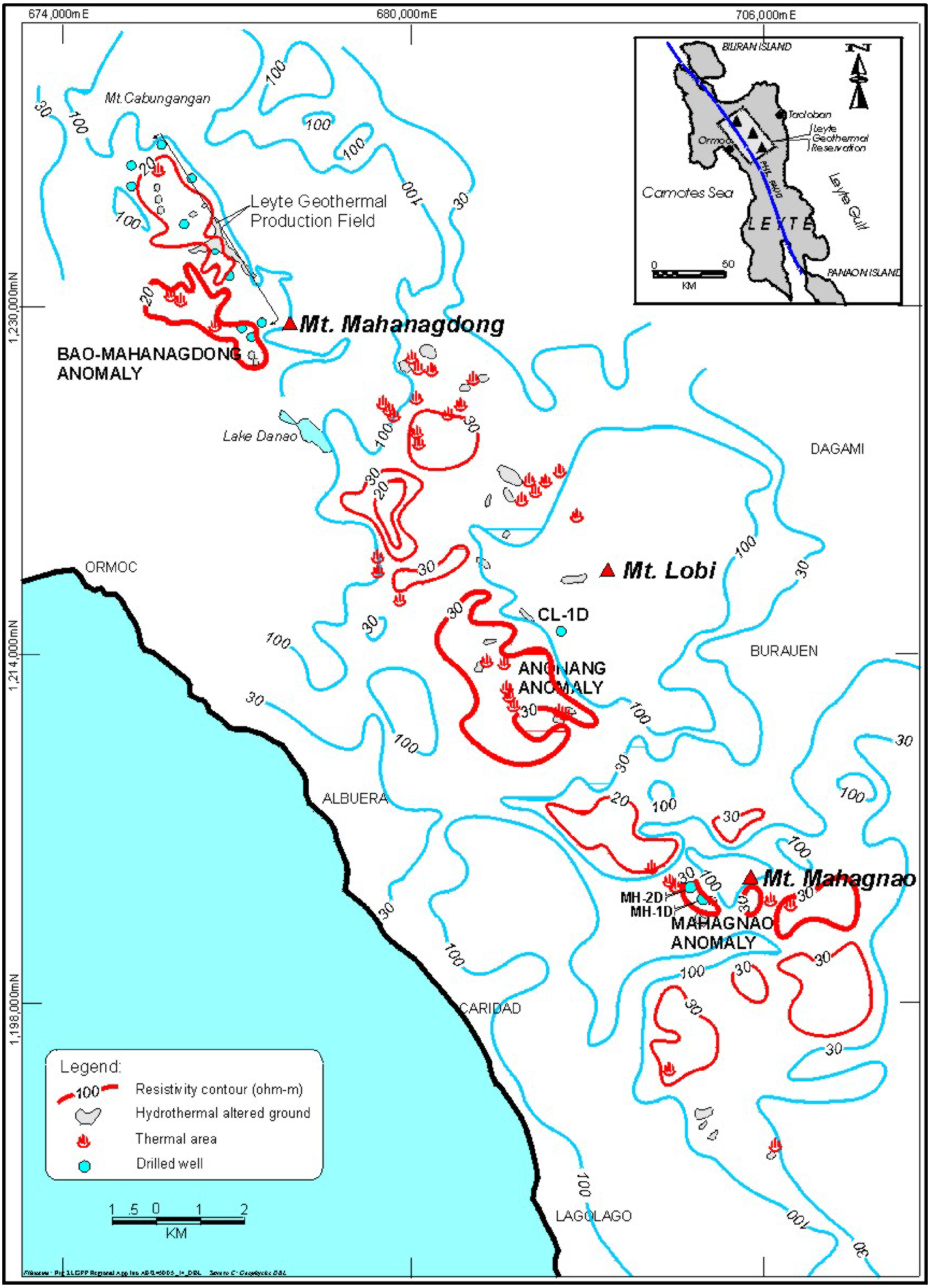

Figure 8: Regional Schlumberger apparent iso-resistivity map at AB/2 = 500 m of Leyte geothermal reservation including Mahanagdong, Lobi and Mahagnao.

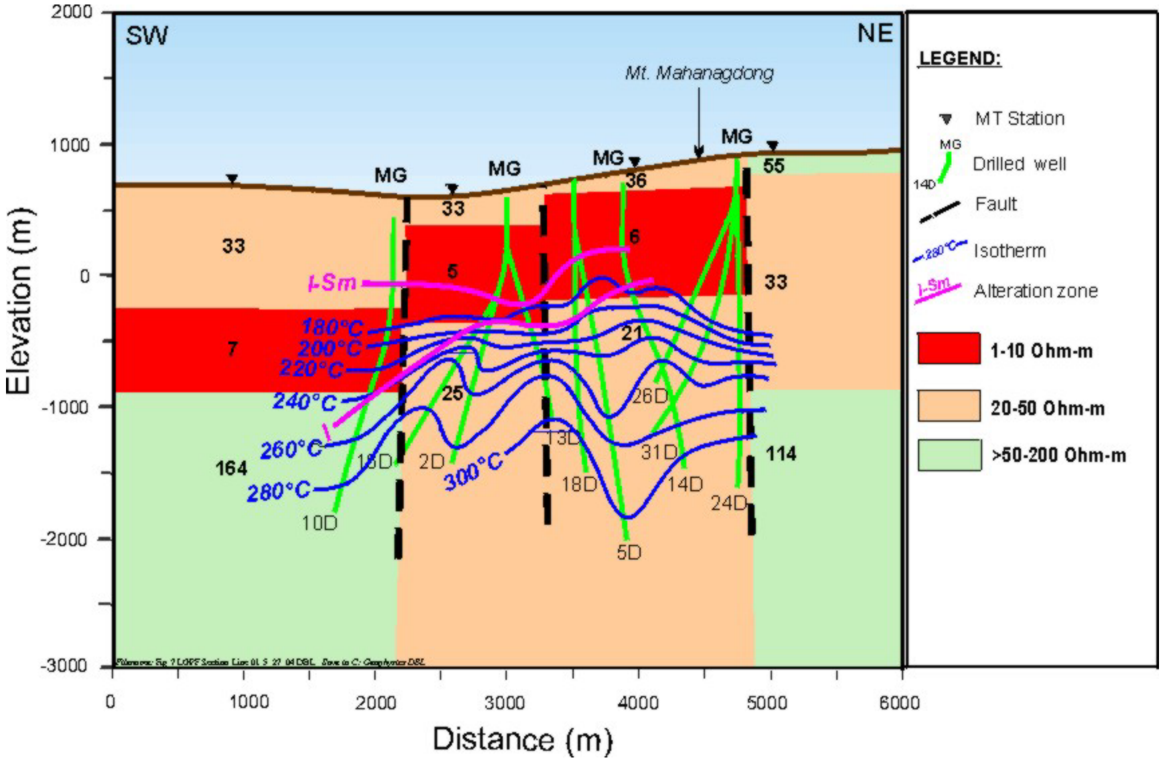

Figure 9: MT resistivity model correlated with temperature and alteration across Mahanagdong field (after Maneja and Los Baños, 2002).

measurements in 2001 (Maneja and Los Baños, 2002) in order to map the probable extension of the resource towards this direction.

The resistivity structure of Mt. Mahanagdong consists of a high resistive surface layer (30-50 ohm-m) which can be correlated with the volcanic deposits covering the survey area, a very conductive middle layer (<10 ohm-m) and a third moderately resistive layer (20-30 ohm-m) (Fig. 9). The interface between the second and the third layer coincides with the occurrence of illite-smectite and illite alteration where temperatures of at least 180°C were measured in the wells. Figure 10 shows a domed-shaped elevation contours of the interface between the second and the third layers. The shallower part of the domed-shaped elevation contours indicates where elevated temperatures could be encountered at shallower depths. It is centered near the Mahanagdong collapse where subsurface temperatures of up to >290°C were recorded (Fig. 10). Based on this, the MT survey was able to delineate a resource extension of about 6 km^2 farther east of Mt. Mahanagdong. This area was unmapped by the earlier Schlumberger surveys and is now recommended for drilling for additional power plant capacity.

2.4 Mahagnao and Lobi, Central Leyte

The Mahagnao and Lobi geothermal prospects are located at the center of Leyte Island. It is approximately 25 km southeast of the Leyte Geothermal Production Field, the largest steamfield in the country with a current installed capacity of 723 MWe (Fig. 1). These two prospects, named after the two Quaternary volcanoes, Mt. Mahagnao and Mt. Lobi, lie along the northwest-southeast-trending volcanic centers along the Philippine Fault that include Mt. Mahanagdong and Mts. Cabalian and Cantoyocdoc in Southern Leyte.

Surface geoscientific investigations including geological, geochemical, and geophysical (SRT and VES) surveys were conducted in the 1980s. Two exploratory wells (MH-1D and MH-2D) were drilled in Mt. Mahagnao in 1990-1991 while one well (CL-1D) was drilled in Mt. Lobi in 2003 (Figs. 8 and 11). The exploration drilling in Mahagnao was based on the pockets of Schlumberger low resistivity anomalies around the volcanic center of Mt. Mahagnao (Fig. 8). On the other hand, the well drilled in 2003 in Lobi was based on the MT data (81 soundings) obtained in 2002 (PNOC-EDC, 2002). Between late 2003 and early 2004, another set of 38 MT soundings gathered in Mahagnao (Rigor et al., 2004) were linked with the Lobi MT data.

Figure 11 shows the MT resistivity structure correlated with lithology, alteration and temperature across the Mt. Mahagnao and Mt. Lobi prospects. Three resistivity layers were identified. The <50-150 ohm-m high resistivity surface layer which generally coincides with the volcanic cover of Mts. Mahagnao and Lobi. The second layer of ≤10 ohm-m is attributed to be due to the combination of sediments and smectite alteration. The increasing resistivity with depth of >20-150 ohm-m comprise the third layer. In Mt. Mahagnao, the top of the third layer generally coincides with the occurrence of chlorite and illite-smetite and the on-set of the ultramafic basement. The increasing resistivity persists with depth accompanied by the presence of higher temperature minerals (illite, epidote and actinolite) and elevated temperatures (≥270°C) measured within the ultramafic basement in well MH-1D. In Mt. Lobi, this third layer roughly coincides with the top of the ultramafic rock where measured temperature in well CL-1D was only 120°C. In contrast with well MH-1D, CL-1D was devoid of hydrothermal alteration indicating poor to total lack of geothermal fluids within the formation.

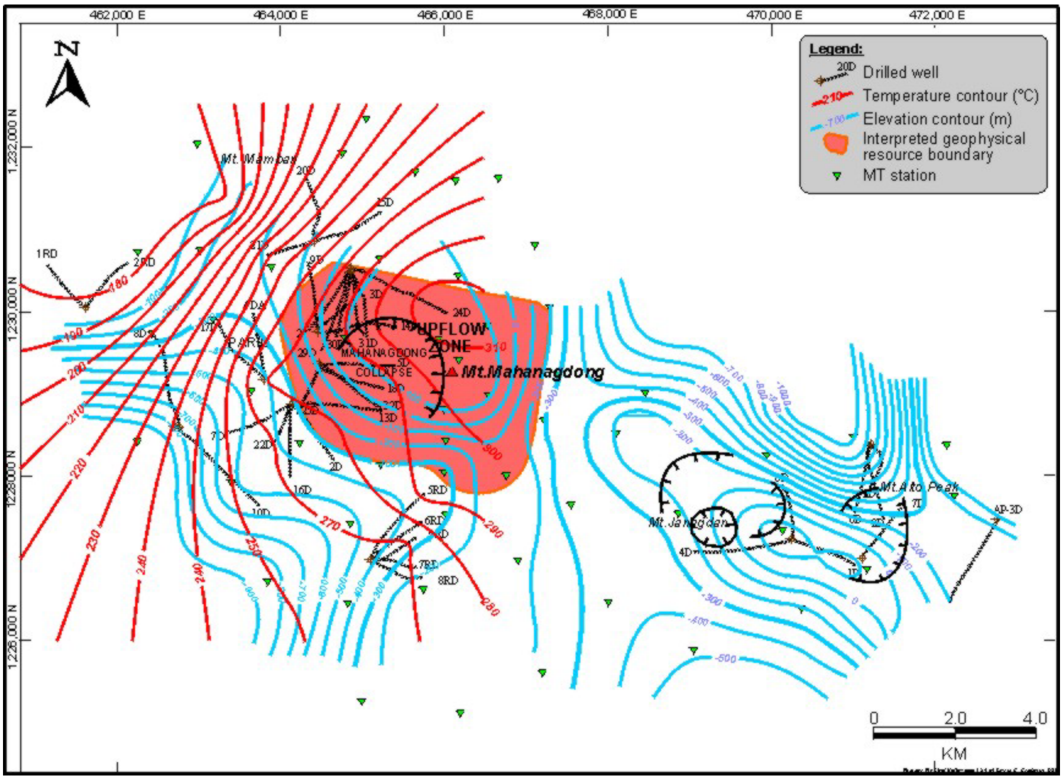

Figure 10: Elevation contour map of the interface between the second layer conductive zone and the third layer resistive base (based on MT) including isotherms, and the proposed geophysical resource boundary at Mahanagdong field (after Maneja and Los Baños, 2002).

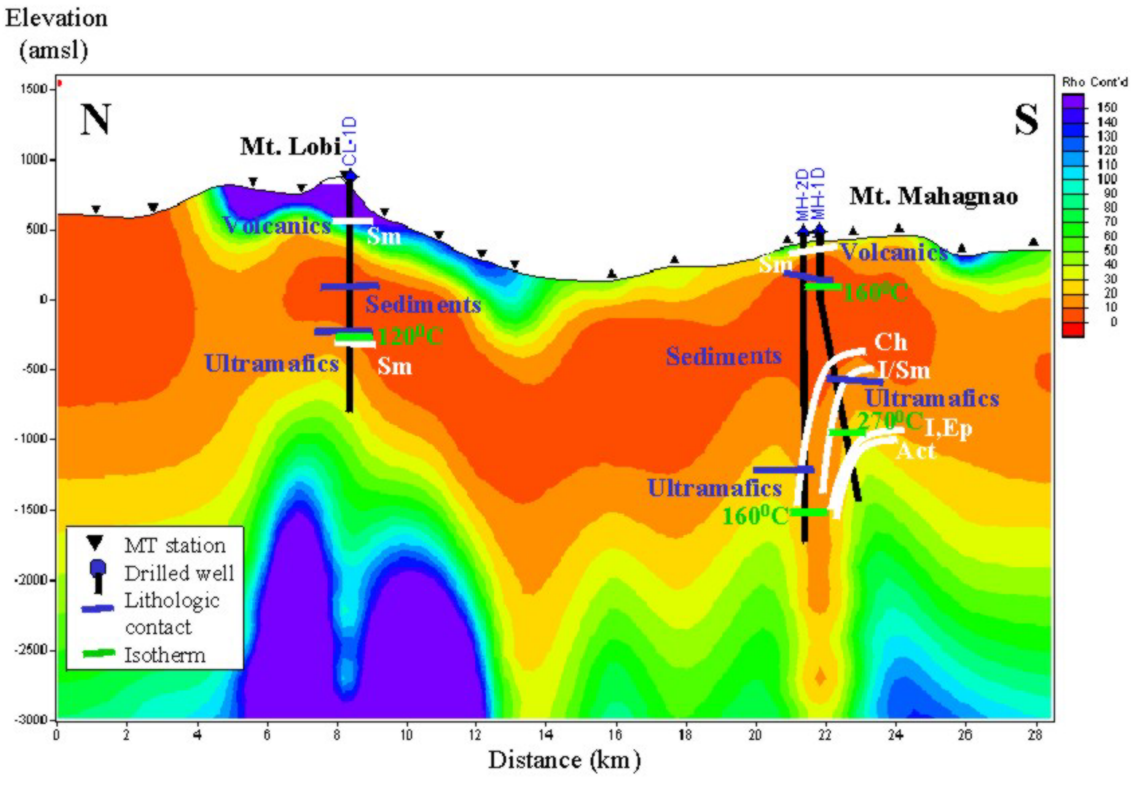

Figure 11: MT resistivity model correlated with lithology, alteration and temperature across Lobi and Mahagnao geothermal prospects (after Rigor, 2004).

The geothermal system in Mahagnao is defined by the convergence of a shallower and small ridge of increasing resistivity with depth, the presence of high-temperature minerals and the high measured temperature in well MH-1D. Although the system is hot, the relatively small (<3 km^2) high resistivity anomaly defined by only three soundings and the total lack of permeable zones within the ultramafic basement measured in MH-1D render the resource in Mahagnao as commercially not viable. The sharp decline of bottom hole temperature of 160°C in the nearby well (MH-2D) lend support to this (Fig. 11).

3. DISCUSSION

The low resistivity anomalies delineated by the Schlumberger resistivity traversing and soundings did not reflect the true resistivity structure of the geothermal systems. These low resistivity anomalies were mostly near-surface found in the low-lying peripheries such as Anonang anomaly in Lobi, Mahagnao anomalies in Mahagnao, Mainit-Mahalo and Nava-Magcasa anomalies in Southern Leyte, Bao-Mahanagdong anomaly in Mahanagdong, and Mambucal, Hagdan and Saray anomalies in Northern Negros. These low resistivity anomalies were part of the conductive second layer (detected later by MT) which the Schlumberger technique was not able to penetrate due to the overlying thick highly resistive volcanic cover.

One example of this is by comparing two simple apparent iso-resistivity maps (Figs. 5a and 6) generated by both Schlumberger (AB/2=500 m) and MT (f=3.03 Hz) surveys in Northern Negros. It is clear in the maps that the high resistivity block bounded by Mambucal, Hagdan and Saray low resistivity anomalies previously mapped by Schlumberger is now a coherent low resistivity anomaly that runs southeasterly from Mambucal, Pataan to Sumaguan. Subsequent drilling revealed that the Pataan-Sumaguan block is the center of the resource. In Southern Leyte , it is also clear that the Schlumberger surveys were not able to penetrate the conductive zone associated with the geothermal system due to high elevations and thick volcanic cover around Mts. Cantoyocdoc and Cabalian (Fig. 2). In contrast, the MT data clearly defined the geothermal system's resistivity structure at deeper levels, successfully located the region of higher temperatures and estimated the most likely size of the resource.

The MT-derived resistivity structure of the five areas presented above shows a similar three-layer model – a high-low-high resistivity pattern. The resistivity layering correlates well with the degree and rank of hydrothermal alteration. The resistivity surface layer (<100-500 ohm-m) generally coincides with the less altered volcanic cover, the conductive middle layer (<10-15) ohm-m is primarily due to smectite clays, and the third layer (>20-100 ohm) corresponds to higher temperature but less conductive minerals such as illite, chlorite, biotite, epidote and actinolite. In the case of Lobi, the same correlation exists except that the third resistive layer corresponds to the ultramafic basement.

The configuration and depth of the resistive third layer immediately below the conductive second layer defines the most probable center of the resource. In Mahanagdong, the shallowest portion of the interface between the conductive and the resistive base (Figs. 9 and 10) coincides with the onset of increasing temperature of at least 180°C. This is also true in Northern Negros where the shallower surface of the resistive third layer underlying the conductive second layer coincides with the increasing subsurface temperatures (Fig. 7). On the other hand, the high resistivity contours of the third layer at –1500 m elevation bounded by the low resistivity zone represent the hottest part of the geothermal system in Southern Leyte (Fig. 4). This was confirmed by the results of the two deep exploratory wells drilled in the area.

4. CONCLUSION

The results and interpretation of MT data in the four areas (excluding Lobi) have shown that the MT technique was able to define the resistivity structure of a geothermal system which the conventional Schlumberger method could not due to its limited depth of investigation. This structure consists of the resistive overburden underlain by a conductive zone which represents the system's extensive hydrothermal clay cap. Beneath this upper two layers is the relatively higher resistivity zone where the high-temperature productive reservoir occur.

The configuration and depth of the third layer could provide the location of the center of and size of the resource as shown in Southern Leyte, Northern Negros and Mahanagdong.

ACKNOWLEDGEMENT

The authors would like to thank the Philippine National Oil Company Energy Development Corporation (PNOC-EDC) for allowing us to publish this paper. We appreciate very much the efforts of Mr. Noel Salonga, who reviewed the draft, Mr. Manny Teoxon, who drafted the figures and Miss Menchie Melo who did the final layout. We are also grateful to our own field crew of geophysicists, geophysical survey technicians and local aides who collected the MT data from the various field areas.

REFERENCES

Layugan, D.B., Catane, J.P.L., Maneja, F.C. and Herras, E.B. and Vergara, M.C. (1990): Resistivity Surveys Across the Tongonan Geothermal Field, Leyte, Philippines. *PNOC-EDC Internal Report*, p. 1-133.

Layugan, D.B., and Apuada, N.A. (1992): Review of SRT and VES surveys at Mambucal-Canlaon Geothermal Project. *PNOC-EDC Internal Report*.

Maneja F.C. and Los Baños, C.F. (2002): Magnetotelluric Sounding at Mahanagdong, Leyte Geothermal Production Field, Central Philippines. *PNOC-EDC Internal Report*, p. 1-25.

Maneja, F.C., Los Baños, Layugan, D.B., Apuada, N.A. and Rigor, David, Jr., (201): Magnetotelluric Survey in the Northern Negros Geothermal Field Central Philippines. *PNOC-EDC Internal Report*, p. 1-203.

Maneja, F.C. Los Baños, C.F., Layugan, D.B., Apuada, N.A., and Rigor, D.M., Jr. (2001): Magnetotelluric Sounding in Northern Negros Geothermal Field, Central Philippines, *Journal of the Geological Society of the Philippines*, Vol. 56 Nos. 3 & 4, 184-198 pp.

PNOC Energy Development Corporation: Resource Re-Assessment of the Central Leyte Geothermal Project (2002). *PNOC-EDC Internal Report*, p. 1-39.

Rigor, D.M. Jr., Catane, J.P.L. and Layugan, D.B. (2001): Imaging the Southern Leyte Geothermal System Using MT Data. *PNOC-EDC Internal Report*, p. 1-22.

Rigor, D.M., Jr., Layugan, D.B. and Los Baños, C.F. (1998): Magnetotelluric and Gravity Measurements in the Northern Negros Geothermal Field, Central Philippines, Proceedings of Asian Geothermal Energy '98, Symposium on "Current and Future Geothermal Energy Development in Asia", Subic, Philippines, Oct. 1998. 115-124 p.

Rigor, D.M., Jr. (2004): Results of MT Survey in Mt. Mahagnao Geothermal Prospect, *PNOC-EDC Internal Report*, In Press.

Rossel, J.B and Zaide-Delfin, M.C. (2004): Resource Potential of the Southern Leyte Geothermal Prospect, Philippines: A Geologic Evaluation, submitted to the *World Geothermal Congress 2005*, Antalya, Turkey.