The Resistivity Structure of the Mahanagdong Geothermal Field, Leyte, Philippines

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ABSTRACT

As early as 1998, the Mahanagdong Geothermal Field has been experiencing problems on injection returns and pressure drawdown in the center of the field, causing the decline of steam supply in this sector. A long-term solution to sustain the 180 MWe steam requirement, is to look for drilling targets in other areas than the current production block. A magnetotellurics (MT) survey was then conducted in 2001 to delineate the resistivity structure of Mahanagdong. Its objectives include delineating the resource boundaries and identifying the permeable structures, which could be targets for future drilling.

The resistivity structure of Mahanagdong consists of a highly resistive cap (>50 Ω-m), a very conductive middle layer (<10 Ω-m) and a moderately resistive third layer (>10-50 Ω-m). Most production wells were drilled within the moderately resistive layer. The postulated upflow region is characterized by a >40 Ω-m dome-shaped anomaly located beneath the Mahanagdong collapse while the main outflow zone is directed towards the southwest.

A still undrilled resource extension of about 6 km^2 was delineated farther east of the Mahanagdong collapse. The primary target for drilling towards the east is the Magaas Fault.

1. INTRODUCTION

Mahanagdong is located within the Leyte Geothermal Production Field (LGPF). It has two sectors, namely, Mahanagdong A and Mahanagdong B, producing 20 MWe and 60 MWe, respectively (Fig. 1). Thirty one (31) production and thirteen (13) reinjection wells have been drilled within the two sectors. Based on the existing production wells, the current resource block has an area of about 9.75 km².

A magnetotelluric (MT) survey was conducted at Mahanagdong from May to July, 2001. A total of 53 soundings were measured using a Phoenix V5 MT system.

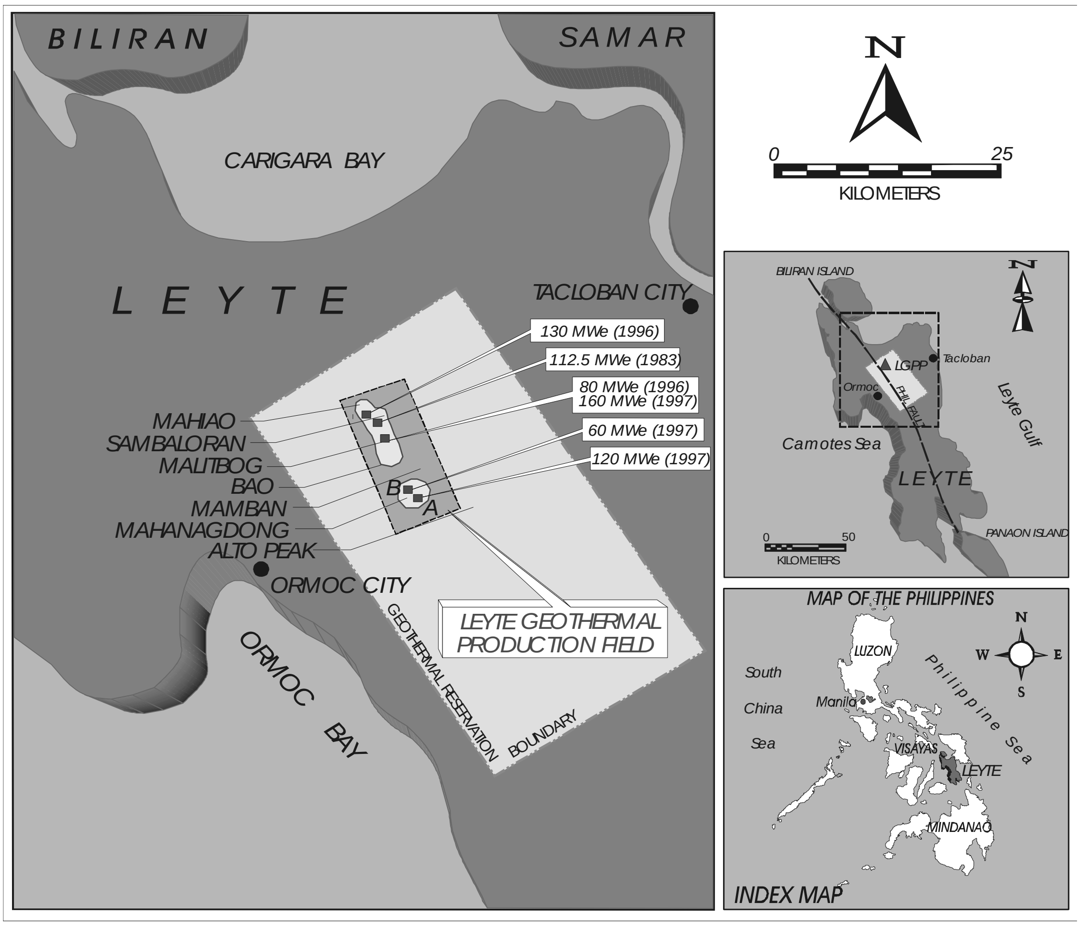

Figure 1: Location map of Leyte geothermal production field.

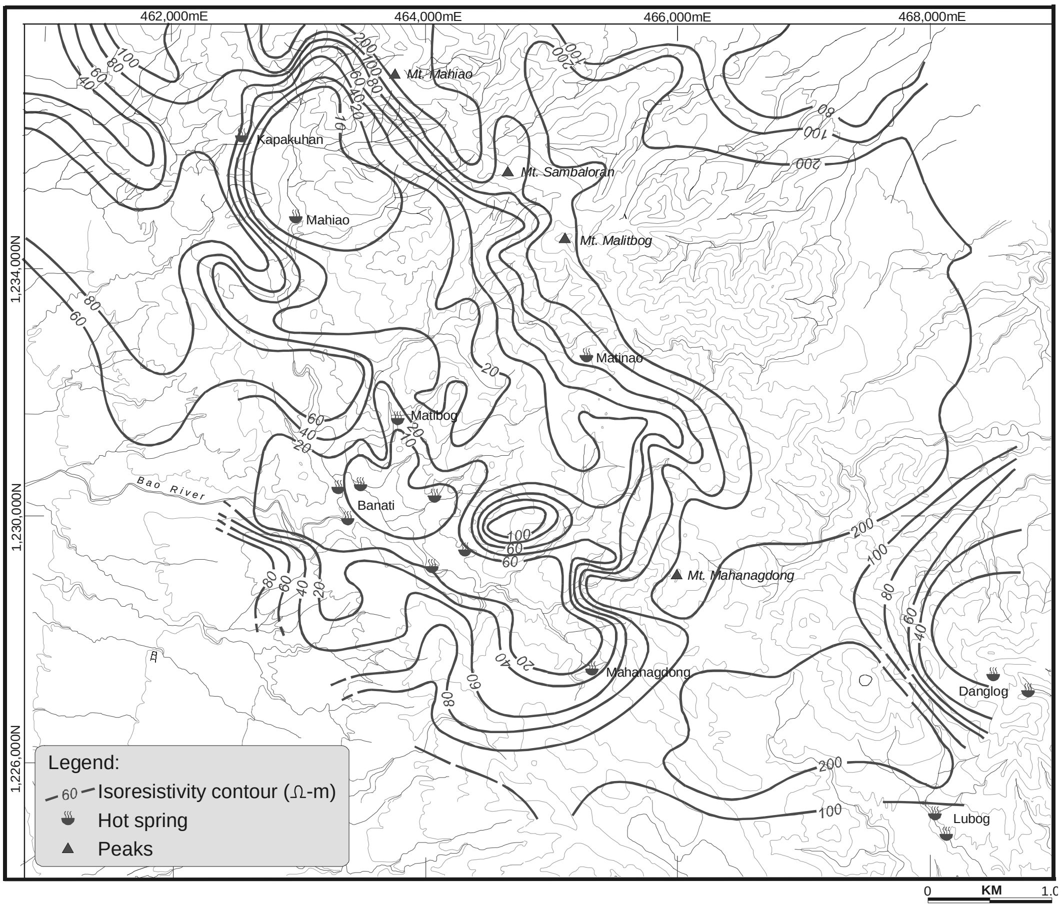

Figure 2: Apparent isoresistivity map at AB/2 = 500m

The objectives of the survey were: 1) to develop a geophysical model of the Mahanagdong geothermal system, 2) to delineate the extent of the resource particularly to the east-southeast portion, and 3) to look for new drilling targets for future production and reinjection wells.

2. PREVIOUS RESISTIVITY SURVEYS

DC Schlumberger resistivity traverses (SRT) with half-current electrode spacing (AB/2) of 250 m and 500 m, and vertical electrical sounding (VES) measurements with maximum sounding arms between 1000 m and 2000 m, were conducted across the Greater Tongonan geothermal field between 1974 and 1990 (Layugan et al., 1990). A total of 737 SRT and 87 VES stations were measured. Results of the SRT survey showed that the highlands east of Mt. Mahanagdong exhibit higher apparent resistivity values (Fig. 2). However, the VES curves showed decreasing resistivity with depth suggesting that the higher values recorded were affected by thick volcanics and high topography. To the southwestern part of Mahanagdong a 20-60 Ω-m closure of approximately 7.5 to 14 km² is present. This closure includes the acid sulphate springs at Mahanagdong, Paril and Hanipolong.

Based on the results of the Schlumberger resistivity surveys, the postulated upflow region in Mahanagdong is situated between Mt. Mahanagdong and Paril Dome where the measured bottom layer resistivity are generally in the order of <10-30 Ω-m. The Mahanagdong system is separated from the Mahiao-Sambaloran-Malitbog system by a zone of >40 Ω-m bottom layer resistivity located beneath Mamban (Fig. 3).

The low resistivity anomaly at Alto Peak is defined by a 20 Ω-m apparent resistivity contour (Fig. 2) and a <10 Ω-m bottom layer resistivity (Fig. 3). The anomaly is open towards the ENE flanks and is bounded on the west and northwest by a high resistivity block with sharp resistivity gradients. The upflow region is believed to be directly beneath the central part of Alto Peak with possible outflows towards the NNE and ESE (Figs. 2 and 3).

3. MT SURVEY

The MT survey at Mahanagdong was conducted using 2 sets of Phoenix™ V5 MT system. The remote-reference technique was usually applied in processing the time-series data. Measurement of MT signals in a remote station is often necessary to correct for some telluric noises in the roving stations, such as those caused by power lines, lightning, cultural noises, and other human activities. During the survey, the remote station was located in Palompon, Leyte, which is about 60 km away from the survey area. Electromagnetic signals were recorded overnight for 10 hours at each station at frequencies ranging from 0.00055 Hz to 384 Hz - eight hours for low-frequency signals (0.00055 - 6 Hz) and two hours for higher frequencies (9 - 384 Hz).

The MT data were robust-processed using the TBS software of Phoenix Geophysics. The robust-processed time series data were further reduced utilizing the WinGlink™ software to generate resistivity curves with varying frequencies.

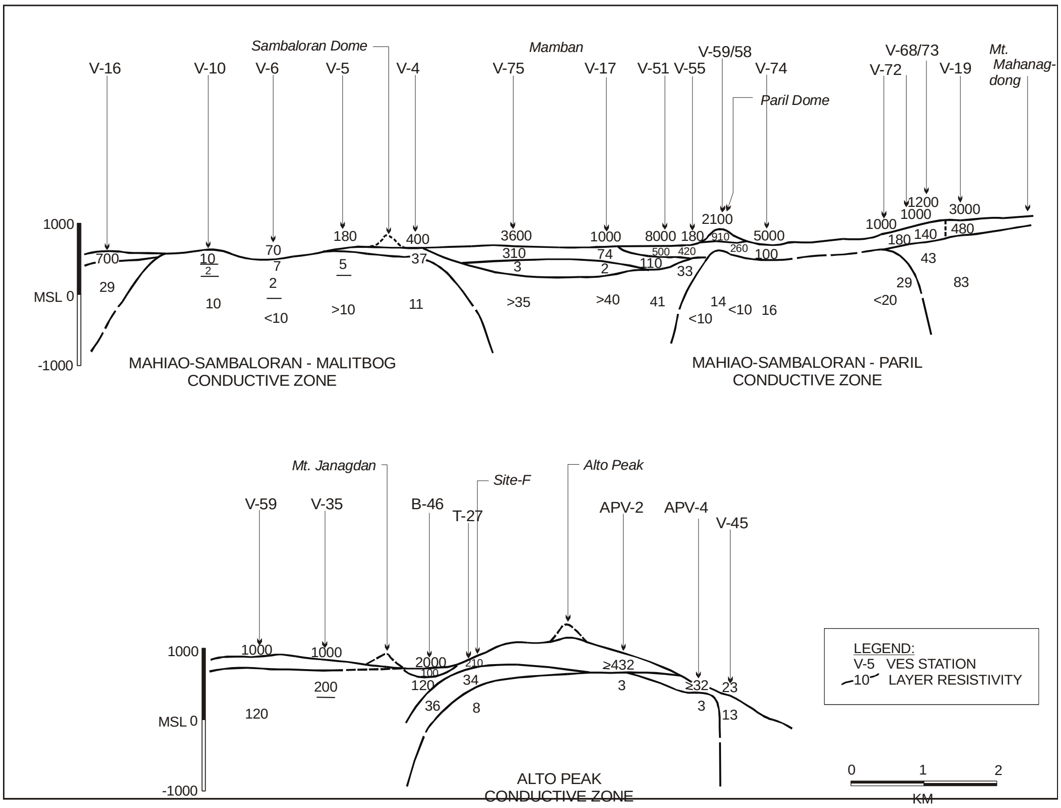

Figure 3: Resistivity model across the Greater Tongonan geothermal field.

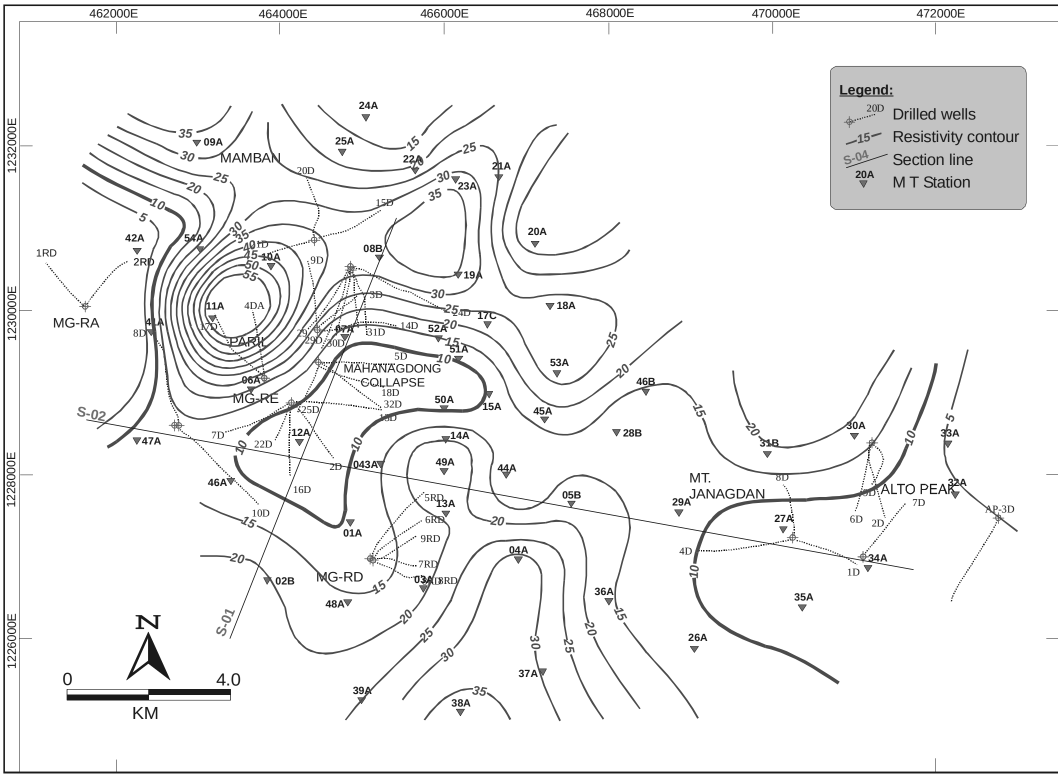

Figure 4: Apparent isoresistivity map at 0.33 second.

MT data points were rotated N43°W, which is the dominant structural strike direction in the area. 1-D layered Marquardt and Occam modeling were applied on the invariant resistivity and transverse electric (TE) were curve models, respectively. Isoresistivity plan maps and section lines were prepared to show the results of the survey.

3.1 Isoresistivity Maps

Figure 4 shows the apparent isoresistivity map at a period (T) of 0.33 second or at a depth of about 500 m. The most prominent feature of this map is the presence of low resistivity anomalies of <10 Ω-m in Mahanagdong and Alto

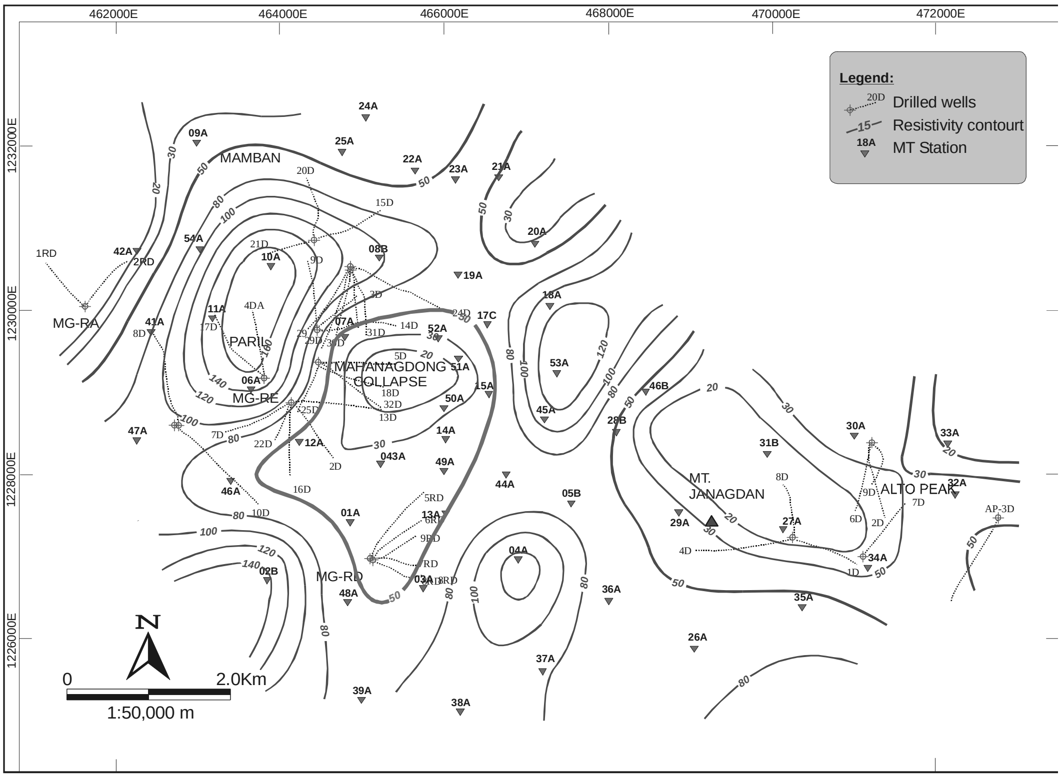

Figure 5: Isoresistivity map of the third layer.

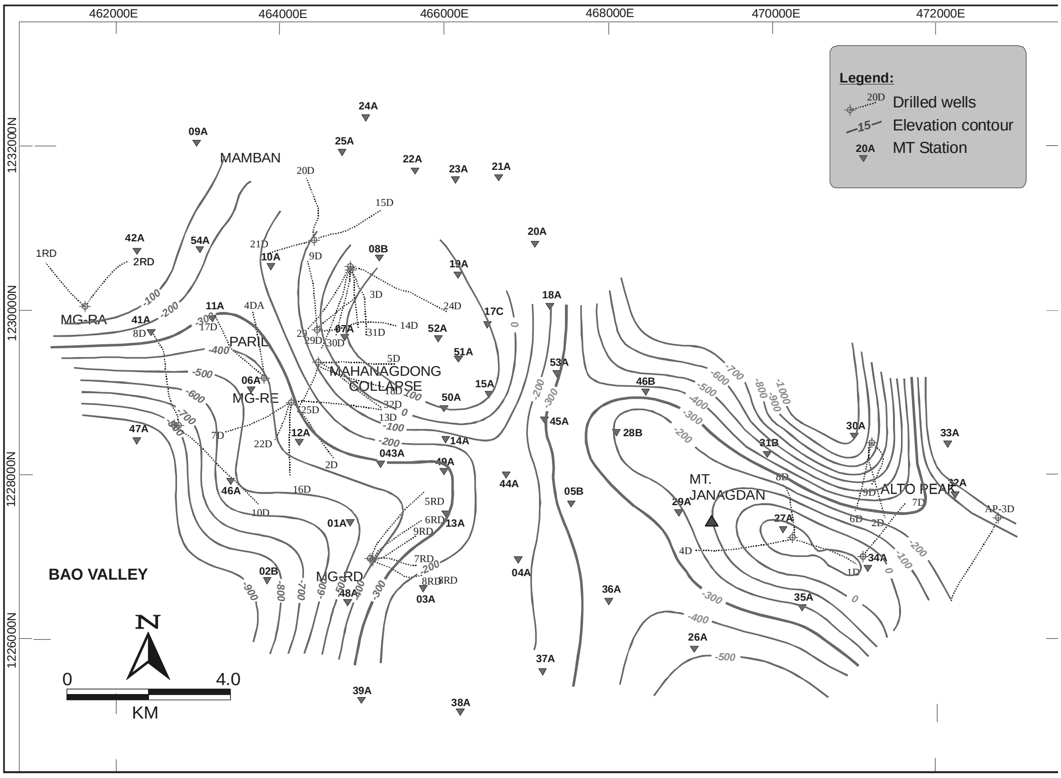

Figure 6: Elevation contour map of the interface between the conductive zone and the third layer.

Peak. Surrounding these anomalies are pockets of higher resistivity values of >20 Ω-m.

The resistivity contour map of the third layer below the conductive zone is shown in Figure 5. Two regions of intermediate resistivity (20-50Ω-m) are found enclosing the vicinities of Mahanagdong and Mt. Janagdan. Higher resistivity contours (>80 Ω-m) surround the two anomalies.

Figure 6 shows the elevation map of the interface between the conductive zone and the top of the third layer. The moderately resistive third layer is shallower at the northeastern side of Mahanagdong and within the well pads of AP-1D, -8D and -4D at Mt. Janagdan-Alto Peak area. It is situated at about –100 mRSL (reduced to sea level) at these sectors. The elevation deepens towards Bao Valley, west-southwest of Mahanagdong and towards the northern and southern portions of the Mt. Janagdan-Alto Peak area.

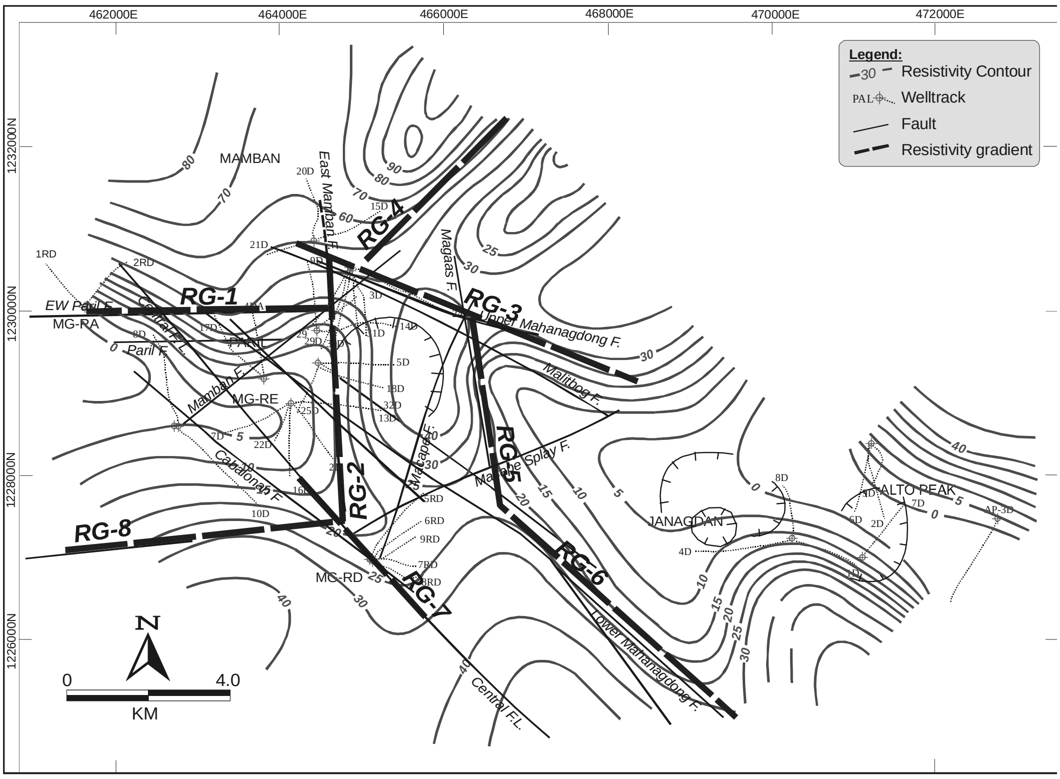

Figure 7: 1-D Occam isoresistivity map at -700 m elevation.

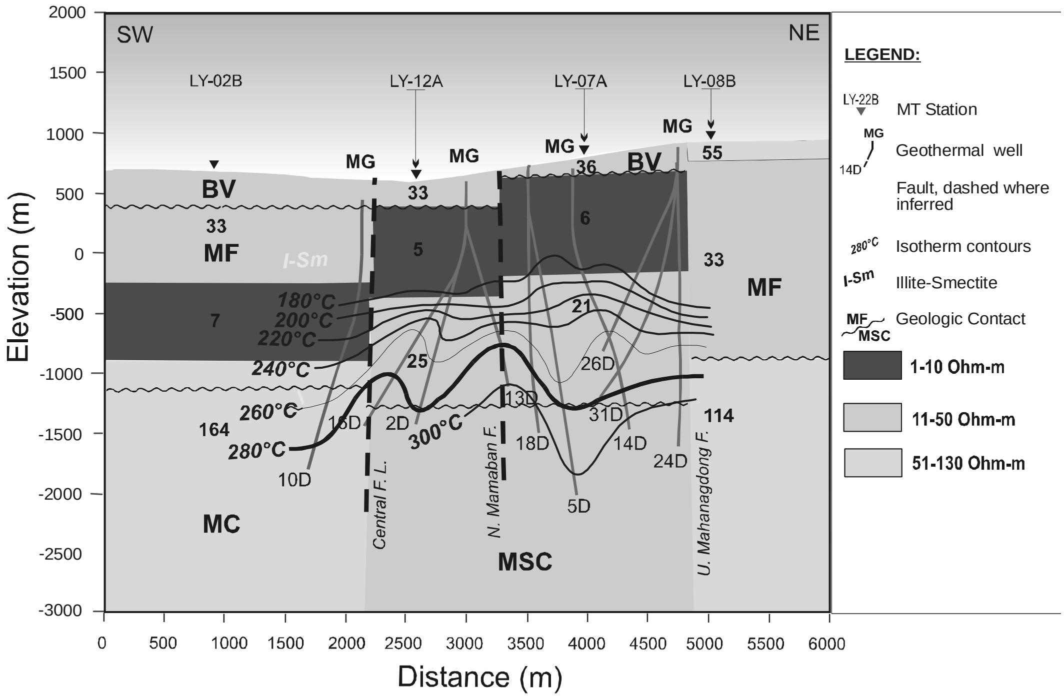

Figure 8: Resistivity model along S-01.

Figure 7 shows the isoresistivity map at –700 m elevation, generated from 1-D Occam modeling. The Mahanagdong area is enclosed by resistivity values >30 Ω-m while on its eastern and western flanks, decreasing resistivity values are shown. Steep resistivity gradients can be also be observed on this figure.

3.2 Resistivity Profiles

The profile lines used are shown in Figure 4. In general, the resistivity sections consist of three layers, namely 1) a resistive cap layer (>50 Ω-m) 2) a conductive middle layer (<10 Ω-m), and 3) and a moderately to highly resistive base layer (>50 Ω-m).

Profile S-01 traverses in a SW-NE direction cutting across MT stations LY-02B, LY-12A, LY-07A and LY-08B (Fig. 8). The topmost layer has resistivity values of 33 to 55 Ω-m. It is only about 200 meter thick beneath LY-07a but thickens to about 700-1000 m. in the southwest and northeast, respectively. This layer is underlain by a highly conductive layer having resistivity values of 1 to 7 Ω-m and

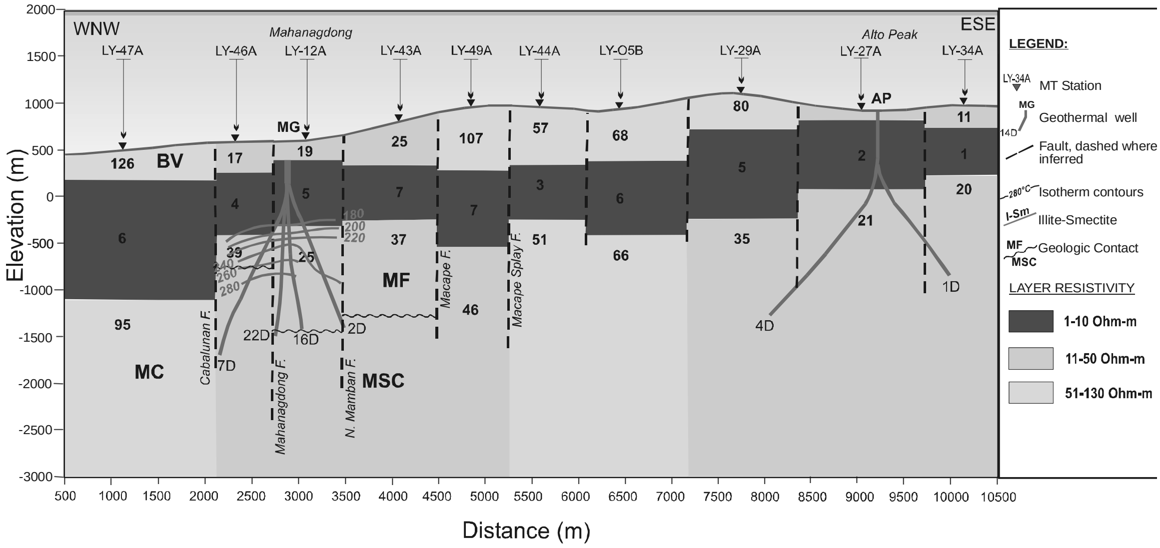

Figure 9: Resistivity model along S-02.

with average thickness of about 700 m. This layer is absent in the northeast. Beneath stations LY-12A and LY-7A, this conductive layer is underlain by a moderately resistive layer with resistivity values of 21-25 Ω-m but below LY-02B and LY-08B, this is underlain by a highly resistive layer with resistivity values of 114-164 Ω-m.

Profile S-02 extends in a WNW-ESE direction, through stations LY-47A, LY-46A, LY-12A, LY-43A, LY-049A, LY 44A, LY-05B, LY-29A, LY-27A and LY-34A (Fig. 9). The resistivity layers encountered were similar to S-01. The first layer has resistivity values of 11 to 126 Ω-m and has average thickness of about 200 m. Underlying this layer is a highly conductive zone (1 to 7 Ω-m) with thickness of about 500 m. Beneath this section, is a layer with resistivity values of 21-95 Ω-m. The Mahanagdong production zone is characterized by resistivity values ranging from 25 to 37 Ω-m.

4. DISCUSSION AND INTERPRETATION

The delineated resistivity models shown in the previous section were correlated with the well data such as clay alteration patterns and measured temperatures of the subsurface (Delfin and Dulce, 1996). The highly conductive middle layer beneath LY-12A and LY-07A coincides with the Smectite and Smectite-Illite alteration zones, as well as the <180^{o}C isotherm contour (Fig. 8 and 9). On the other hand, the underlying moderately resistive layer lies within the Illite, Biotite and Chlorite alteration zone, which is characterized by temperatures >180^{o}C (Fig. 8). Most of the production wells in this sector were drilled within this layer. The highest measured well temperature was also recorded within this layer (Andrino and Hingoyon, 1998). The highly resistive topmost layer can be correlated to the relatively fresh to less altered volcanic deposits blanketing the entire survey area.

Correlating the elevation contour map (the interface of the second and third layers) with the measured well temperatures showed that the shallowest portion of the moderately conductive layer, which is near the Mahanagdong collapse, coincides with the >300^{o}C isotherm (Fig. 10). It is postulated that this uplifted area corresponds to the hotter part of the geothermal system or where the upflow zone is situated. Furthermore, the steep elevation contours around it could represent the margin of the geothermal resource. A similar interpretation can be made from the isoresistivity contour map at –700 m elevation derived from 1-D Occam modeling, wherein the higher resistivity region, which is centered beneath the Mahanagdong collapse and marked by 25-40 Ω-m, coincides with the location of the high-temperature region (Fig. 7).

The major outflow direction at Mahanagdong is towards Bao Valley in the southwest as indicated by the deepening of the conductive zone in this direction (Fig. 6). Another possible outflow zone is towards the southeast as shown by the ≤10 Ω-m contour line in the apparent isoresistivity map at 0.33 sec (Fig. 4).

The Occam isoresistivity map also shows several steep resistivity gradients (RG), which can be associated with some of the major faults mapped in the area and which could be permeable. These include: 1) the Paril/E-W Paril Fault (RG1), 2) East Mamban Fault (RG2), 3) Upper Mahanagdong Fault/Malitbog Fault (RG3), 4) Mamban Fault (RG4), 5) Magaas Fault (RG5), 6) Lower Mahanagdong Fault (RG6), 7) Central Fault Line (RG7), and 8) an unnamed fault, striking east-west, south of the Paril Fault (RG8).

Majority of the production wells at Mahanagdong were drilled on the western part of the anomaly. A still considerable portion of the resource, about 6 km^2, is still untapped by drilling.

5. CONCLUSIONS AND RECOMMENDATIONS

The resistivity structure of Mahanagdong consists of a highly resistivity cap layer (>50 Ω-m) which can be correlated to the relatively fresh to less altered volcanic deposits blanketing the survey area, a very conductive middle layer (<10 Ω-m) which is associated with the Smectite and Smectite-Illite clay alteration, and a third moderately resistive layer (>10-50 Ω-m), which corresponds to higher temperature but less conductive minerals like illite, biotite and chlorite. The postulated upflow region is beneath the Mahanagdong collapse while the main outflow zone is towards Bao Valley in the southwest.

A considerable resource (about 6 km^2) still untapped by drilling was delineated farther east of the Mahanagdong collapse. This is bounded by the Upper Mahanagdong Fault

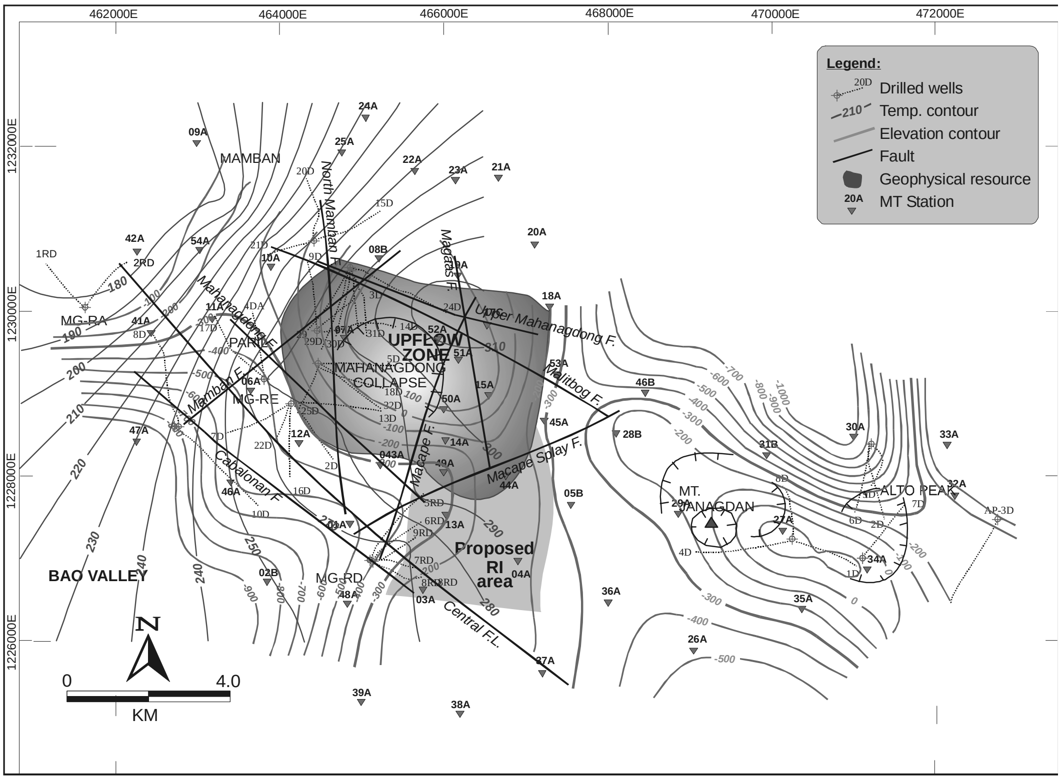

Figure 10: Correlation between elevation and temperature contours at -1500 mASL.

(RG-3) in the north, by the Magaas Fault (RG-5) in the east, and the Macape Splay Fault in the south/southeast.

The primary target for the future drilling at Mahanagdong field is towards the east, to intersect the Magaas Fault (RG5). This will confirm the postulated upflow zone and define the eastern limit of the resource in the area.

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