

MAGNETOTELLURIC SOUNDING IN THE NORTHERN NEGROS GEOTHERMAL FIELD, CENTRAL PHILIPPINES

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ABSTRACT

Interpretation of magnetotelluric (MT) soundings collected in 92 stations in 1995 and 2000 provide a better and deeper picture of the resistivity structure of the Northern Negros geothermal field (NNGF) than previously obtained from DC electrical resistivity surveys. The resulting three-layer resistivity structure interpreted from MT data is consistent with drillhole information as well as data from previous geophysical surveys. A thin, ~300-m thick, highly resistive (30 to >100 ohm-m) layer blanketing the area corresponds to young and fresh extrusives from Mt. Canlaon. Immediately underlying this stratum is a 0.5- to 1.0-km thick highly conductive (1-10 ohm-m) second layer that extends from Mambucal in the northwest to Sumaguan in the southeast. This conductor represents the hydrothermal system's clay cap and may also partly coincide with the shallow and structurally-confined outflow in the northwest. Over the productive region of NNGF, the base of this conductive second layer coincides with the transition from smectite- and illite-smectite-dominated argillic alteration to a secondary assemblage dominated by higher temperature but less conductive minerals like biotite, epidote, and illite. The resistivity of the third layer varies from place to place. In Pataan, the bottom layer is a 2-km thick moderately resistive (20-30 ohm-m) stratum that drillhole data confirm to be part of the geothermal reservoir. This block is juxtaposed to the north by the Mambucal B Fault against highly resistive (30 to >100 ohm-m) third layer that underlies the Catugasan and Mambucal and which corresponds to cold geothermal aquitard. In Sumaguan, southeast of Pataan, the third layer becomes slightly more conductive (10-20 ohm-m) implying the presence of saline and hotter fluids in this sector; the identification of Sumaguan as the prime resource block in NNGF should be tested by deep exploratory drilling. South of Pataan, a narrow resistive block

bounded by the Pataan C and Maa East faults separates the high-temperature geothermal resource in Pataan-Sumaguan from that in Uagdan. In addition to being geophysically less coherent, the Uagdan resource is believed to be of lower grade and merits lower priority for deep delineation drilling.

1.0 INTRODUCTION

The Northern Negros Geothermal Field (NNGF) is located in the province of Negros Occidental in central Philippines and lies on Mt. Canlaon's northwestern flank (Fig. 1). Geothermal exploration by PNOC Energy Development Corporation (PNOC-EDC) in Canlaon Volcano began in the mid-1970s. In 1978-1979, two

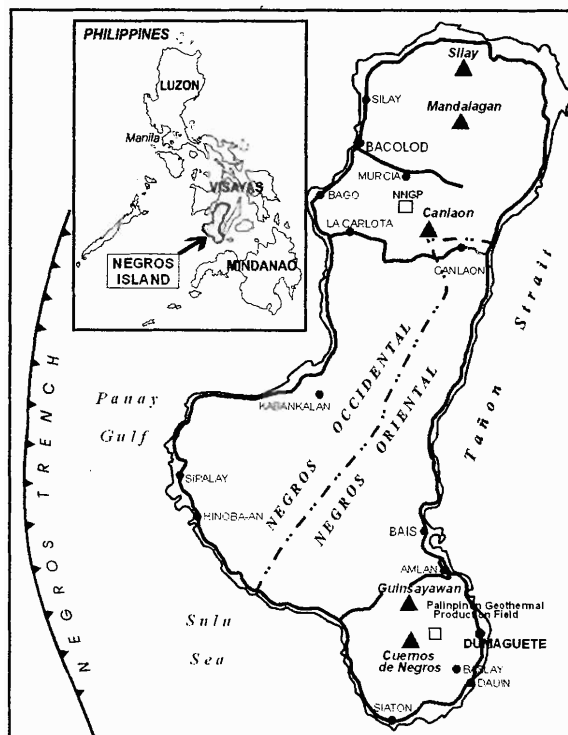


Figure 1. Map of Negros Island showing major center (A) and location of Northern Negros geothermal field (NNGF).

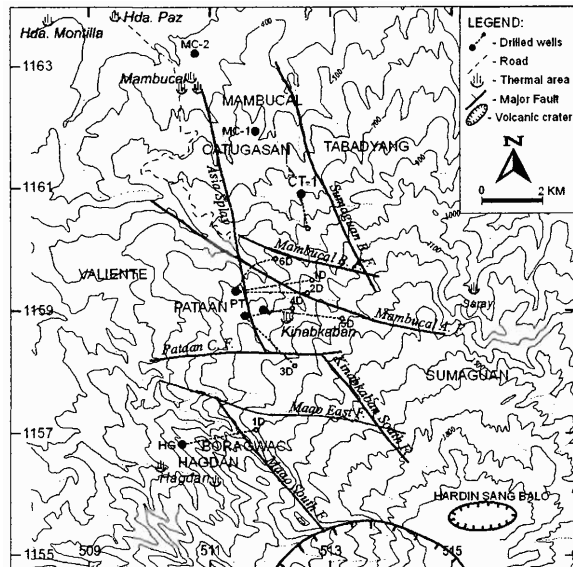


Figure 2. Topographic map of NNGF showing major structures.

intermediate depth (4,500 m) exploration wells MC-1 and MC-2 drilled near Mambucal (Fig. 2) encountered sub-commercial temperature $\leq 190^{\circ}\text{C}$ and calcite-supersaturated fluids. Further exploration activity was then halted and resumed only in 1989 with the conduct of additional geological and hydrogeochemical surveys that pointed to the region south of Mambucal as highly prospective. In 1994, wells HG-1D, PT-1D, and CT-1D, were drilled in the Hagdan, Pataan, and Catugasan sectors, respectively (Fig. 2). High temperature of about 250°C was obtained by PT-1D but the well flowed only briefly and was later lost due to casing damage. HG-1D and PT-1D, on the other hand, yielded relatively lower temperatures of 230°C and 210°C , respectively. Well PT-2D, with a 5 MWe output, confirmed the presence of high-temperature (250°C) neutral-pH chloride (Cl) fluids beneath Pataan. Two more wells, PT-3D and PT-4D, were drilled in 1996-1997 and helped delineate the geothermal resource in the Pataan sector. Further drilling is now underway for the development of a 40 MWe steam field for commissioning by 2004.

Geophysical studies were important in the exploration and development of NNGF. Direct current (D.C.) electrical resistivity surveys were employed in the mid-1970s and early 1980s. A regional Bouguer gravity survey was also completed in 1996 to define the gross subsurface features of NNGF. In 1995, PNO-

EDC undertook magnetotelluric (MT) soundings in 34 survey stations to aid the geothermal drilling program. From June to September 2000, 58 new MT stations were surveyed to provide greater detail of the field's resistivity structure.

The aim of this paper is to present the results of the 1995 and 2000 MT surveys in NNGF. Interpretation and modeling of the MT data form critical constraints in blocking and drilling the geothermal resource in NNGF. In addition, information from MT can also be used to understand the substructure of Mt. Canlaon and its implications to the volcano's evolution.

20 BRIEF GEOLOGIC SETTING

Canlaon Volcano along with Mts. Silay and Mandalagan in northern Negros and Mts Guinsayawan and Cuernos de Negros in the south constitute the Negros Arc. The latter is an N-S-trending chain of Quaternary andesitic volcanoes related to the eastward-subduction of the Sulu Sea oceanic crust along the Negros Trench (Fig. 1).

Mt. Canlaon which last erupted in 1989, is an active multi-vent composite volcano made up largely of andesite and subordinate dacite and basalt extrusives collectively named Canlaon volcanics (CnV) (Pamatian et al., 1992; Martinez-Villegas et al., 2001). Immediately underlying the volcano is a sequence of recrystallized and fossiliferous coralline limestone, sandstone, claystone and volcanic breccia belonging to the Miocene Talave Formation (TF). These units crop out east of the volcano but has been intersected by wells drilled in NNGF. The local basement is the Cretaceous-Oligocene Basak Formation (BF) made up of basaltic lavas intercalated with mudstones and claystone (PNO-EDC, 1995).

The most remarkable tectonic feature in Canlaon Volcano is the N-S alignment of volcanic craters and vents, which generally young to the south (Pamatian et al., 1992; Umbal and Arboleda, undated). This trend mirrors the regional structural grain of the Negros Arc. One of these craters is the 2-km wide Hardin Sang Balo crater, located about 12 km southeast of NNGF (Fig. 2). NS- and NW-trending faults that transect Canlaon volcano provide most of the subsurface permeability that allow deep hot fluids to leak at the surface.

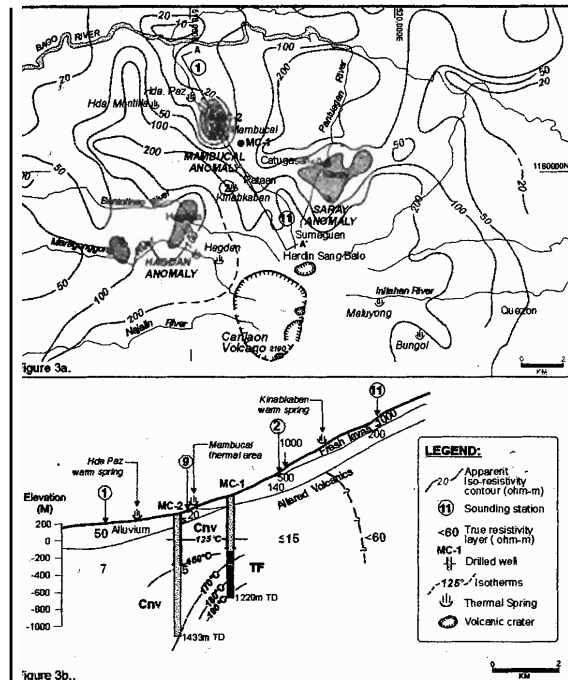
Hydrothermal manifestations around the volcano include fumaroles, hot springs, warm seeps and patches of hydrothermally altered grounds. Most of these are concentrated on Mt. Canlaon's northwest flank although a few occur east and south of the volcano.

3.0 PREVIOUS GEOPHYSICAL WORK

DC Schlumberger resistivity traverses (SRT) with half-current electrode spacing (AB/2) of 250 and 500 m were completed in Canlaon, and adjoining Mt. Mandalagan, in 1978. SRT results in the form of an apparent iso-resistivity map (Fig. 3a) yielded three 50 ohm-m low-resistivity anomalies (Mambucal, Hagdan, and Saray) which are separated by moderately high (100-200 ohm-m) resistivity contours. Used as a basis for siting MC-1 and MC-2, the SRT survey results were only moderately successful.

In 1982, DC resistivity vertical electrical sounding (VES) at maximum AB/2 of 1,000 m was completed to provide deeper resistivity information (Layugan and Apuada, 1992). VES curves located between the three low-resistivity areas show decreasing resistivity with depth. Interpretation of these suggested that all three anomalies are connected at depth and that the geothermal upwelling zone lies at higher elevation than Mambucal, closer to the Kinabkaban spring between Hagdan and Saray (Fig. 3b). VES thus provided a better guide, compared with SRT, to the location of the resource block as proven by subsequent deep drilling in Pataan.

The regional Bouguer gravity survey completed in 1996 covered 428 stations around Canlaon volcano (Rigor et al., 1999). A La Coste & Romberg G-type gravimeter was employed for gravity reading and single-base barometry was used to determine station elevation. A residual Bouguer anomaly map of the area (Fig. 4), derived from the total Bouguer gravity minus the regional trends, shows a pronounced positive gravity high over the region. Two local positive gravity anomalies within this broad high were delineated: one southeast of Hagdan (20 mgal) and the other between Catugasan and Saray (12 mgal). These anomalies were modelled to be dense intrusive bodies that lie as shallow as 1-3 km from the surface. Surrounding the central gravity high in Canlaon are regions of gravity lows in the west, northeast, east, and south



Figures 3a and 3b. Apparent iso-resistivity map at AB/2 = 500 m based on SRT and resistivity model along A-A' based on VES.

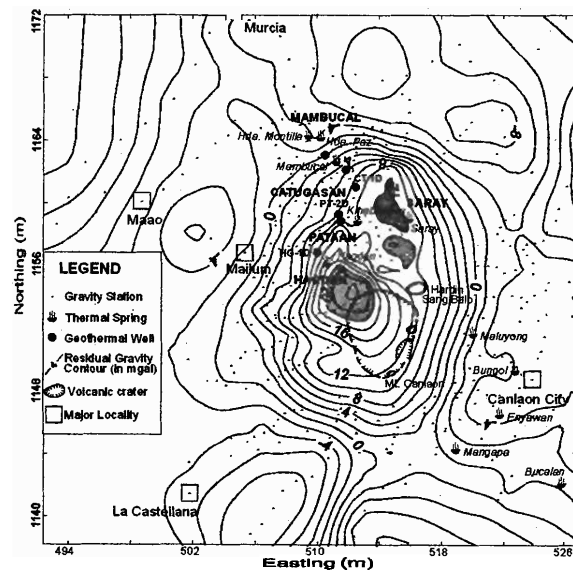


Figure 4. Residual gravity contour map of the Mt. Canlaon Volcanic Complex.

(Fig. 4). These gravity lows were interpreted to manifest the thickening of less dense Tertiary sedimentary pile beneath the Quaternary volcanics. The residual gravity map also shows increasing values northwest of Maaao (Fig. 4), perhaps reflecting the gradual rise of dense basement rocks to shallow levels in this region.

4.0 RESULTS OF MT SOUNDING

MT sounding in NNGF was conducted using a Phoenix^mV5 MT system employed in a remote-reference mode where one roving MT receiver collected data in different scattered stations while another MT receiver collected MT data in a fixed remote site. Measurement of MT data in a remote station is often necessary to correct for some telluric noises in the roving stations, such as those caused by overhead power lines, lighting, cultural noises, and other human activities. In NNGF, the remote station was sited 20 km away in Maa, Bago City. Sounding was made 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 timeseries data collected on each site, robust-processing was employed on data from both remote and roving stations. To generate resistivity curves with varying frequencies from the robust-processed time-series data, further processing using WinGlinkTM software was then made. The resulting TE (transverse electric mode) curves were rotated N37°W parallel to the general structural strike in NNGF while the TM (transverse magnetic mode) curves were correspondingly rotated perpendicular to the strike. The invariant resistivity was used in the processing and interpretation to give equal weight to the two modes. Hence, no static shift was applied to the MT curves. The curves generally show 1-D behavior from surface down to between 0.1 and 0.01 Hz. Resistivity values at selected frequencies from each of the 92 stations were then contoured to show iso-resistivity patterns over the whole project area.

Figure 5 is an apparent iso-resistivity map at sounding frequency of 0.33 seconds (3.03 Hz). Depth of penetration at this frequency reaches up to 1.5 km. The most prominent feature in this map is a 1.5 - 2-km wide, northwest-trending low-resistivity (<10 ohm-m) zone extending from Sumaguan in the southeastern highland to Mambucal in the northwestern foothills (Fig. 5). Thermal areas located within this anomaly are Kinabkaban and Mambucal; springs in Hda. Montilla and Hda. Paz may be considered within the northwestern extension of this anomaly (Fig. 5). Flanked by moderate resistivity values (10-16 ohm-m) except near the Pataan wellpad

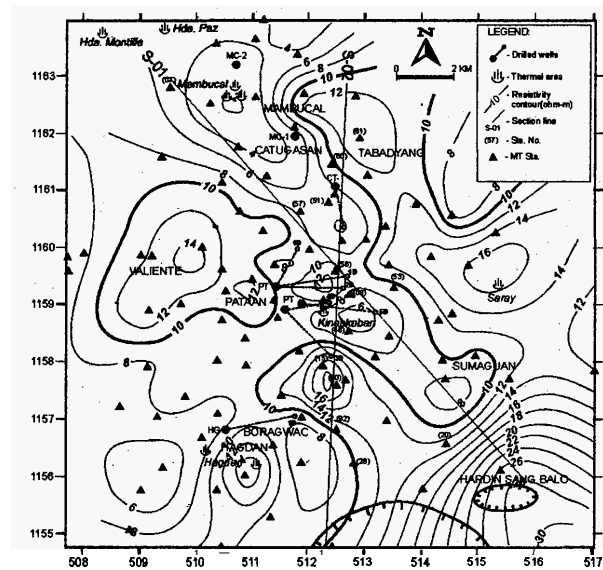


Figure 5. Apparent iso-resistivity map at 0.33 sec based on MT.

where this moderately resistive border is broken, the anomaly's southeastern edge is sharply defined by higher resistivities (>20 ohm-m) that cover Mt. Canlaon's summit vents.

The higher resistivities measured around Hardin Sang Balo at this frequency generally continue to the north towards Saray and east of Tabadyang (Fig. 5). At Hagdan, the resistivity picture is somewhat incoherent. Resistivity contours of 10-14 ohm-m cover the Hagdan thermal springs but a broad region of <10 ohm-m is mapped north of well HG-ID. In addition, a prominent lobe of about 16 ohm-m is found between HG-ID and PT-3D (Fig. 5).

Profile S-01 (Fig. 6) shows the vertical distribution of resistivity layers along the strike of the anomaly. A three-layer resistivity structure is present down to -3000 m elevation. A resistive (30- 100 ohm-m) surficial layer blanketing the project area is underlain by a highly conductive (1-8 ohm-m) second layer 500 to 1000 m thick from station NNG-20 to station NNG-07 (Fig. 6). This highly conductive second layer is absent beneath Hardin where it is replaced by a 3-km thick moderately resistive body. The third layer consistently has higher resistivity values compared with their immediate overburden. Beneath Mambucal and Hardin, the third layer is very resistive, from 40 to >200 ohm-m. The third layer is only moderately resistive (< 30 ohm-m) below Pataan and moderately conductive (10-20 ohm-m) below Sumaguan (Fig. 6).

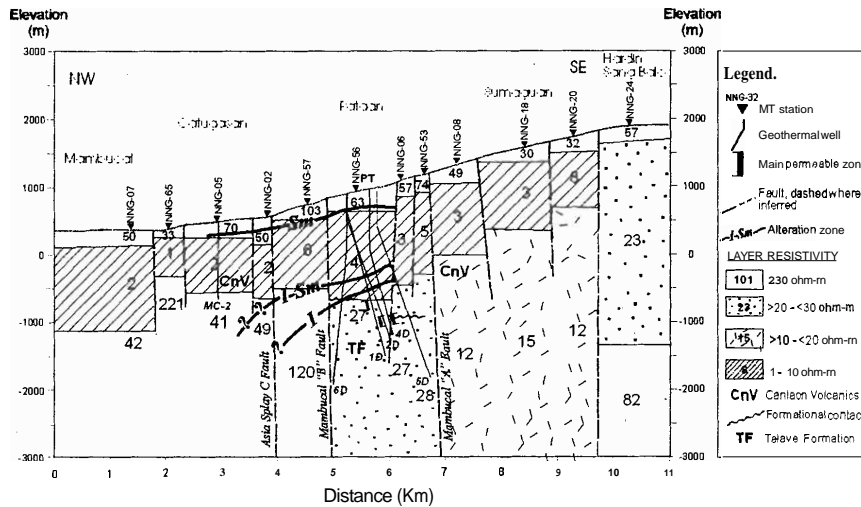


Figure 6. Interpreted resistivity model along section line S-01 based on MT.

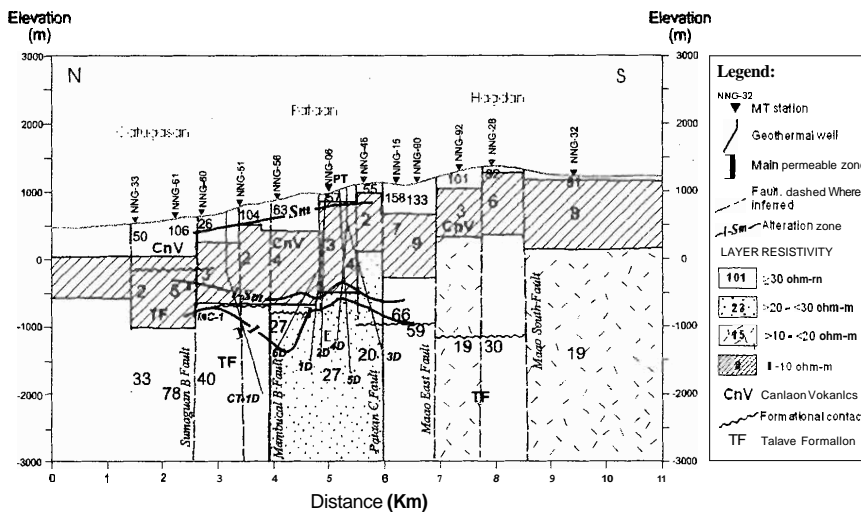


Figure 7. Interpreted resistivity model along section line S-02 based on MT.

A N-S section, Profile S-02 (Fig. 7) shows the same three-layer resistivity structure across the field. A very conductive second layer up to 1 km thick is covered by a thinner resistive surficial layer. A narrow resistive block beneath stations NNG-15 and NNG-90 separates the moderately conductive bottom layers beneath Hagdan and Patana. Further north, the bottom layer beneath Catugasan assumes resistive values (33-78 ohm-m).

5.0 MT DATA INTERPRETATION

5.1 Correlation with Drillhole Information

To understand the geological meaning and geothermal implications of the MT results, the

delineated three-layer resistivity structure in Figures 6 and 7 is correlated with some key drillhole data.

The correlation shows that the resistivity layers do not coincide with formation boundaries. In Figure 6, for instance, data from Patana wells indicate that beneath MT sites NNG-6 and NNG-56, the Canlaon Volcanics (CnV) encompass all three resistivity layers - from the surficial resistive layer through the highly conductive second layer and to the upper portion of the moderately conductive third layer. Similarly, the Talave Formation (TF) has no unique resistivity signature; it is moderately conductive beneath Patana (sites NNG-56, 06, 46) and Hagdan (sites NNG-92, 28) but resistive below Catugasan (sites NNG-61, 60, 51) (Fig. 7).

A better correlation exists between resistivity layering and the degree and rank of hydrothermal alteration. The resistive first layer coincides very well with the young and unaltered lavas and pyroclastics of the CnV (Figs. 6 and 7). Clay alteration, marked by the top of the Smectite (Sm) zone begins at depth equivalent to the top of the highly conductive second 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 (150°C) to Illite (I) zone (220°C). In other words, the highly conductive second layer corresponds to an extensive hydrothermal clay cap developed largely, but not entirely, within the CnV (Figs. 6 and 7).

The hydrothermal nature of the third layer varies from place to place. Beneath Mambucal and Catugasan where the third layer is resistive, measured temperatures at corresponding depths are relatively low (<220°C). These results to deeper occurrence of higher grade alterations manifested by the steep plunge in the top of the I-Sm and I zones (Fig. 6). 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-rich hydrothermal alteration from 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.

The MT results also revealed significant lateral resistivity boundaries at depth. Figure 6 shows a major lateral boundary between Pataan and Catugasan beginning at about -1000 m elevation. Located midway from MT sites NNG-57 and NNG-56 and close to the surface projection of PT-6D's bottom hole, this boundary juxtaposes the highly resistive third layer (120 ohm-m) of the Catugasan sector with the moderately resistive (<30 ohm-m) third layer beneath Pataan. Geological correlation suggests that this major lateral boundary is most likely the

WNW-trending Mambucal B Fault (Fig. 2).. Another deep lateral boundary is revealed near MT station NNG-53 where the moderately conductive third layer of Sumaguan comes into contact with Pataan's moderately resistive layer at about -500 m elevation. Although believed to be associated with the major WNW-trending Mambucal A fault, the resistivity contrast across this boundary is less sharp than the one along the Mambucal B Fault (Fig. 6) implying a gradational geothermal boundary at depth between Sumaguan and Pataan.

The Mambucal B Fault is again identified as the likely lateral boundary of the third resistivity layer between Catugasan and Pataan beneath MT station NNG-56 (Fig. 7). A narrow 1 km-wide resistive block beginning at about -500 m elevation separates the Pataan sector from the Hagdan block. The structural boundaries of this resistive block are believed to be the Pataan C and Maa East faults - (Fig. 7), both of which are EW-trending structures (Fig. 2)..

5.2 Geophysical Model of the NNGF Geothermal Resources

The trends and correlation discussed above provide the basis for constructing a conceptual geophysical model of the geothermal resource in NNGF (Fig. 8).

The thin (-300 m) resistive layer blanketing the area is believed to correspond to the young deposits of Canlaon Volcano which are fresh or weakly altered andesitic lavas and pyroclastics. Beneath this, the 0.5 to 1 km-thick highly conductive second layer represents the geothermal system's clay cap. Towards Mambucal to the north, this layer may also correspond partly with the system's outflow. This shallow lateral plume of hydrothermal fluids is confined along a narrow NNW-trending corridor bounded by the Sumaguan B and Asia Splay faults (Fig. 2). The clay cap extends to Sumaguan in the southeast where no surface hydrothermal manifestation has been identified. Below Pataan, the base of the clay cap coincides with the transition zone towards higher temperature illite (I) alteration zone where temperature is at least 220°C. North of Pataan, however, the I alteration zone plunges steeply and diverges from the base of the conductive second layer implying a dramatic drop in temperature at shallow levels towards Catugasan. This trend is confirmed by measured temperatures in wells CT-1D, MC-1, and MC-2.

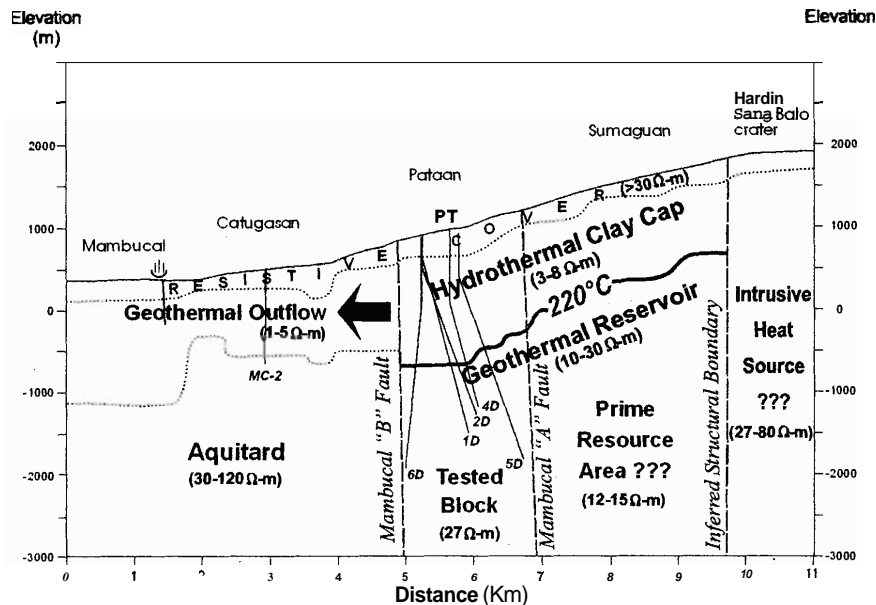


Figure 8. Conceptual geophysical model of NNGF.

The moderately resistive third layer beneath Pataan, bounded by the Mambucal B and Mambucal A faults, coincides with the generally productive block in Pataan tested by deep drilling. Both requisite temperature and permeability (Figs. 6 and 7) have been confirmed in this resistivity layer indicating that the reservoir expresses itself as a block slightly more resistive than the immediately overlying conductive second layer. The increased resistivity of the resource is interpreted to be function of decreasing clay content and increasing fraction of higher-temperature but less conductive secondary minerals like biotite, epidote, and illite in the geothermal reservoir. If this trend is correct, then the moderately conductive third layer beneath Sumaguan most likely represents high-temperature geothermal resource, too. Although the alteration assemblage beneath Pataan and Sumaguan may be roughly similar, the more conductive character of the third layer beneath Sumaguan is probably due to the greater amount of hot mineralized fluids circulating within this sector compared to Pataan. Based on this MT model and the increasing subsurface temperature towards PT-5D, the Sumaguan block is believed to be the upwelling zone of the geothermal resource in NNGF.

Southeast of MT site NNG-20 (Fig. 5 and 6), the resistivity signatures of the clay cap (conductive second layer) and geothermal resource (slightly

more resistive third layer) are both missing. This suggests that the southeastern limit of the geothermal reservoir lies in the vicinity of MT site NNG-20. This region, characterized by steep resistivity gradient towards higher values (Fig. 5) is dominated by the Hardin Sang Balo crater, the northern-most and possibly oldest vent among Mt. Canlaon's N-S line of volcanic eruption centers (Figs. 2 and 3). Also partly coinciding with this region is the local residual positive anomaly mapped by the Bouguer gravity survey in 1995 (Fig. 4). If this anomaly is truly caused by sub-volcanic stocks and intrusives, then the close spatial relationship between the inferred Sumaguan upwelling zone and the Hardin Sang Balo crater region suggests that intrusive bodies beneath Hardin Sang Balo may be fueling the upwelling geothermal fluids in adjacent Sumaguan (Fig. 8).

The resistivity signature at Hagdan, south of Pataan, also implies the existence of a geothermal system in this sector (Fig. 7). Well HG-ID which intersected 230°C fluids beneath Hagdan confirms this system. However, the prominent high resistivity block defined by the Pataan C and Maa East faults separates this Hagdan geothermal system from that in Pataan-Sumaguan. In addition, the incoherence of the MT trends around Hagdan makes the geothermal resource in this sector difficult to evaluate.

6.0 SUMMARY AND CONCLUSIONS

MT sounding has provided a deeper and better analysis of the resistivity structure of NNGF than DC electrical resistivity techniques (compared Fig. 3b with Fig. 6). A three-layer resistivity model of the field is consistent with data obtained from drillholes and previous geophysical investigations. A shallow highly resistive (>30 ohm-m) layer represents fresh and young extrusives from Mt. Canlaon that blanket the area. This overlies a 0.5 to 1.0-km thick highly conductive (1-10 ohm-m) second layer representing the hydrothermal system's clay cap. This clay cap extends farther southeast than previously known from deep drilling and underlies the Sumaguan sector, an area devoid of active thermal manifestations. The geothermal resource is represented by a third layer that is slightly more resistive (10-30 ohm-m) than the overlying layer and separated from adjacent highly resistive third layer by structures coinciding with mapped faults. Our geophysical model of NNGF has several important implications to geothermal resource development, to wit:

Although productive, the Pataan sector represents only the outer margin of the geothermal reservoir; a higher temperature resource may be found farther southeast beneath Sumaguan.

The Mambucal B Fault is the likely northern structural boundary of the Pataan-Sumaguan reservoir; deep production drilling beyond (or north of) this structure is not recommended.

In the productive sectors, the base of the clay cap (and the top of the geothermal reservoir) is deepest beneath Pataan where it lies at about -700 m elevation. Casing of future production wells in Pataan should be set at equivalent depths. The base of the clay cap shallows at Sumaguan to elevation just above mean sea level. Future drillholes targeted in this block should have their production casing shoes set at equivalent depths.

The Hagdan block harbors a geothermal system distinct and separate from that in Pataan-Sumaguan. Although requiring further confirmation, we rate this system to be of lower grade and coherence compared with the Pataan-Sumaguan geothermal resource.

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