

MAGNETOTELLURICS-DERIVED RESISTIVITY MODEL OF THE DAUIN GEOTHERMAL PROSPECT, SOUTHERN NEGROS, CENTRAL PHILIPPINES

Rhoel Enrico R. Olivar and Nilo A. Apuada

PNOC Energy Development Corporation, Merritt Road, Fort Bonifacio, Taguig City, Philippines

ABSTRACT

Success of modular power plant development and economic considerations revived interest in the Dauin Geothermal Prospect. This prompted a recent geophysical reinvestigation of the area using magnetotellurics (MT). The MT survey delineated two regions of shallow occurring high-resistivity ($>50 - 100 \Omega\text{-m}$) overlain by a zone of low resistivity ($\leq 10 \Omega\text{-m}$), one of which centers beneath Lagunao Dome, and another beneath Mt. Talines and Cuernos de Negros. The former, a larger anomaly, is related to the Palinpinon geothermal system at the Southern Negros Geothermal Production Field (SNGPF), while the latter, a smaller anomaly, is thought to define a separate geothermal system, referred to as the Dauin prospect. The high-resistivity anomalies are associated with high temperature but low conductivity mineral alteration products (illite, epidote, chlorite, etc.) that dominate most geothermal systems. The low-resistivity ($\leq 10 \Omega\text{-m}$) layer is associated with clay hydrothermal alterations (smectite and illite-smectite) that normally occur at regimes of intermediate temperatures ($\sim 70^\circ\text{C}$). The resistivity model supports the idea of two geothermal systems separated by a zone of high-sulfidation. This high-sulfidation zone coincides with the region of intermediate resistivity likely defined by the Malingin Fault, which also separates the two high-resistivity anomalies. A single heat source possibly fuelling the two systems at deeper levels, however, is not discounted.

1.0 INTRODUCTION

The Dauin geothermal prospect is situated about 6 km southeast of the 192.5 MWe Southern Negros Geothermal Production Field (SNGPF) in Negros Island, Central Philippines (Fig. 1). The two lie on opposite flanks of the dormant volcanic complex that centers in Cuernos de

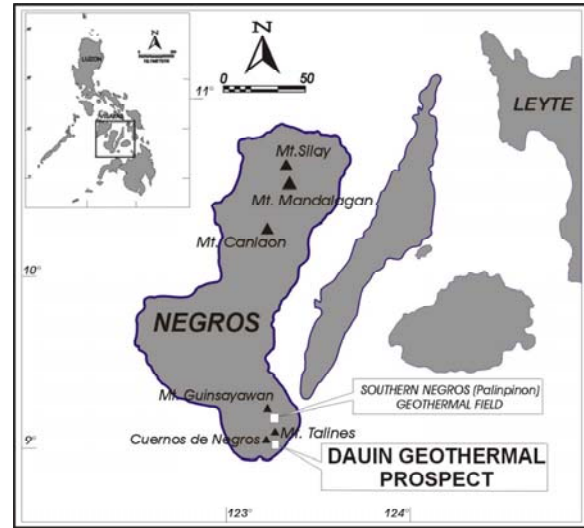


Figure 1. Location map of Dauin geothermal prospect.

Negros (1,800 masl). Impressive thermal manifestations in Dauin merited its thorough geoscientific investigation that began in 1973 and led to the drilling of two deep exploratory wells, DN-1 and DN-2, between 1982 and 1983. Well DN-1 encountered near neutral fluids with maximum temperature of 240°C and reservoir Cl of 3,300 mg/kg. However, it discharged a substantial amount of elemental sulfur.

The sulfur polluted the vicinity of the well and corroded and eroded the wellhead. This prompted the well to be shut after only three days of discharge. Well DN-2, 4 km to the southwest of DN-1 did not discharge due to poor permeability and lower temperature (180°C). The relatively high temperature encountered in DN-1 suggested the existence of a commercially exploitable geothermal system in the area and encouraged further exploratory studies for its development. Furthermore, success in the development of modular power plant technology and economic considerations elevated the level of interest to the testing of new approaches in the geoscientific reevaluation of the area.

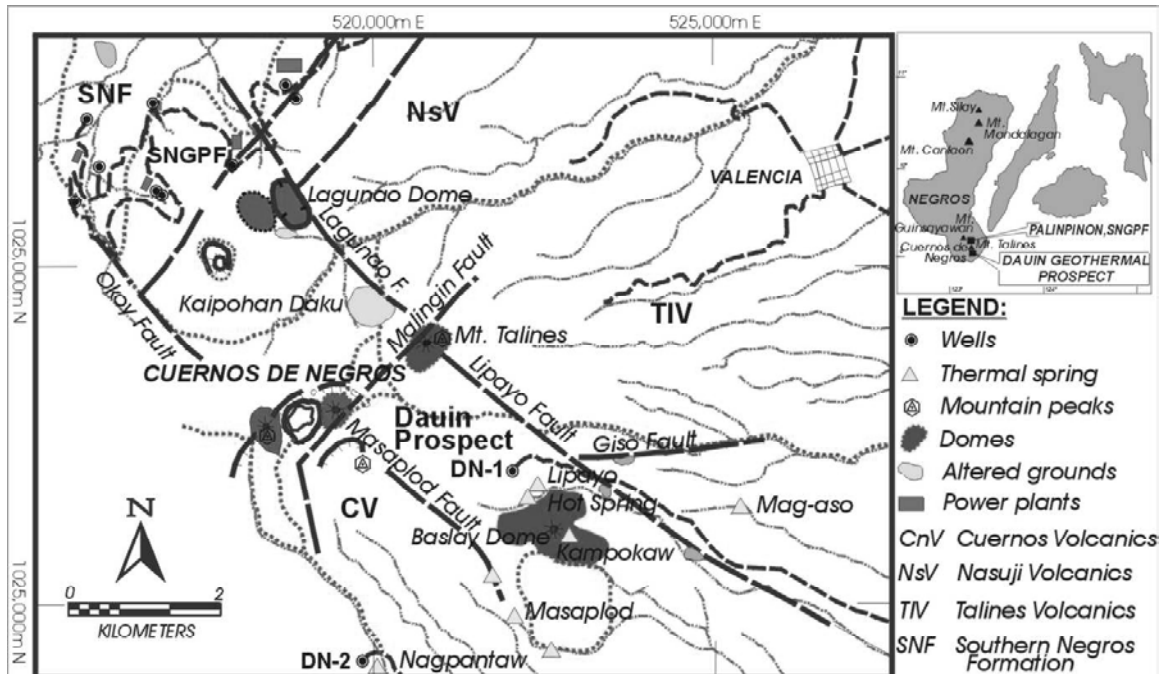


Figure 2. Surface geology, volcanic features and major structures of SNGPF and Dauin (after Pamatian, 1992).

Advances in computing technology hastened the development of magnetotellurics (MT) application and is now proving to be an effective tool in geophysical exploration studies. Recently, it is gaining favor in the field of geothermal exploration where the areas being considered have distinct resistivity properties. MT's advantage stems from its power to penetrate deeper into the earth than conventional resistivity methods. MT resistivity is derived from naturally induced currents by the time-dependent variations of the earth's electromagnetic field. The deep penetration capability of MT enables geothermal prospectors to "see" beyond the low-resistivity layer delineated by previous methods and henceforth, conceptualize a more holistic model of the geothermal system being studied. With this fairly new technology, an MT program was designed to reinvestigate the Dauin prospect to determine the subsurface geophysical structure of the area including SNGPF.

2.0 GEOLOGIC SETTING

The Dauin geothermal prospect lies in the southeastern quadrant of the coalescing volcanoes of Talines, Guinsayawan, and Cuernos de Negros. This group of dormant

volcanoes forms the southern counterpart of andesitic-dacitic volcanic complexes that dominate the island of Negros. Mts. Mandalagan, Silay, and Canlaon comprise the volcanoes in the north (Fig. 1). The Dauin prospect is generally covered with the effusives and extrusives of Cuernos de Negros (Alincastre, 1982). Dispersed within the area are thermal manifestations characterized by warm to hot springs with flows up to 10 li/sec, extensive altered grounds, gas seepages, and fumaroles (Bayrante, 1997). Geomorphologically towering within the prospect area are the distinct volcanic plugs and domes such as the Cuernos de Negros and Mt. Talines lying at the central point and Baslay Dome in the southeastern flanks (Fig. 2).

Cuernos Volcanics (CV), the youngest stratigraphic layer in the area is of Pleistocene to Recent age and composed mainly of clinopyroxene hornblende andesite lava flows with intercalated paleosols. Underlying the CV is the Plio-Pleistocene Southern Negros Formation (SNF) consisting of fresh to weakly altered andesitic to dacitic crystal tuff, volcanoclastic breccias, and hornblende-clinopyroxene andesite lava flows intercalated with thin lenses of fossiliferous calcarenite and calcisiltite. The oldest stratum encountered by drilling is the Late

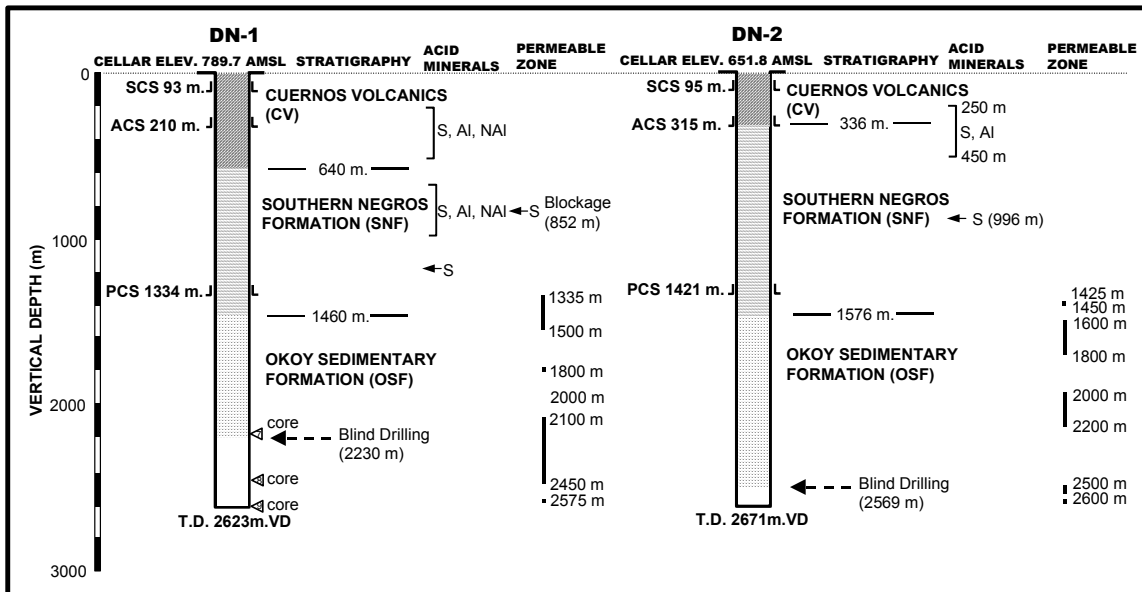


Figure 3. Stratigraphy, location of acid alteration mineralogy and permeable zones in wells DN-1 and DN-2 (after Reyes, 1983).

Pliocene to Early Pleistocene Okoy Sedimentary Formation (OSF) also composed of lava flows but is distinguished from the SNF by the presence of intercalated fossiliferous calcarenites, calcisiltites, and limestones (Reyes, 1983) (Fig. 3). The three units are correlatable with the formations encountered in the Puhagan and Nasuji-Sogongon sectors of SNGPF with lithologic characteristics and age as basis (Pamatian, 1992). The formations equivalent to the Miocene Puhagan Volcaniclastic Formation (PVF) and the late Miocene Nasuji Pluton (NP) encountered at deeper levels of Nasuji sector in SNGPF were not encountered in the two wells in Dauin but are suggested to be present, also at deeper levels (Bayrante, 1997).

Impressive hot springs and steaming grounds attest to subsurface permeability though minor fault structures do not appear extensively. These minor faults are probably covered by the younger volcanic deposits consisting of extensive lahar, flow breccias and pyroclastic flows (Bayrante, 1997).

Two major faults mapped in Dauin, the Lipayo and Masaplod Faults, are thought to control the distribution of local thermal features (Fig. 2). The SE trending Lipayo Fault appears to channel and control the Lipayo, Campocaw, Mag-aso, and the San Miguel hot springs (Fig. 4). The parallel Masaplod Fault, on the other hand,

controls the Masaplod springs in the SW. Pamatian (1992) links the Lipayo Fault to Lagunao Fault transecting SNGPF in the northwest and Tebar (1990) correlates Masaplod Fault to Okoy Fault, likewise transecting SNGPF.

3.0 PREVIOUS GEOPHYSICAL SURVEYS

Schlumberger resistivity traversing (SRT) survey was conducted in Dauin as early as 1973 by the Commission on Volcanology (COMVOL). In 1975 to 1976, extensive D.C. resistivity survey was conducted by PNOG-EDC and Kingston Reynolds Thom and Allardice (KRTA). Two distinct low-apparent resistivity anomalies ($\leq 50 \Omega\text{-m}$) were delineated in the then Baslay-Dauin prospect, one follows the direction of Lipayo Fault extending from DN-1 to the coastal hot springs at San Miguel and another centers in Nagpantaw, encompassing the thermal springs mapped in Tibanglan and Nagpantaw area (Harper, 1982). A third anomaly associated with the Palinpinon geothermal system was mapped at SNGPF (Fig. 4).

Vertical electrical sounding (VES) measurements were also conducted in Dauin in early 1982 and in 1992. The more recent survey incorporated the earlier data and revealed low resistivity values of $< 50 \Omega\text{-m}$ at depth south of Lagunao and Nasuji Volcanic Domes and the

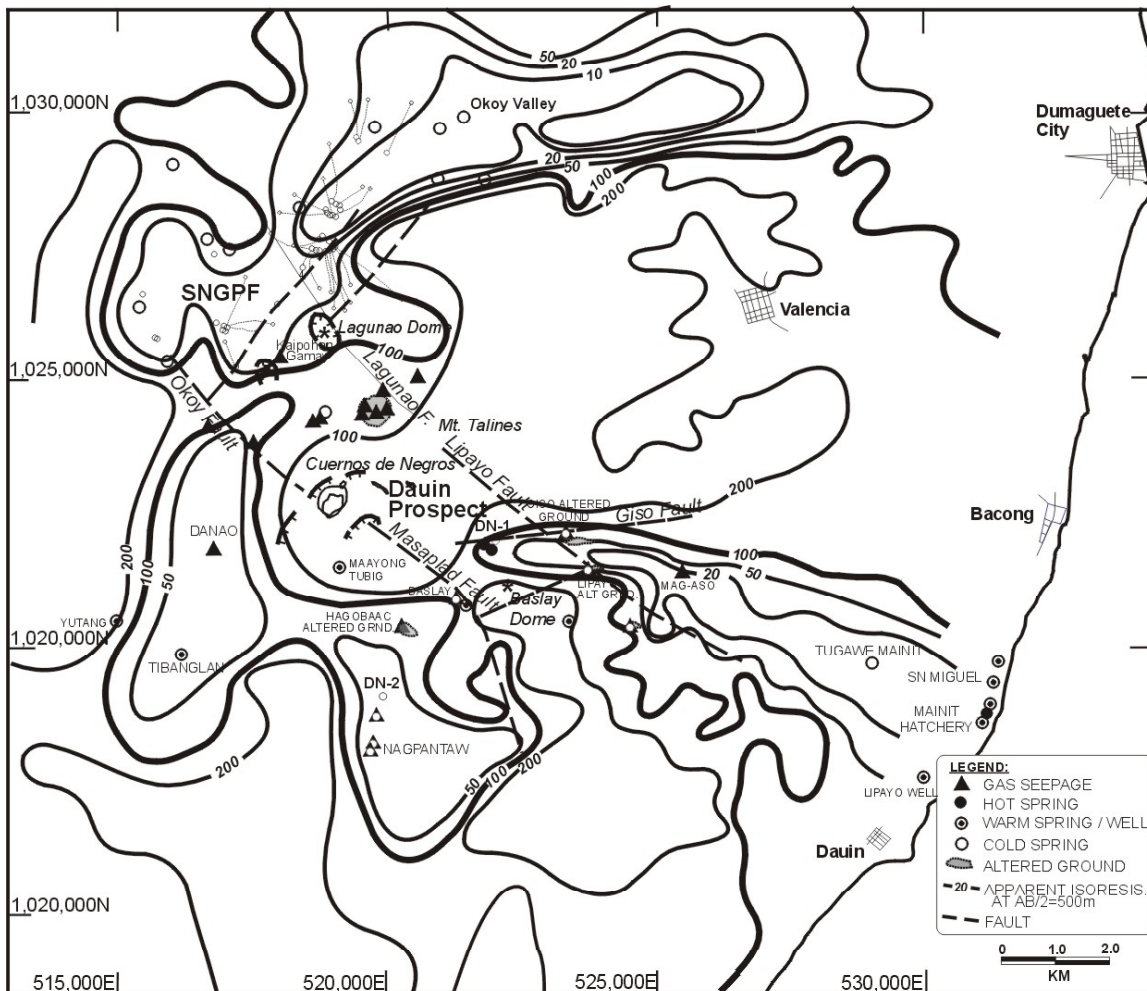


Figure 4. Apparent isoresistivity map at AB/2 = 500 m based on SRT.

Kaipohan altered grounds. It also resulted to the delineation of a significant low resistivity anomaly of $<30 \Omega\text{-m}$ coinciding with the Lipayo anomaly observed in the earlier SRT survey. Soundings conducted at Tibanglan/Nagpantaw area generally showed increasing resistivity with depth, implying that the previously mapped low resistivity anomaly was due only to near-surface alterations and probably represents a shallow outflow zone draining the thermal springs at Tibanglan and Yutang from the Palinpinon field (Layugan, 1992).

4.0 MAGNETOTELLURICS (MT) SURVEY

The magnetotellurics (MT) survey was conducted between May and August 2003. A total of seventy-one (71) MT stations were occupied including 16 retests covering an approximate area of 180 km^2 . A single-station

method was employed using the Phoenix™ V5 MT System for data acquisition. The SNGPF was included in the survey coverage to calibrate MT with the field's known subsurface and correlate this with the MT data obtained in Dauin.

The field data were generally of good quality, with the exception of a few soundings that were gathered during rainy days. These few soundings, however, were retested whenever possible. The raw data were pre-processed using a Tbasic-based robust processing program. Final processing was done in the 1.39.8 version of WinGlink™, an integrated geophysical interpretation software. The invariant mode curves, with the principal axis rotated to the predominant regional strike direction of $N45^\circ E$, were modeled using the 1-D Marquardt layered inversion.

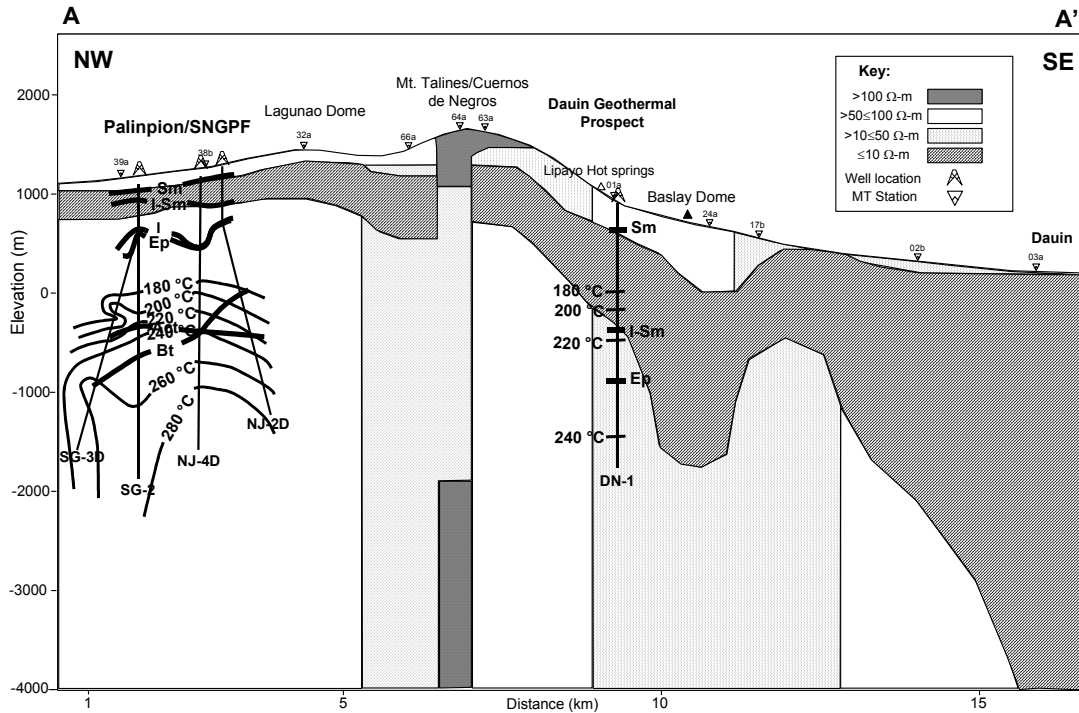


Figure 5. Vertical resistivity distribution along section AA' based on MT (isotherms and mineralogy after Zaide-Delfin and Ramos, 2002).

Data interpretation was based on a typical MT resistivity model, where the low-resistivities observed at intermediate temperatures (~70°C) are correlated with clay hydrothermal alterations (e.g. smectites, illite-smectites) that form in such temperature regimes (Ussher, et al, 2000). High-resistivity regions predict the appearance of illite and other high-temperature alteration minerals (chlorite, epidote, etc.), which form at temperatures of >180°C. Typical high-resistivity regions have values between 20 and 100 Ω-m (Anderson, et al, 1999).

4.1 Discussions and Interpretation

4.1.1 Resistivity Profile

A three-layered resistivity model of a geothermal system consists of a high-resistivity surface layer (~100 Ω-m) corresponding to fresh to less altered volcanic cover underlain by a layer of low resistivity (≤10 Ω-m), characterized by the occurrence of low-temperature clay minerals (smectite, illite-smectite, etc.). These are in turn underlain by a region of increasing resistivity (>10 Ω-m) where high-temperature alteration minerals like illites and epidotes are normally formed (Anderson, et. al, 1999).

Section AA' passes from Sogongon in the northwest, across Cuernos de Negros and is oriented along the trace of the Lipayo Schlumberger resistivity anomaly in the southeast (Figs. 5 and 6). It cuts through wells SG-3D, SG-2, NJ-4D, and NJ-2D in the SNGPF, and DN-1 in Dauin geothermal prospect. Surface resistivity values of >50-100 Ω-m are observed in the vicinity of SNGPF and persist up to the NW flanks of Cuernos de Negros. The area around Cuernos de Negros exhibit higher values of >100 Ω-m. Further SE towards Dauin, surface resistivity varies from >50-100 Ω-m at DN-1 and Basalay Dome to >10-50 Ω-m around the town of Dauin and near the coast. Underlying the first layer are two low-resistivity horizons (≤10 Ω-m) separated by a narrow region of >10-50 Ω-m material beneath Cuernos de Negros. This layer of low-resistivity beneath SNGPF is generally thinner averaging 700 m thick, with the shallowest section in the vicinity of wells NJ-2D and NJ-4D. The low-resistivity horizon beneath Dauin is thicker and reaches a thickness of more than 4000 m near the coast. A shallow portion, however, is seen beneath the SE flanks of the Cuernos de Negros. At farther depth, two regions of increasing resistivity (>50-100 Ω-m) can be

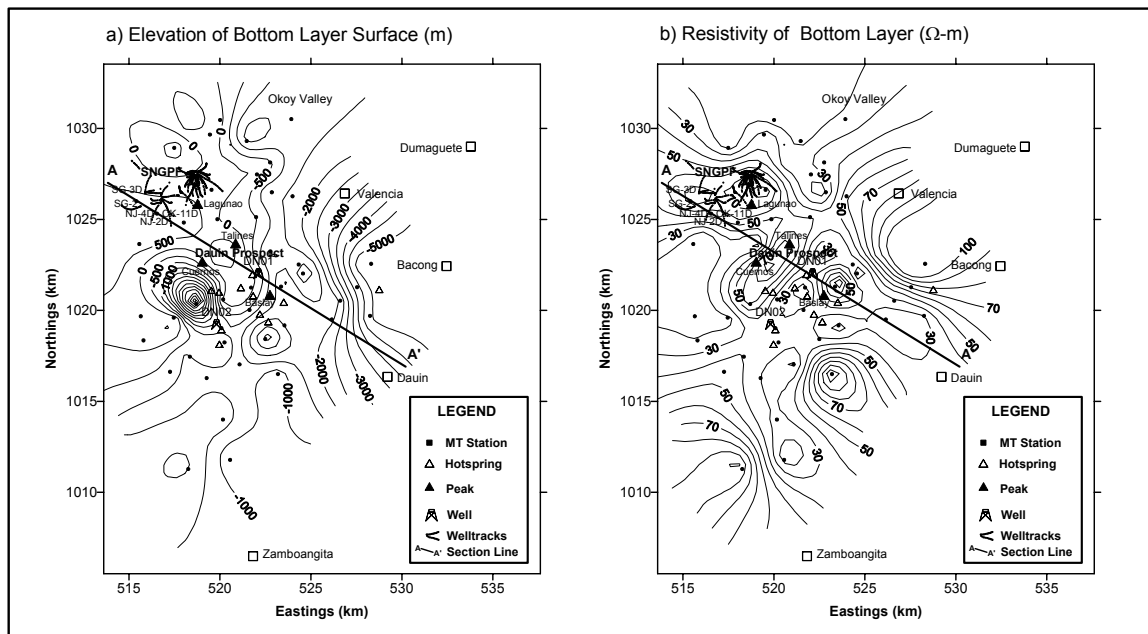


Figure 6. Surface elevation and resistivity of bottom layer at SNGPF and Dauin based on MT.

observed, underlying each of the two low resistivity bands. The $>50\text{-}100\ \Omega\text{-m}$ region with greater extent coincides with the production sector of SNGPF while the smaller one lies between the SE flanks of the Cuernos de Negros and Lipayo hot springs. A narrow zone of $>100\ \Omega\text{-m}$ resistivity appears at $\sim 2000\ \text{m}$ elevation further beneath Cuernos de Negros.

Isotherms from drillhole data at SNGPF indicate that higher temperatures of $180\text{-}280^\circ\text{C}$ are generally encountered within the $>50\text{-}100\ \Omega\text{-m}$ high-resistivity third layer (Fig. 6). In the Dauin prospect, a maximum temperature of 240°C was encountered at DN-1, which was drilled slightly beyond the southeastern periphery of the $>50\text{-}100\ \Omega\text{-m}$ zone.

Correlation with alteration mineralogy shows that the smectite (Sm) and illite-smectite (I-Sm) zones generally correspond with the conductive second layer ($\leq 10\ \Omega\text{-m}$) representing the conductive clay cap (Fig. 5). Illites (I), epidotes (Ep) and other high-temperature alteration minerals are found well within the $>50\text{-}100\ \Omega\text{-m}$ region in SNGPF, while epidotes are encountered in Dauin near the high to intermediate resistivity boundary (Zaide-Delfin and Ramos, pers. comm, 2003).

4.1.2 Plan Maps

Figure 6a illustrates the topography of the interface between the conductive clay cap ($\leq 10\ \Omega\text{-m}$) and the top of the relatively high-resistivity third layer ($>50\text{-}100\ \Omega\text{-m}$). It shows that the shallower occurrence of this interface generally lies in the NW quadrant where SNGPF is found. The production sector of SNGPF lies within the $500\ \text{masl}$ contour. Another region of shallow occurrence but of lesser extent can be observed SE of SNGPF and approximately centers around Mt. Talines. The surface dips outward, reaching levels of $>5,000\ \text{masl}$ beneath the town of Bacong in the east. A deep funnel-like depression occurs south of Cuernos de Negros, but this is based on a single station.

The Isoresistivity map of the bottom layer reveal two significant areas where $> 50\ \Omega\text{-m}$ values occur (Fig. 6b). These are: 1) the east-west trending $>50\ \Omega\text{-m}$ zone that lies over the production field of SNGPF, and 2) the SW-NE oriented region of high-resistivity, which coincides with the Dauin prospect.

The $>50\ \Omega\text{-m}$ resistivity anomaly in SNGPF becomes more significant because it occurs where the interface between the conductive clay cap and the zone of increasing resistivity is nearest to the surface ($>500\ \text{masl}$). This tallies with the typical resistivity model of a well-

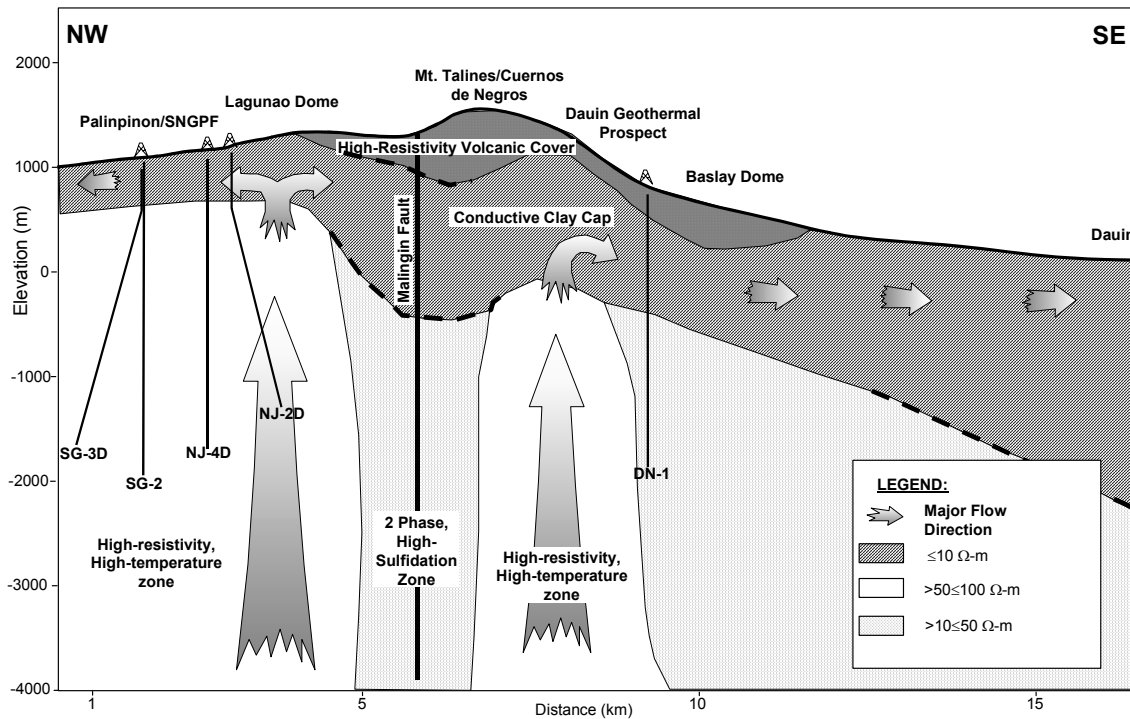


Figure 7. Proposed hydrogeophysical model of Palinpinon and Dauin based on MT.

developed geothermal system, in which the shallowest portion of the region of increasing resistivity most likely defines the configuration of the existing geothermal system. Similar MT resistivity signature was observed by Maneja, et al. (2001) over the Northern Negros Geothermal Project (NNGP), in the northern part of Negros Island and by Apuada and Rigor (2001) at Bacon-Manito Geothermal Production Field (BGPF) in Southern Luzon. Furthermore, the higher measured temperatures of 200-300°C encountered at elevations of -1000 m in SNGPF are generally found within the region of the >50 Ω-m anomaly and the shallowest occurrence of the interface between the conductive second layer and the high-resistivity bottom layer.

The other >50 Ω-m resistivity anomaly found in the Dauin prospect occurs at elevations comparable to SNGPF. Well DN-1 drilled at the periphery of the northwestern half of the >50 Ω-m zone encountered maximum temperature of 240°C. However, the southwestern portion is likely an outflow area as evidenced by the deeper interface between the conductive clay cap and the bottom layer and the lower temperature (180°C) and poor permeability encountered in well DN-2.

5.0 HYDROGEOPHYSICAL MODEL

The zone of increasing resistivity overlain by a layer of low-resistivity delineated in the production sector of the Palinpinon geothermal system is consistent with the typical resistivity signature of a well-developed geothermal system. The low-resistivity ($\leq 10 \Omega\text{-m}$) layer corresponds to the conductive clay cap where upflowing geothermal brine interacts with the surrounding rock to form clay alteration minerals such as smectite and illite-smectite. Illites and epidotes encountered in the hotter portion of Palinpinon correspond to regions of increasing resistivity (>50-100 Ω-m) and demonstrate how resistivity could define the high-temperature region in a geothermal system. The shallow occurrence of higher temperature near the center of the >50-100 Ω-m zone suggests that the area corresponds to the region where hot geothermal fluids flow upward and out towards the periphery. Similar trends were observed and proven to be correct in the Bacon-Manito Geothermal Production Field (BGPF) in Southern Luzon (Apuada and Rigor, 2001) and in the Northern Negros Geothermal Project (NNGP) in the northern part of Negros Island (Maneja, et al., 2001). Both models were derived from MT resistivity data.

The same trend observed in Dauin suggests that a distinct geothermal system is likely present in the area, separated from Palinpinon by a narrow region of intermediate resistivity (>10 - 50 Ω -m). The resistivity model is generally in good agreement with the model proposed by Ramos-Candelaria (pers. comm., 2002), wherein two convection systems developed in Palinpinon and Dauin, separated by a two-phase, high-sulfidation system. It is not unlikely, however, that the two convection systems share the same heat source at further depth (>4000 mbsl). The intermediate resistivity region (>50 Ω -m) separating the >50-100 Ω -m anomalies at Palinpinon and Dauin likely defines this two-phase system. The location of the zone of intermediate resistivity coincides with Malingin Fault, which transects the Cuernos Volcanic Complex. Malingin Fault could be the conduit to the proposed two-phase system that appear on the surface as "kaipohan" type of hydrothermal alterations such as the Kaipohang Daku to the NW of Mt. Talines (Fig. 2).

A hydrological model (Fig. 7) of Palinpinon and Dauin systems is proposed, wherein two geothermal convective systems exist, defined by the >50-100 Ω -m resistivity zones in Palinpinon and in the Dauin prospect. The upflow zone in Palinpinon possibly lies in the vicinity of Lagunao Dome where a maximum of 310°C was tapped at well OK-5 and outflows to the west near the Sogongon sector. The hot fluids likewise head towards the Okoy valley and Dumaguete to the NE. On the other hand, Mt. Talines possibly marks the central upflow region in Dauin, where the bottom of the conductive clay cap is shallowest (Fig. 7a). A major outflow from the Dauin system is directed to the SE, coinciding with the Lipayo Schlumberger resistivity anomaly, and a southwesterly outflow direction towards DN-2, where a thick layer of low-resistivity is delineated. The convection cells may be driven by just a single heat source at depth (>4000 m) or separate heat sources.

Based on the proposed hydrological model of SNGPF and Dauin, the geothermal system in Dauin probably lies beneath the center of the >50-100 Ω -m anomaly located between Mt. Talines and Cuernos de Negros (Figs. 6 and 7). Testing the model by deep drilling farther NW of DN-1 is recommended to determine the area's power potential.

REFERENCES

- Alicastre, R.S. (1982). Geology of Baslay-Dauin prospect. *PNOC-EDC Internal Report*, 24 p.
- Anderson, E., Crosby, D., and Ussher, G. (1999). As plain as the nose on your face: geothermal systems revealed by deep resistivity. *Proceedings 21st New Zealand Geothermal Workshop*, pp. 107-112.
- Apuada, N.A. and Rigor, D.M. (2001). The geothermal systems in the Bacon-Manito geothermal production field and Manito Lowlands as revealed by magnetotelluric method. *PNOC-EDC Internal Report*, 40 p.
- Bayrante, L.F., Hermoso, D.Z., Ramos-Candelaria, M.N., Pamatian, P.I., and Mejorada, A.V. (1997). Development potential of the Dauin geothermal prospect, Negros Oriental, Philippines. *Geothermal Resources Council Transactions*, vol. 21, pp. 609-615.
- Bromley, C.J. (1982). Baslay-Dauin resistivity survey: vertical electrical soundings interpretation report, southern Negros geothermal project. *PNOC-EDC Internal Report*, 7 p.
- Harper, R.T. and Arevalo, E.M. (1982). A geoscientific evaluation of the Baslay-Dauin prospect, Negros Oriental, Philippines. *Proceedings Pacific Geothermal Conference and 4th New Zealand Geothermal Workshop*; pp. 235-240.
- Layugan, D.B. and Maneja, F.C. (1992). Resistivity structure of the Southern Negros geothermal project, Negros Oriental. *PNOC-EDC Internal Report*, 12 p.
- Maneja, F.C., Los Baños, C.F., Layugan, D.B., Apuada, N.A., and Rigor, D.M. (2001). Magnetotelluric sounding in the northern Negros geothermal field, Central Philippines. *Journal of Geological Society of the Philippines Special Issue in Honor of Prof. Arturo P. Alcaraz*, pp 184-198.
- Pamatian, P.I. (1992). Surface structures and related thermal features in the south Lagunao and Baslay-Dauin sectors. *PNOC-EDC Internal Report*.

Ramos-Candelaria, M.N. (1992). Geochemical assessment of south Lagunao and Baslay-Dauin, SNGP. *PNOC-EDC Internal Report*, 16 p.

Reyes, A.G. (1983) Petrology of well Dauin-1 (revised), Baslay-Dauin, southern Negros geothermal project. *PNOC-EDC Internal Report*, 12 p.

Reyes, A.G. (1983). Petrology of well Dauin-2, Baslay-Dauin, southern Negros geothermal project. *PNOC-EDC Internal Report*, 10 p.

Tebar, H.J. and Pamatian, P.I. (1990). Fault structures at the southern Negros geothermal field. *PNOC-EDC Internal Report*, 13 p.

Ussher, G., Harvey, C., Johnstone, R, Anderson, E. (2000). Understanding the resistivities observed in geothermal systems. *Proceedings World Geothermal Congress 2000*, pp. 1915-1919.