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Hydro-Geophysical Model of the Southern Negros Geothermal Project, Central Philippines Based on Magnetotellurics Resistivity

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ABSTRACT

A geophysical investigation using magnetotellurics (MT) resistivity was conducted over the Southern Negros Geothermal Project in central Philippines. A 1-D layered resistivity modeling of the MT data resulted to the delineation of two high-resistivity anomalies (>50 - 100 Ω-m) overlain by a zone of low resistivity (≤10 Ω-m). One anomaly centers beneath Lagunao Dome, and defines the upflow center of the Southern Negros Geothermal Production Field in Palinpinon. A smaller anomaly on the other hand was delineated beneath Mt. Talines and Cuernos de Negros and is thought to describe a separate geothermal system, referred to as the Dauin prospect. The high-resistivity anomalies are associated with the presence of high temperature but low conductivity mineral alteration products such as illite, epidote, chlorite, etc. that dominate most geothermal systems. The low-resistivity (≤10 Ω-m) layer in turn is associated with clay hydrothermal alterations like smectite and illite-smectite normally occurring at regimes of intermediate temperatures (~70ºC).

1. INTRODUCTION

The Southern Negros Geothermal Project is situated at the southeastern tip of Negros Island in the west-central part of the Philippine archipelago. The Southern Negros Geothermal Production Field (SNGPF) in Palinpinon occupies the northwestern part of the project area, while approximately 6 km to the south lies the Dauin geothermal prospect (Fig. 1). The two lie on opposite flanks of the dormant volcanic complex that centers on Cuernos de Negros (1,800 masl). Attention for geothermal development was initially focused on Palinpinon geothermal field due to indications of higher subsurface temperature (>250^{o}C) and a more coherent hydrological model (Bayrante, 1997). To date, SNGPF generates almost 200 MWe of power from geothermal energy. Palinpinon Field will be used interchangeably with SNGPF in this paper to refer to the currently producing geothermal field in SNGP.

Substantial geoscientific investigation has been conducted over the Dauin prospect where two deep exploratory wells, DN-1 and DN-2 were drilled between the years 1982 and 1983. Well DN-1 encountered near neutral fluids with maximum temperature of 240ºC and reservoir Cl of 3,300 mg/kg, but also discharged a substantial amount of elemental sulfur, which prompted the well to be shut after discharging for only three days. Well DN-2, 4 km to the southwest of DN-1 was not discharged because of poor permeability and lower temperature (180ºC). The relatively high temperature encountered in DN-1 suggested the existence of a commercially viable geothermal system in the area and is the basis in the pursuit of further exploratory studies for its development.

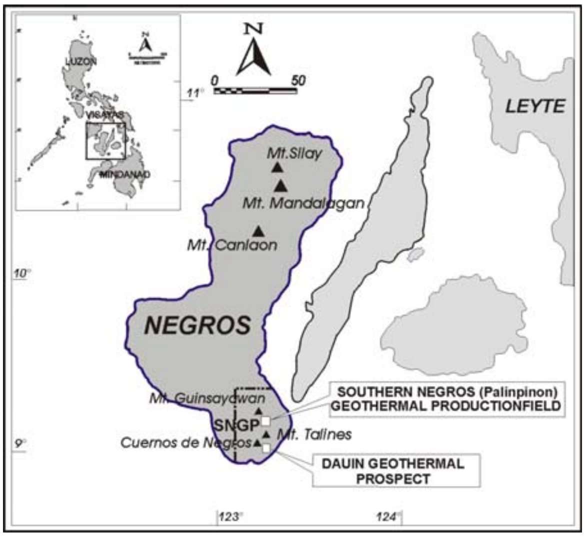

Figure 1: Location of the Southern Negros Geothermal Project.

Advances in computing technology hastened the development of magnetotellurics (MT) technology, which is now a foremost tool in the field of resistivity studies. It is favored in the field of geothermal exploration where the considered areas have distinctive resistivity properties. MT resistivity is derived from naturally induced currents by the time-dependent variations of the earth's electromagnetic field. Its advantage stems from its ability to acquire resistivity information at far greater depths than conventional resistivity methods. 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 comprehensive model of the geothermal system being studied. With this technology, a resistivity survey was programmed to investigate the Southern Negros Geothermal Project to determine its subsurface geophysical structure for the purpose of geothermal prospecting.

2. GEOLOGIC SETTING

The Southern Negros Geothermal Project is characterized by the overlapping volcanoes of Talines, Guinsayawan, and Cuernos de Negros. This group of dormant volcanoes forms the southern counterpart of andesitic-dacitic volcanic complexes dominating the island of Negros, and are aligned parallel to the northeast-southwest conjugate segment of the Philippine Fault. Mts. Mandalagan, Silay, and Canlaon comprise the volcanoes in the north (Fig. 1). The oldest exposed rocks in Palinpinon are volcanic sediments classified as the Southern Negros Formation (SNF), which are of late Miocene to Pliocene in age. The Dauin prospect

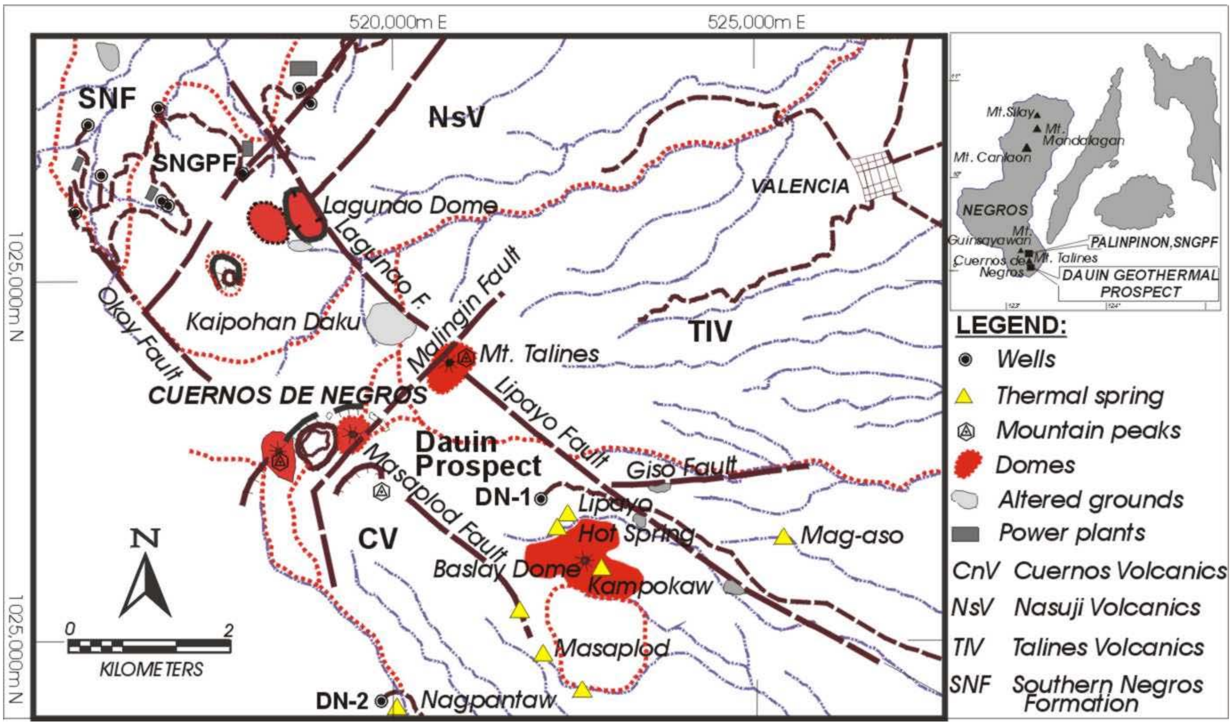

Figure 2: Surface geology and major fault structures in the Southern Negros Geothermal Project.

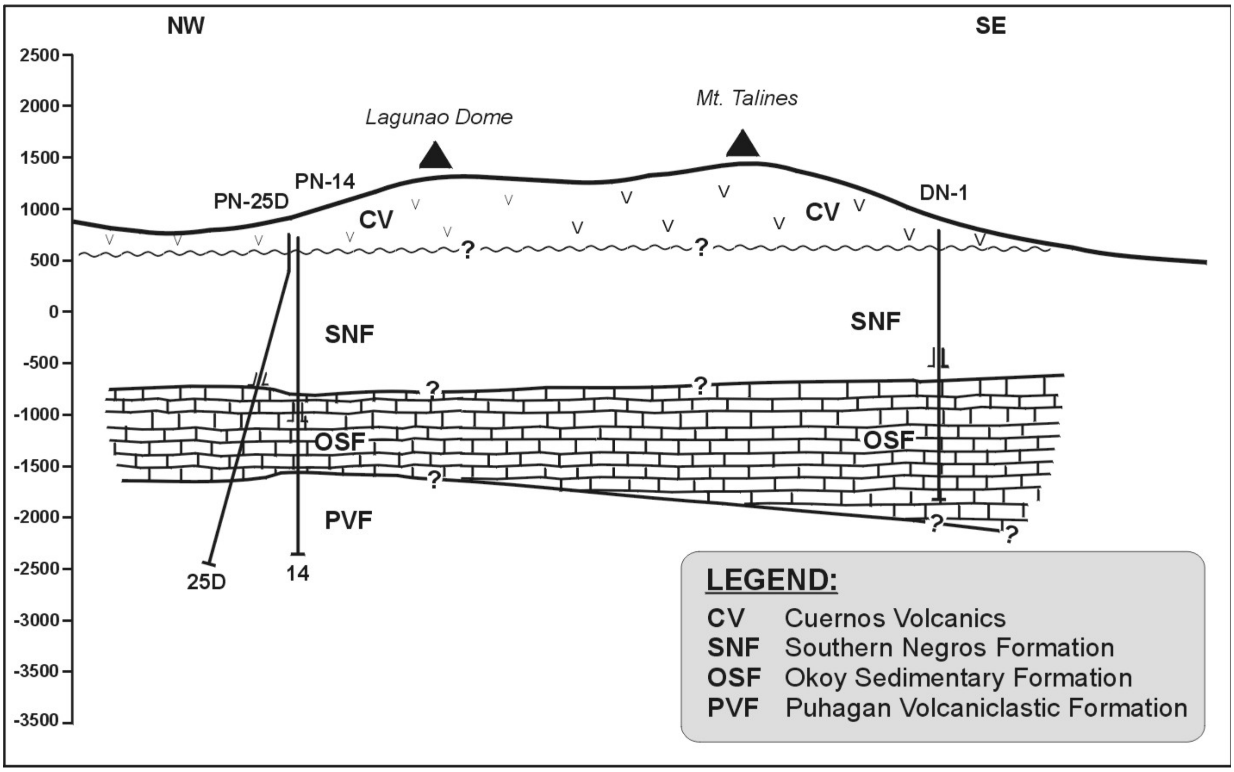

Figure 3: Generalized stratigraphy of SNGPF and Dauin Prospect, after Zaide-Delfin and Ramos, 2003.

on the other hand is generally covered with the effusives and extrusives of Cuernos de Negros (Alincastre, 1982). Geomorphologically towering within the project area are volcanic plugs and domes such as the Cuernos de Negros and Mt. Talines lying at the central point and Lagunao and Baslay Domes in the northwestern and southeastern flanks, respectively (Fig. 2).

The Southern Negros Geothermal Project is underlain by a suite of volcanic, sedimentary, and intrusive rocks ranging in age from Miocene to Recent (Fig. 3). These rocks were then intruded by andesite dikes that are related to the latest volcanism event. Table 1 gives a summary of the underlying lithologies in SNGP as encountered by drilling. 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

Table 1: Stratigraphy of the Southern Negros Geothermal Project, after Aniceto-Villarosa, 1988.

Formation	Age	Lithology
Puhagan Volcaniclastic Formation (PVF)	Early to middle Late Miocene (5.1 - 24.6 My)	Moderately to intensely altered interbedded andesite lavas, volcanic breccias, and sedimentary rocks.
Nasuji Pluton (NP)	Late Miocene (5.6 - 10.5 My)	Massive quartz monzo-diorite intrusive, with two events of intrusion.
Okoy Sedimentary Formation (OSF)	Early Pliocene	Fossiliferous calcisiltites, calcarenites, calcareous sedimentary breccia, andesitic volcanic breccia, and minor andesite lavas.
Southern Negros Formation (SNF)	Late Pliocene to Early Pleistocene	Undifferentiated highly alteredandesite lavas, hyaloclastites, and volcanic breccias.
Cuernos Volcanics (CV)	Early Pleistocene to Recent (0.0145 - 0.87 My)	Fresh to weakly altered hornblende two-pyroxeneandesite lava, tuff, and volcanic breccia, with minor dacite lavas.

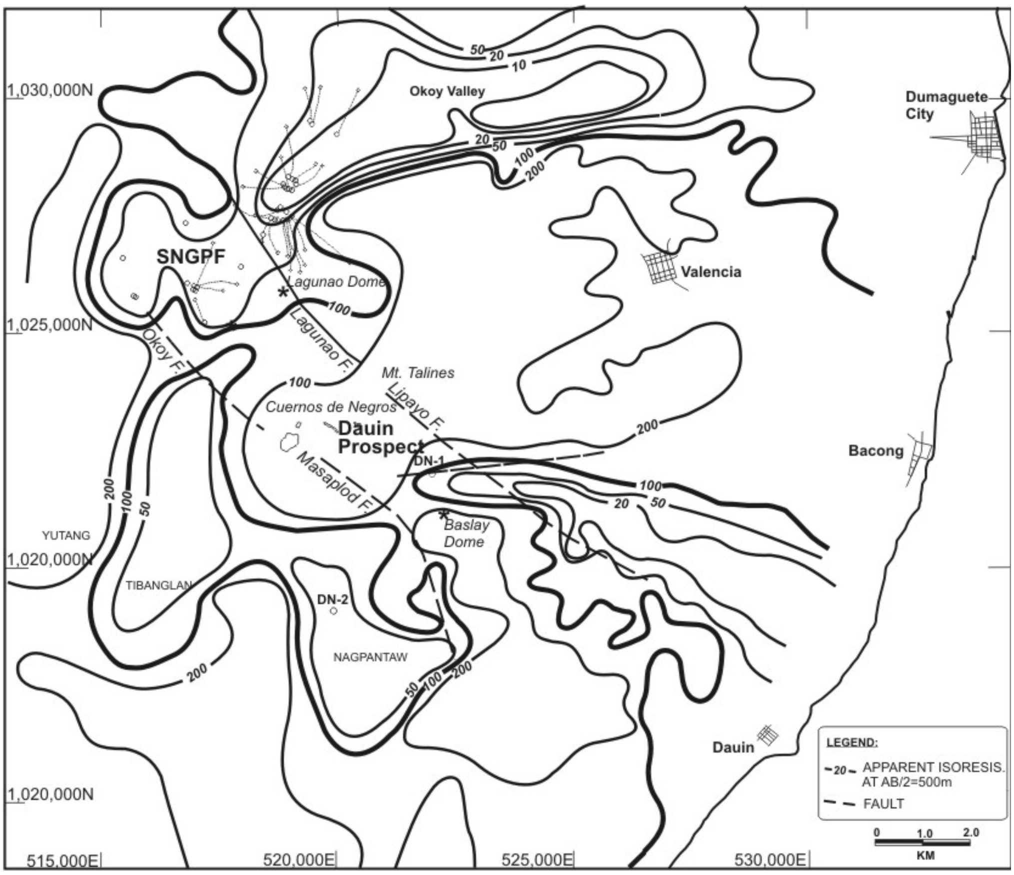

Figure 4: Apparent isoresistivity map of SNGP at AB/2=500m.

the two wells in Dauin but are suggested to be present, also at deeper levels (Bayrante, 1997).

Palinpinon Geothermal Field is transected by numerous fault structures to which field permeability is attributed. Outstanding are the west-northwesterly system of faults, which appear to control the field's hydrology. In Dauin, the Lipayo and Masaplod fault structures are thought to control the distribution of local thermal features (Fig. 2). The southeast 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. These faults are correlated with those found in Palinpinon, where the Lipayo and Masaplod Faults are thought to be respective extensions of Lagunao and Okoy Faults transecting SNGPF in the northwest.

3. PREVIOUS GEOPHYSICAL STUDIES

The Commission on Volcanology (COMVOL) conducted Schlumberger resistivity traversing (SRT) survey in the Southern Negros Geothermal Project as early as 1973. From 1975 to 1976, PNOC-EDC and Kingston Reynolds Thom and Allardice (KRTA) conducted extensive D.C.

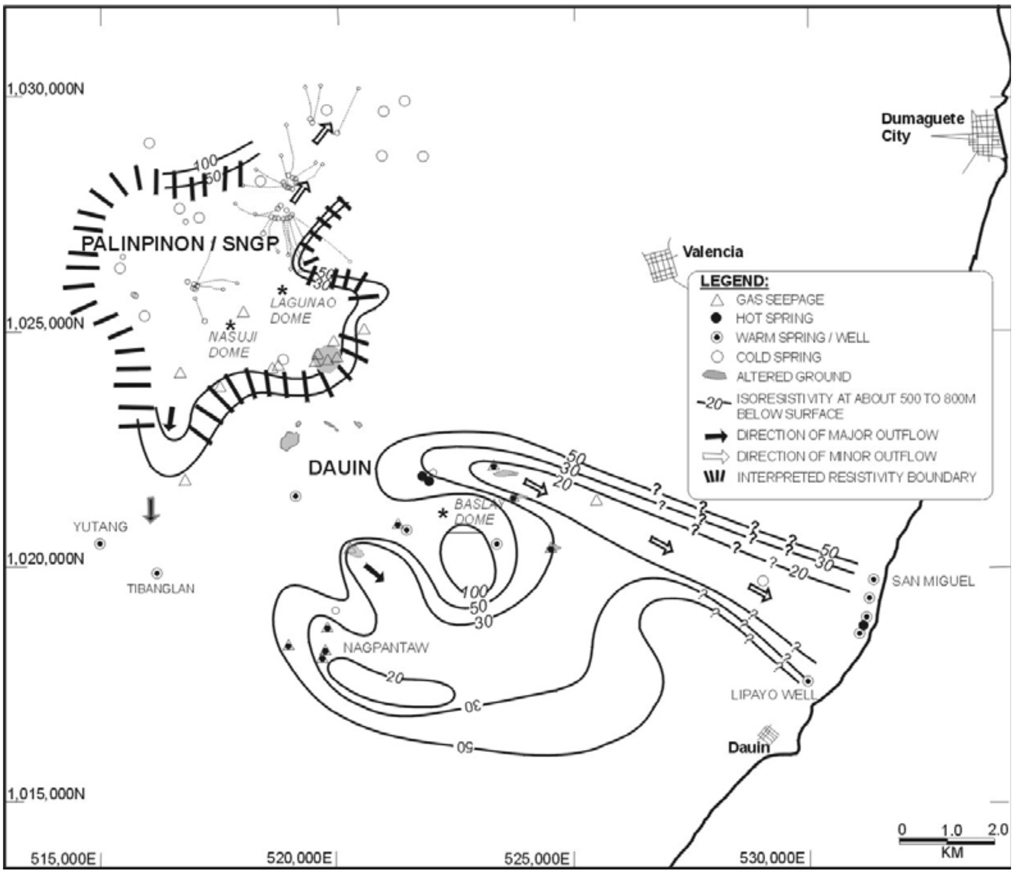

Figure 5: Isoresistivity of bottom layer at about 500-800 m depth of SNGP, after Layugan and Maneja, 1992.

resistivity survey in the area. Three distinct low-apparent resistivity anomalies (≤50 Ω-m) were delineated. The largest anomaly mapped was associated with the Palinpinon geothermal system. The two relatively smaller anomalies were mapped in the then Baslay-Dauin prospect, where 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)(Fig. 4).

Vertical electrical sounding (VES) measurements were also conducted over the area in early 1982 and in 1992 (Fig. 5). The incorporated data of the two surveys revealed low resistivity values of <50 Ω-m at depth south of Lagunao and Nasuji Volcanic Domes and the Kaipohan altered grounds. It also resulted to the delineation of a significant low resistivity anomaly of <30 Ω-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 and Maneja, 1992).

4. MAGNETOTELLURICS 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. Single-station method was employed using the Phoenix™ V5 MT System for data acquisition.

The sounding data were generally of good quality. Soundings gathered during rainy weather, however, were often of poor quality; repeat measurements were therefore conducted whenever necessary. 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 approximately N45°E were modeled using the 1-D Marquardt layered inversion.

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)

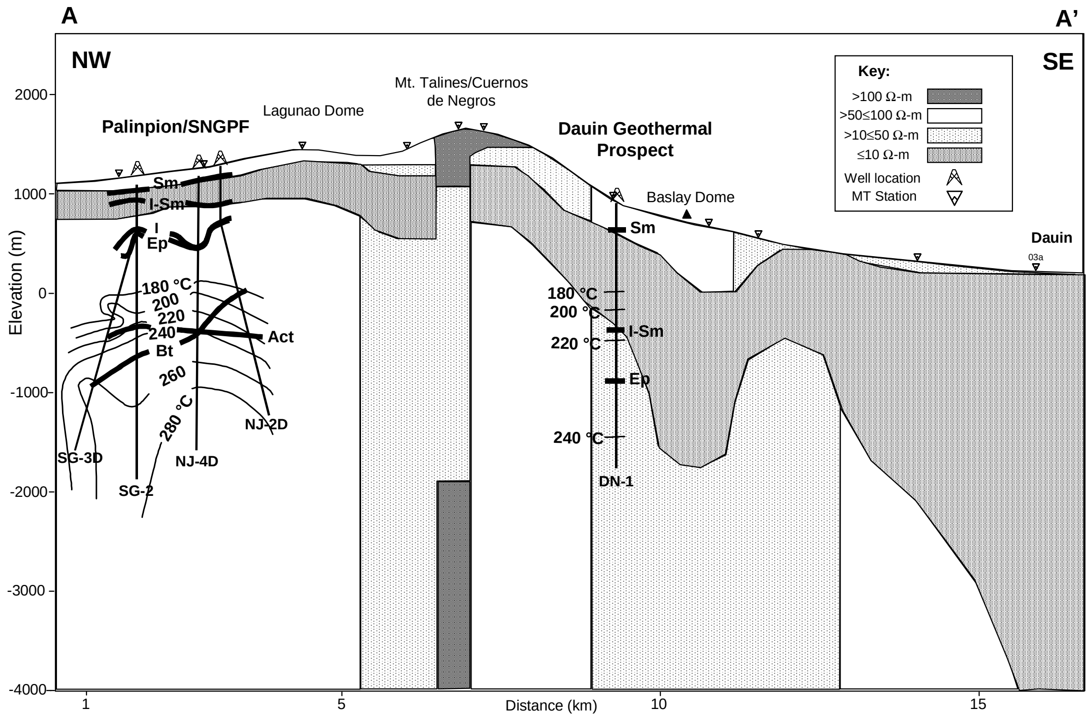

Figure 6: Vertical resistivity distribution along sectin AA', based on magnetotellurics.

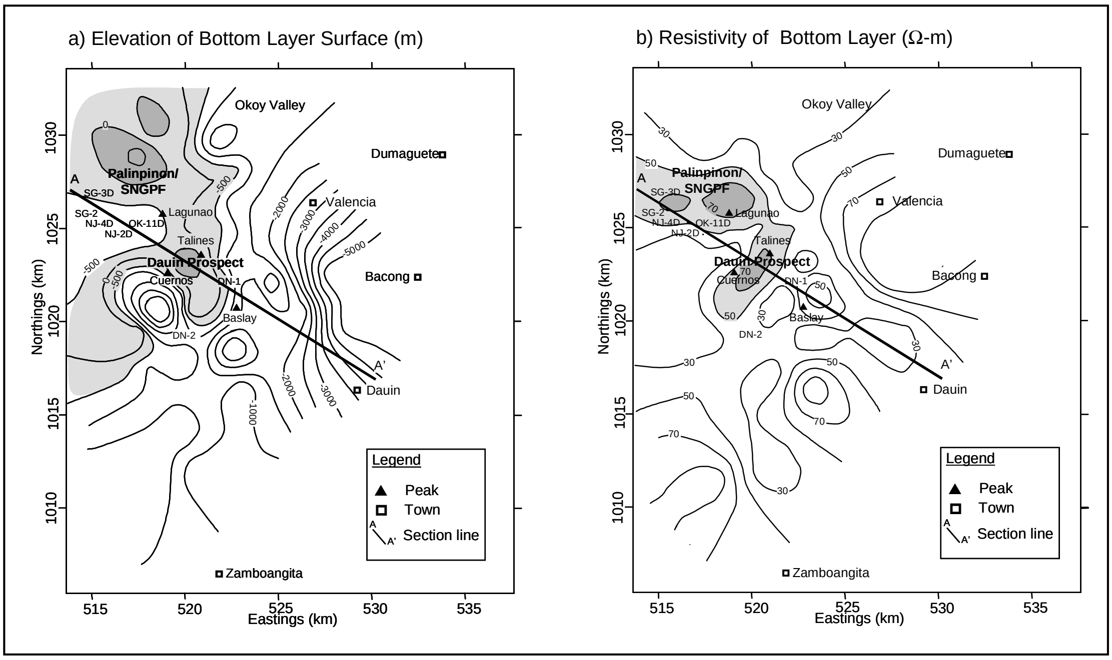

Figure 7: Surface elevation and resistivity of bottom layer at SNGP, based on magnetotellurics.

where high-temperature alteration minerals like illites and epidotes are normally formed (Anderson, et. al, 1999).

Section AA' passes from the Sogongon sector of SNGPF in the northwest, across Cuernos de Negros and is oriented towards the Dauin prospect, along the trace of the Lipayo Schlumberger resistivity anomaly in the southeast (Figs. 6 and 7). It cuts through wells SG-3D, SG-2, NJ-4D, and NJ-2D in the SNGPF, and DN-1 in Dauin. Surface resistivity values of >50-100 Ω-m are observed in the vicinity of SNGPF and persist up to the northwestern flanks of Cuernos de Negros. The area around Cuernos de Negros exhibit higher values of >100 Ω-m. Farther southeast, surface resistivity varies from >50-100 Ω-m at DN-1 and Baslay 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 beneath Cuernos de Negros by a narrow region of >10-50 Ω-m material. This layer of low-resistivity beneath SNGPF is generally thinner averaging 700 m thick, with the shallowest portion 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 southeastern flanks of the Cuernos de Negros.

At farther depth, two regions of increasing resistivity (>50-100 Ω-m) can be observed, underlying each of the two low resistivity bands. The >50-100 Ω-m region with greater extent coincides with the production sector of SNGPF while the smaller one lies between the southeastern flanks of the Cuernos de Negros and Lipayo hot springs. A narrow zone of >100 Ω-m resistivity appears at -2000 m elevation further beneath Cuernos de Negros.

Isotherms from drillhole data at SNGPF indicate that higher temperatures of 180-280°C are generally encountered within the >50-100 Ω-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 >50-100 Ω-m zone.

Correlation with alteration mineralogy shows that the smectite (Sm) and illite-smectite (I-Sm) zones generally correspond with the conductive second layer (≤10 Ω-m) representing the conductive clay cap (Fig. 6). Illites (I), epidotes (Ep) and other high-temperature alteration minerals are found well within the >50-100 Ω-m region in SNGPF, while epidotes are encountered in Dauin near the high to intermediate resistivity boundary (Zaide-Delfin and Ramos, 2003).

4.1.2 Plan Maps

Figure 7a illustrates the topography of the interface between the conductive clay cap (≤10 Ω-m) and the top of the relatively high-resistivity third layer (>50-100 Ω-m). It shows that the shallower occurrence of this interface generally lies in the northwest quadrant where SNGPF is located. The production sector of SNGPF lies within the 500 masl contour. Another region of shallow occurrence but of lesser extent can be observed southeast of SNGPF and approximately centers around Mt. Talines. The surface dips outward, reaching levels of >5,000 mbsl beneath the town of Bacong in the east. A deep funnel-like depression occurs south of Cuernos de Negros, but is based on a single station anomaly.

The Isoresistivity map of the bottom layer reveal two significant areas where > 50 Ω-m values occur (Fig. 7b). These are: 1) the east-west trending >50 Ω-m zone that lies over the production field of SNGPF, and 2) the southwest-northeast oriented region of high-resistivity, which coincides with the Dauin prospect.

The >50 Ω-m resistivity anomaly in SNGPF is significant because it lies where the interface between the conductive clay cap and the zone of increasing resistivity is nearest to the surface (>500 masl). This tallies with the typical resistivity model of a well-developed geothermal system, in which the shallowest portion of the region where the resistivity increases most likely defines the geothermal system. Similar MT resistivity signature was observed by Maneja, et al. (2001) over the Northern Negros Geothermal Project (NNGP), north of Negros Island and by Apuada and Rigor (2001) at Bacon-Manito Geothermal Production Field (BGPF) in Southern Luzon. Furthermore, higher measured temperatures of 200-300°C 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 >50 Ω-m resistivity anomaly found in the Dauin prospect occurs at elevations comparable to that of SNGPF. Well DN-1, drilled at the periphery of the northwestern half of the >50 Ω-m zone encountered maximum temperature of 240˚C. The southwestern portion probably is an outflow area as evidenced by the deeper interface between the conductive clay cap and the bottom layer. This concept is augmented by the fact that lower temperature (180˚C) and poor permeability were encountered in well DN-2.

5. CONCLUSIONS

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 (≤10 Ω-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 MT resistivity defines 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). It is not unlikely, however, that the two convection systems share the same heat source at farther depth (>4000 mbsl).

A hydro-geophysical model (Fig. 8) of the Southern Negros Geothermal Project is proposed, wherein two geothermal convective systems exist, defined by the >50-100 Ω-m resistivity zones mapped in Palinpinon and in the Dauin prospect. The upflow zone in Palinpinon possibly lies in the vicinity of Lagunao Dome where a maximum of 310ºC 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 northeast. 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 southeast, coinciding with the Lipayo Schlumberger resistivity anomaly, and a southwesterly outflow direction towards DN-2, where a thick layer of low- resistivity is delineated. This theory however does not discount the possibility of a single heat source fuelling the two convective cells at farther depths (>4000 bsl).

Present data indications warrant drilling of another exploratory well in Dauin as the next step towards its development as a possible producing geothermal field.

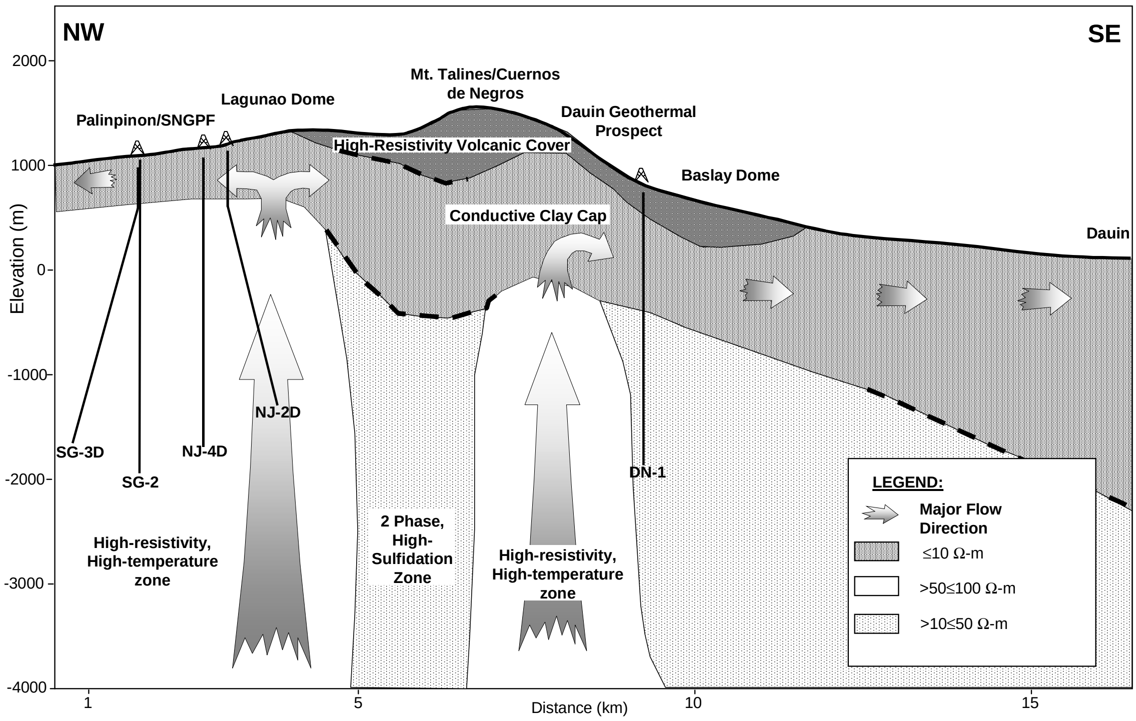

Figure 8: Proposed hydrogeophysical model of SNGP, based on magnetotellurics resistivity.

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