Magnetotelluric (MT) and Gravity Measurements in the Northern Negros Geothermal Field, Mt. Canlaon, Central Philippines

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Abstract

The observed broad positive gravity anomaly located at the center of the survey area is believed to be associated with the Canlaon Volcanic Complex. This anomaly is modeled to be a single diorite body at depth below 6 km that branched into three smaller bodies as it moved nearer the surface intruding the sedimentary deposits of the ***Basak,*** *Talave and Caliling Formations. In between the two* ***of*** *the three modeled smaller bodies lies the Northern Negros geothermal system delineated by the –10 ohm-m resistivity anomaly defined by the magnetotelluric (MT) survey. The – 10 ohm-m isoresistivity contour at a depth of 2500, appear to be commonly bounded to the north by the 12 mgal gravity and the 50 to 130 ohm-m isoresistivity contours. The steep gravity gradient near the positive gravity peak possibly define a northwest trending structure that may serve as the southern boundary of the hydrothermal system.*

Among the recently drilled wells, PT-2D appears to be closest to the upflow region. HG-1D and CT-1D that show relatively poorer permeabilities are probably drilled at the edge of the reservoir nearer the interpreted high density intrusive body. PT-3D designed to penetrate the ***low*** *resistivity anomaly defined by MT data is targetting the postulated center of resource.*

MT and gravity data suggest that the resource is hosted by the Caliling/Talave Sedimentary Formation.

1.0 Introduction

Geoscientific studies of the Northern Negros Geothermal Project (NNGP) located in north central Negros Island (Fig 1), were started in **1973** when the then Commission on Volcanology (now Philippine Institute of Volcanology and Seismology, PHIVOLCS) made a reconnaisance **survey** of the Mambucal area. Follow-up investigations were conducted by the National Power Corporation and subsequently **by** PNOC-EDC with assistance from the New Zealand's Department of Scientific and Industrial Research **(DSIR)** and the consulting company Kingston Reynolds **Thom** and Allardice **(KRTA ,** now KML).

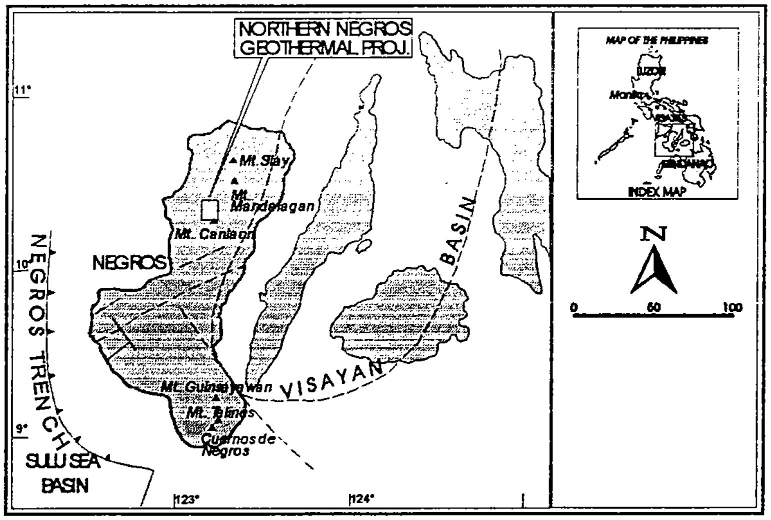

Figure 1. *Location map of the Northern Negros Geothermal Field.*

Two exploratory wells, MC-**1** and MC-2, drilled in **1978** to depths **of** ~ **1400 m** within the delineated Schlumberger resistivity anomaly confirmed the presence of near-neutral pH **fluids** with chloride

(CI) contents of about 8400 mg/kg, and temperature of ~ 200 °C. Temperature trends from the hvo wells suggest a hotter portion of the geothermal system (> 250 "C) exist southeast of the drilled wells. Deposition of calcite blockages in both wells forced the temporary abandonment of the project.

Further studies conducted by Alincastre (1983), Pornuevo (1988), Gerardo (1990). Layugan and Apuada (1992), and Pamatian et al. (1992) led to deep exploratory dnlling of wells HG-ID, PT-1D, PT-2D and CT-1D in 1994. HG-1D encountered temperature of 230 "C and was able to sustain discharge for one month producing neutral-pH water with Cl contents of 13,000 mg/kg. The highest temperature (–250 "C) was measured near the vicinity of PT-2D, a replacement well of IT-ID which had to be abandoned due to irreparable casing break. Although PT-2D was also discharged for about a month, its bore output was sub-commercial.

In 1995. with the granting of a Special Assistance for Project Formation (SAPROF) by the Overseas Economic Cooperation Fund (OECF) of Japan, magnetotelluric (MT) and misse-a-la-masse (MAM) surveys were conducted in NNGP. The resistivity anomalies defined by these surveys, particularly MT. were the targets of the new wells (PT-3D, PT-4D) currently being dnlled in the area. To complete and better define the geophysical model of the field. a regional gravity survey was conducted from December, 1995 to April. 1996.

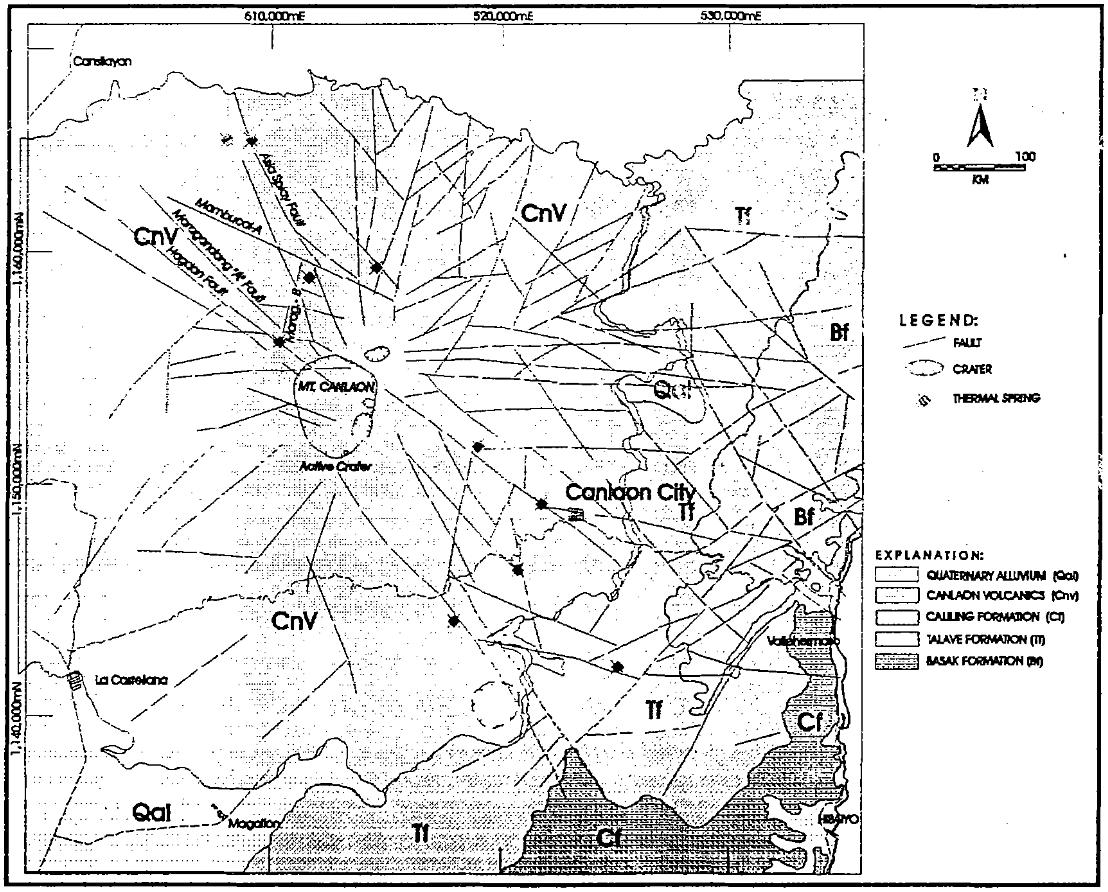

Figure 2. Simplified Geologic Map of Mt. Canlaon. (after Pamatian et al., 1992)

2.0 Brief Geologic Background

The structural setting of Negros Island is mainly controlled by the subduction of Sulu Sea oceanic crust underneath the Negros Trench (Fig 1). Shallow- to intermediatedepth hypocenters suggest that the underthrusting has penetrated to a depth of 150 km (Acharya and Agganval. 1980). This tectonism resulted in the formation of the Negros Volcanic Arc- a northeasterly alignment of Quaternary volcanic chain composed of Mts. Silay, Mandalagan and Canlaon in the north and Cuernos de Negros, Guinsayawan and Talines in the south (Fig. 1).

The geologic map of Mt. Canlaon is shown in Figure 2. The Cretaceous-Paleogene Basak Formation (Bf) outcropping along the eastern coast is the oldest rock unit mapped in the region. Pamatian et al. (1992) describe this unit as a very thick interbedded sequences of two-pyroxene basalt lavas and clastic sedimentary rocks composed of mudstones, claystones, and granule conglomerates. Overlying the Basak Formation is the Miocene Talave Formation (Tf) consisting of an interbedded sequence of recrystallized fossiliferous coralline limestone, sandstone, siltstone, claystone, conglomerate, and volcaniclastic breccia (PNOC-EDC, 1995). Previous workers have identified all the sedimentary units intersected by NNGP wells to be associated with the Tf. Recently however, Zaide-Delfin (1996) using Hayashi's (1996) zircon studies, inferred that Tf was probably penetrated only by well CT-ID. She proposed that overlying the Tf is the Pliocene limestones of the Caliling Formation (Cf) which has a maximum thickness of about 1000 m as intersected by CT-ID. These limestones are moderately fossiliferous and are interbedded with andesite and microdiorite breccias, sandstones and finer grained clastics. The youngest stratigraphic unit in NNGP is the Pleistocene-Recent Canlaon Volcanics (CnV) that consist in the wells of a thin layer of andesite lavas underlain by a thicker pile of tuff breccias with. subordinate amount of dacite and basaltic lavas.

Thermal areas are concentrated along the NW-SE alignment and signify that the most permeable structures in the area are oriented along this direction. Some of these NW-SE-trending faults were positively identified to be controlling the major permeable zones of the drilled wells. The most permeable zone in PT-1D is believed to be related with the Mambucal "A' Fault. Permeability of wells HG-1D and CT-ID, on the other hand, were mostly associated with the Maragandang B Splay and Asia Faults, respectively.

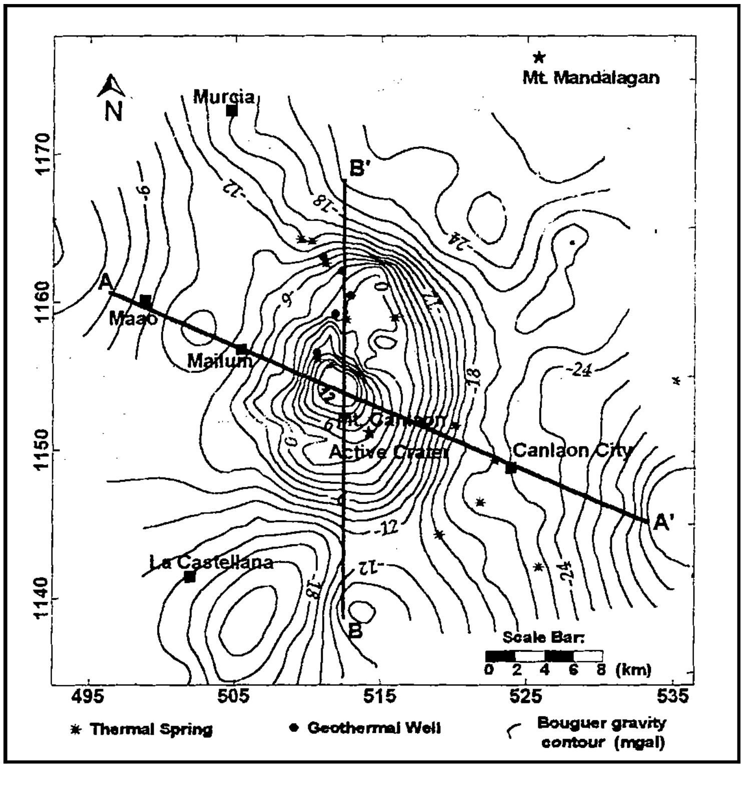

Figure 3. Total Bouguer gravity anomaly map.

3.0 Results of the gravity survey

Four-hundred twenty-eight (428) gravity stations were occupied using a La Coste and Romberg G-277 gravimeter. Single based altimetry method was used to calculate station elevation utilizing two Baromec microbarometers. Surface samples representing various stratigraphic units were collected for density measurements. A reduction density of 2.3 g/cc, the mean density value of all rock samples, was used in the 2.5D gravity modeling.

The total Bouguer gravity anomaly map is shown in Figure 3. A prominent 12 mgal gravity peak is mapped northwest of the active crater. Three gravity lows were identified - one in the east near Canlaon City, one in the northeast located southwest of Mt. Mandalagan and the other to the south near La Castellana.

Regonal gravity trend (not shown) shows a decreasing gravity gradient towards the east. This decreasing gradient is postulated to reflect the general eastward thickening of the sedimentary deposits as shown in the gravity profile P01 (Fig. 4A). Profile P02 (Fig. 4B) is a N-S section line that passes along the broad gravity high from well MC-1 to the north and up to 4 km SSW of the active vent in the south. The broad positive anomaly is modeled to be a single diorite body at depth of 8 km that branched into three smaller bodies as it intruded the sedimentary and volcanic pile closer to the surface. The depths of the northerly aligned smaller bodies vary from 4 to 1 km below the surface. The deepest intrusive body modeled beneath CT-1D and MC1 is coincidentally overlain by the uplifted Tf/Cf penetrated by the two wells. The shallowest body is about 3.5 km NW of the active vent.

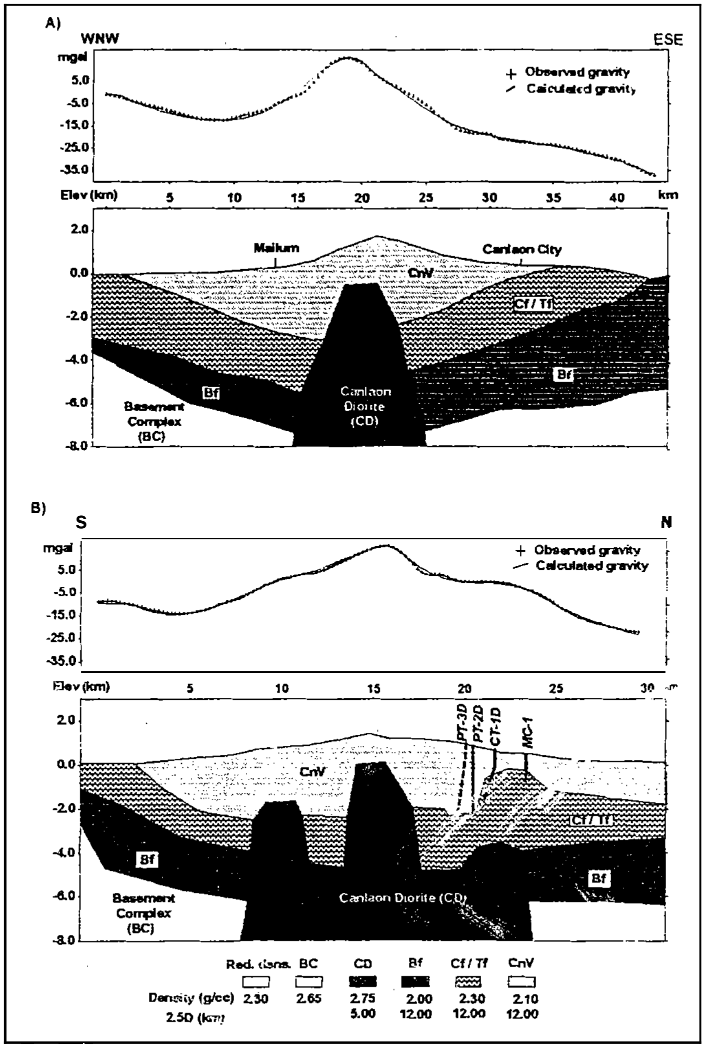

Figure 4. *Two and one-half dimensional gravity model along A) Cross section A - A' and B) Cross section B - B'. (Polygon densities and half-strike lenghts are shown below model base. Section lines are drawn in Fig. 3).*

Figure 5 highlights the identified gravity anomalies. The most prominent among them is the broad positive gravity anomaly at the center of the surveyed area interpreted to be a diorite body most probably associated with the CVC. The regional gravity gradient shows a thickening of the sedimentary deposits towards the east coincident with the western edge of the Visayan Basin. The lowest residual gravity contoured in the easternmost part of the survey area represents the mapped Basak Formation that has the least measured density of 2.0 g/cc among the stratigraphic units. The other less prominent gravity anomalies were the relatively low gravity southwest of Mt. Mandalagan and east of La Castellana that are modeled to be thick alluvial and pyroclastic materials. To the east of these gravity lows are two moderately high residual gravity that correspond to the exposed Talave Formation that has a higher density of 2.3 g/cc compared to the 2.1 g/cc of CnV. The residual gravity high of >4 mgal west of Maao is interpreted to be the thinning of the volcanics and sedimentary deposits towards the west. and the consequent rise in the basement complex.

4.0 Results of the Magnetotelluric Survey

Thirty-five stations were occupied during the MT survey conducted from July 18 to August 13, 1995 using Phoenix Geophysics Ltd. V5 Receiver and SPV5 Sensor Processor. The sounding sites were located mostly on the southwest flanks of Mt. Canlaon and were selected based on previous Schlumberger survey results. The recorded time-series electromagnetic data were robust processed using far-remote reference technique

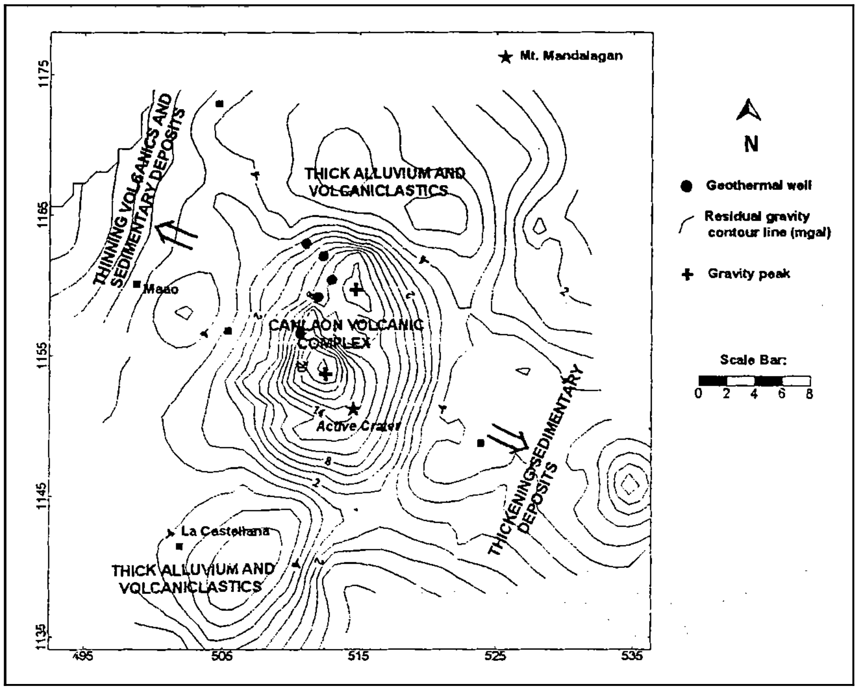

*Figure 5. **Gravity interpretation sunnary based on the residual Bouguer** gravity anomaly.*

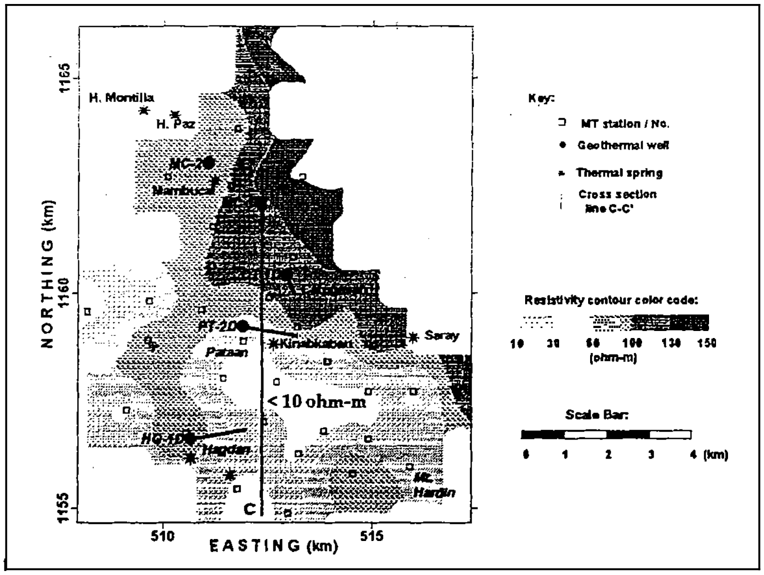

Figure 6. Isoresistivity map at about 2500 m depth.

The results of the MT survey is presented in the form of contours of the resisitvity layers at depth of about 2500 m (Fig. 6). The resitivity layers were derived from one-dimensional Marquardt inversion of the MT curves using Geotools software.

The map on Figure 6 shows a prominent 10 ohm-m resistivity anomaly mapped upstream of Pataan. The anomaly is bounded by steep resisitvity gradient in the northwest near Kinabkaban warm spring and in the souhwest near the Hagdan thermal areas. Mambucal and Catugasan areas where wells MC-1, MC-2 and CT-1D were drilled, reveal relatively higher resistivity values of <100 -

150 ohm-m. However. these high resistivity values are overlain by low resistivity layer of <10 - 20 ohm. MT-stations located further southeast near Mt. Hardin consistently eshibit relatively high resistiviy values of <50 - 150 ohm-m from the surface down to depths of >3000m.

5.0 Geophysical model of the Northern Negros Geothermal System

The geophysical model of the Northern Negros geothermal system is based on the results of the MT and gravity surveys which are best summarized in Figures 6 and 7.

The outline of the geothermal resource could roughly be represented by the 10 ohm-m resistivity contour. The resource is sandwiched by two positive gravity peaks located in the northwest and southwest (Fig. 5). These positive gravity peaks are attributed to the combination of the high density (2.3 - 2.75 g/cc) rocks of the Talave/Caliling Formation and the Canlaon Diorite. The northwest trending Mambucal "A" and Hagdan Faults provide the margins of the resource. These two faults also coincide with the edges of the two gravity peaks and probably define a graben which is clearly shown in Figure 7.

The geothermal system in NNGP is probably centered beneath the thickest low resisitvity layer (Fig. 7). The upflow of geothermal fluids within the center of the resource alter the low density Canlaon Volcanics. which gives rise to the low resistivity layer. Outflows to the north-northwest feeding the springs of Mambucal, Hacienda Montilla, and Hacienda Paz could be provided by the thinning low resistivity Canlaon Volcanics and channeled along the Asia Splay Fault. (Fig. 2). The intermediate resistivity layer values of ≤ 15 ohm-m beneath station MT-32 may provide the resistivity boundary to the south. The heat source of the present geothermal system could be associated to the cooling intrusive body related to the Canlaon Volcanic Complex. The large circular gravity high in Figure 5 could reflect this intrusive body.

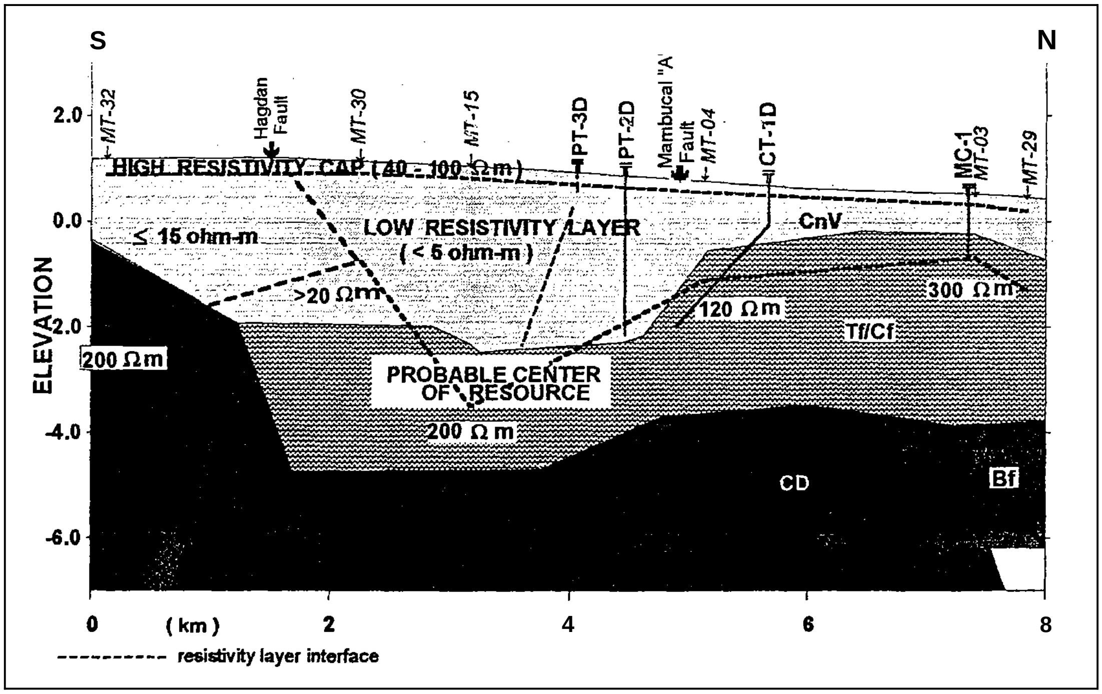

Figure 7. ***One-dimensional resistivity model (Marquardt inversion) on 2.50 gravity model along profile P03. (section line is drawn in Fig, 5)***

The general trend of the resistive basement delineated **by** the 1-D resistivity model generally correlates with the high density rocks of the Talave/Caliling Formation and the Canlaon **diorite body.** From a depth of of about 5 km at the middle **of** the profile, the resistive basement abruptly shallows to the north beneath CT-ID and MC1 coinciding with the uplifted Tf/Cf and **is** underlain **by** the the modeled intruding diorite *body.* This indicates that CT-1D is probably drilled at the edge of the geothermal reservoir while PT-1D showing a better permeability seems to be closer to upflow zone.

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