A GRAVITY INVESTIGATION OF THE SOUTHERN LEYTE GEOTHERMAL PROSPECT

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Abstract

A gravity investigation was undertaken in and adjacent to the Southern Leyte Geothermal Prospect. 'This work was done in conjunction with a detailed geologic and geochemical resurvey inorder to reevaluate the geothermal resource potential of the area. The residual gravity map displays a large central positive anomaly with at least two superimposed smaller positive anomalies. A shallow intrusive beneath the edifice of Mts. Cabalian anti Cantodoc, and a dense dike-like body west-northwest of the volcano, identifed on the surface as a probable microdiorite body, may be the cause of the positive gravity anomalies superimposed on the main anomaly. Ultramafic rocks which had risen to shallow depths as a result of faulting and uplift is responsible for the positive anomaly in the extreme west-southwestern port of SLGP. Two-dimensional models to explain the local gravity anomalies indicate a near horizontal sequence of old volcanics and sediments overlying an ultramafic basement. The main heat source for the geothermal phenomena in SLGP is apparently the broad and most recent intrusion which feeds the eruption vent of Mt. Cabalian. The host rocks consisting of less dense volcanics and Tertian, sediments most likely comprise the reservoir rocks of the postulated hydrothermal system at **SLGP.**

.1.0 INTRODUCTION

A regional gravity survey was conducted at the Southern Leyte Geothermal Prospect (SLGP) from May to September 1996. **A** total of **8** base stations and 238 gravity stations were occupied. covering an area of about 530 sq.km. Together with a detailed geologic and geochemical resurvey of the area. these recent investigations were intended to follow up an integrated geoscientific study conducted in 1989 to reassess the postulated geothermal resource of the prospect area. The purpose **of** the gravity survey was to delineate any anomaly field present and to interpret it in terms of subsurface structure as well as try to locate the source and distribution of the hydrothermal resource at Southern Leyte.

2.0 GEOPHYSICAL, SETTING

2.1 Seismicity of the Southern Leyte Geothermal Prospect

The Southern Leyte Geothermal Prospect lies in a region characterized **by** a high level of seismic activity. Earthquakes observed in this area are attributed to either active subduction processes along the Philippine Trench to the east, or to movements along the Philippine Fault Zone. Historic records show that the area has experienced at least one large magnitude earthquake (1907, Intensity X, located in Cabalian Bay) as well as several undocumented shocks **of** intermediate magnitude in more recent times, from 1960 thru 1980 (Daligdig and Besana, 1991; Lanuza, et **al,** 1994). A number of shallow (0-10 km) and intermediate (10-20 km) **depth** earthquakes have been observed ever since **a** more dedicated seismic monitoring was started at SLGP **by** the Philippine Institute **of** Volcanology and Seismology (PHIVOLCS) after a seismic swarm in May 1991. Two moderately large magnitude earthquakes **had** occurred recently near **SLGP:** on 06 May 1991 (M=5.8) centered in the Cabalian Bay and on 05 July 1994 (Ms=6.2) placed at 8 km north-northeast of Libagon, Southern Leyte.

Preceding the 05 July 1994 main shock, positions and depths of possible forerunning events were fairly constrained with the deployment of additional portable seismographs around Mt. Cnbnlian (Lanuza, et al, 1994). A summary plot of foreshock activity located by the PHIVOLCS seismic array from 08 March thru 27 April 1994 is exhibited in Figure 1. This seismic data set was used and plotted to provide **us** with background statistics in a preliminary attempt to delineate active fault zones which have the potential of channeling geothermal fluids to the surface. Allowing for uncertainties in the position of the epicenters, it was found that about 70% of the shallow earthquakes occurred beneath the Ginapugan and Patong areas, some 7 km north-northwest of Mt. Cnbnlian. Epicenters cluster along a set of parallel, north-south trending faults and have assigned depths of 0 - 15 km, thus supporting the inference that these earthquakes were probably induced by tectonic forces rather than being volcanic in nature. The proposed contract service area' designated by PNOC-EDC was not characterized by any unusual seismic activity as very **few** earthquakes were located within the bounds **of** the delineated geothernial area.

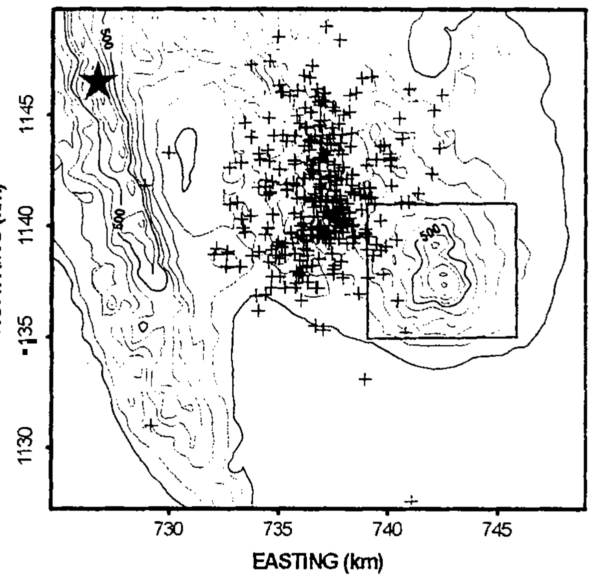

Figure **1.** Plot of epicentral events preceding the 05 July 1994 earthquake (Ms=6.2).

2.2 Resistivity Studies

A geophysical study at SLGP, consisting of direct current methods and electrical soundings to map out lateral and vertical variations in apparent resistivity, was conducted in early 1989 by PNOC-EDC. These surveys outlined at least two zones of low resistivity (<30 ohm-m) situated at the eastern (Mainit-Mahalo) and west-southwestern (Nava-Magcasa) flanks of Mt. Cabalian, associated with remarkable surface thermal manifestations (Tebar, et al, 1989). The anomaly configurations have been thought to represent outflow signatures towards their respective open-ended direction with a possible connection of both anomalies at depth located in the region beneath Mts. Cabalian and Cantodoc (Figure **2). A** cross-section (Figure 3) based on 1D inversion modeling of the resistivity **data** shows three basic resistivity **units as** follows: (1) a highly resistive surface layer (>50 ohm-m) extending to depths of about 200 meters; (2) a second layer of intermediate resistivity (between 30 to 50 ohm-m) with an average thickness of about 30 to 100 meters; and (3) a highly conductive (30 to <10 ohm-m) bottom layer.

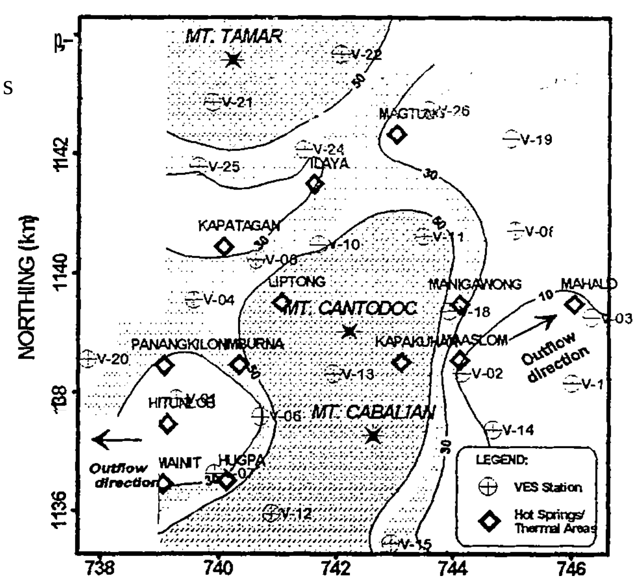

Figure 2. **Apparent** resistivity **map** at AB/2=1000m based on resistivity **data from** the **1989 survey.** Circles **with** crosses indicate VES stations and diamonds represent thermal manifestations. Contour **interval** is 20 ohm-m

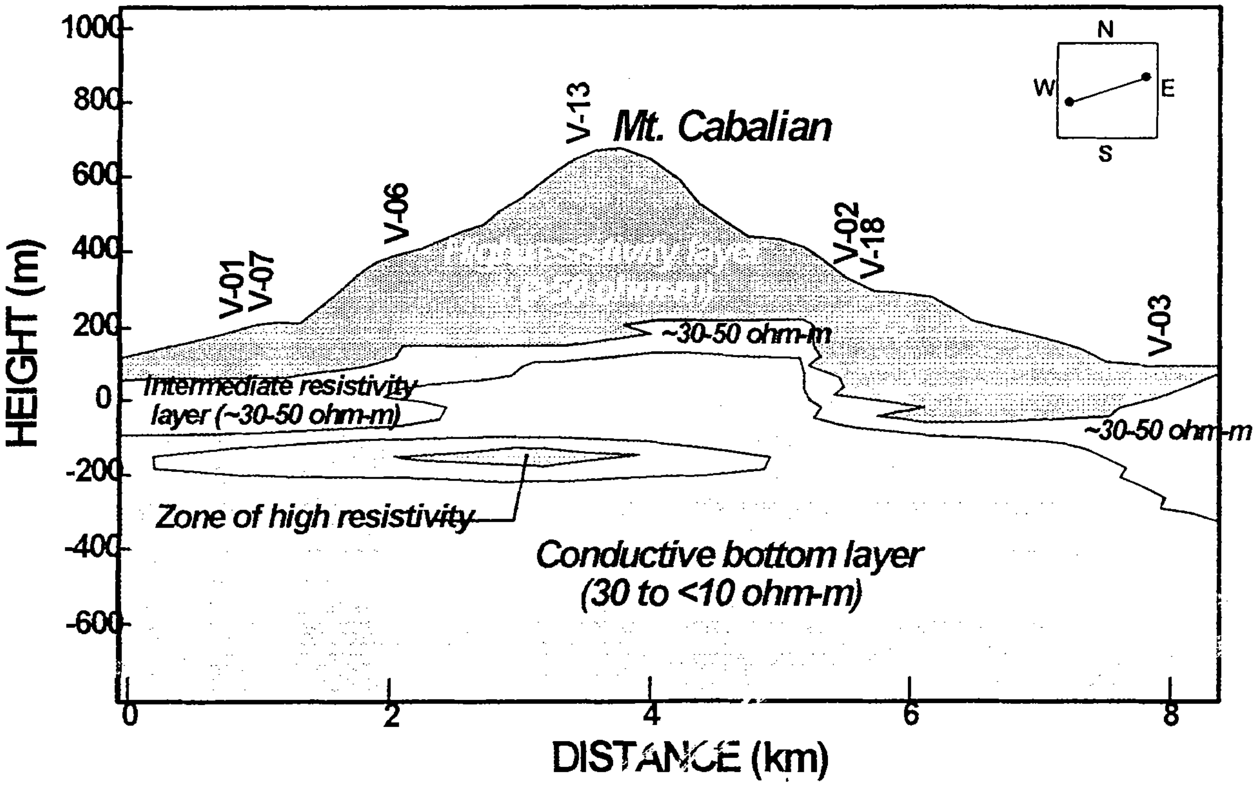

Figure 3 Resistivity cross-section of Mt. Cabalian based on 1D inversion modeling of the 1989 resisitivity data.

3.0 GRAVITY SURVEY

The regional gravity survey at SLGP was conducted by means of a La Coste and Romberg G-277 gravity meter. Elevation control was achieved by a single base barometric heighting technique, using 2 Baromec microbarometers. We used a gravih- station located at the base of the Rizal monument in the municipality of San Juan to tie observed gravity values for all 246 stations. This gravity control point was established by the Bureau of Coasts and Geodetic Suvey in 1967 as part of a regional network of gravity stations throughout the country. Standard gravity reduction with the help of the GREDUC™ software was performed to convert field data into mGal after corrections were made for instrument drift and earth tide effects. Theoretical gravity values were obtained using the 1980 reference system formula.

One important aspect in our gravity data analysis is the choice of a density for Bouguer reduction. This value was determined by volumetric displacement (Los Bafios, et al, 1996) of several samples gathered from the representative rock units in the area and obtaining a reasonable average. Important points drawn from our density determination measurements are as follows:

1. Serpentinites of the Cretaceous ultramafics exhibit broadly distributed densities based only from a handful of samples. We have assigned a reasonable density value of about 2.65 gr/cc to this unit which only occurs at the extreme western sector outside the prospect area.

2. Tertiary limestones have a slightly higher average density as compared *to* the Tertiary clastics, with an average density contrast of about 0.1 gr/cc. These sedimentary rocks are not widely exposed in

the prospect area but could influence the **gravity** anonialics **if** located at shallow depths in significant voltimes.

3. Tertiary and Quaternary volcanic rocks have widely variable but generally low average densities. typically less than 2.5 g r/cc. There is a good correlation between the relntive age **of** the volcanic products and density as younger extrusives exhibit lower average densities because they **are** presumably the least consolidated.

4. A microdiorite intrusion (Leynes. personal communication. **1996)** is postulated to exist west-northwest of the town of Nava. It has an average density of 2.7 gr/cc based on a few surface samples. This rock unit has a positive density contrast of about 0.4 gr/cc with respect to the Tertiary volcanics it intrudes and should have a significant effect on the gross gravity anomaly configuration over the area.

Applying a reduction density of 2.3 gm/cc. Bouguer gravity anomalies were calculated **via** the GEOSOFT™ software using USGS standard reduction equations. Terrain corrections were computed from digitized maps for each station out to a distance of 167 km.

4.0 GRAVITY ANOMALY FEATURES

The Bouguer anomaly map is presented in Figure 4. At the extreme west-southwestern sector of SLGP. the Bouguer gravity values amount to about 60 mGal gradually increasing towards the NE where they **peak** to about 130 mGal. Within the vicinity of the prospect area. the anomaly field forms a roughly circular pattern characterized by anomaly values between 110-120 mGal. enclosing the areas behveen Mts. Cabalian. Cantodoc and Tamar

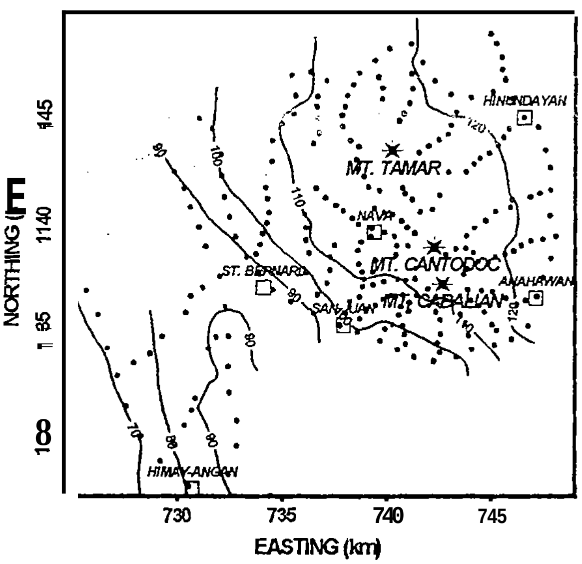

Figure 4. Generalized Bouguer anomaly map of SLGP and vicinity. Contour interval is **10** mGal.

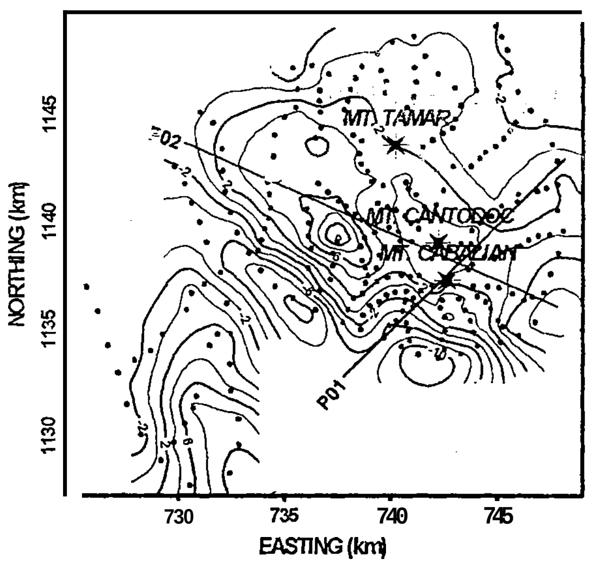

Figure **5.** Residual gravity anomaly map at SLGP. Contour interval is 2 mGal and the location **for** the profiles PO1 and **PO2 are** shwon **for** reference.

In order **to** isolate gravity anomalies that best express the effects of bodies up *to* intermediate **depths** (i.e. approximately at **3** km depths), the regional field **was** derived by polynomial fitting **and subtracted** from the complete Bouguer gravity field to yield a residual anomaly (Figure 5). The residual gravity **map** is dominated by a large elongate gravity high that trends NW-SE with steep gradients on its southwestern side and has **an** amplitude of about **2** mGal. Superimposed on this central gravity high are two smaller gravity highs flanking the north-northwest and east-southeastern vicinities of Mt. Cabalian. possessing approximately equal amplitudes (>10 mGal) and have about a ***6*** mGal relief above the main gravity high. **A** third gravity high of relatively low amplitude that coincides with the saddle between the Cabalian and Cantodoc peaks separates the 2 larger positive 'anomalies.

To the southwest of Mt. Cabalian. the field is characterized by another gravity **high.** The broader shape and the open-ended configuration of the field anomaly is attributable to sparser station density in the southwestern half of the map area. Between the 2 positive gravity anomalies mapped in SLGP is an elongated gravity low (-12 mGal) similarly oriented in **a** west-southeast trend.

5.0 GRAVITY MODELING

Gravity modeling **was** carried out using Geolink™ which is capable of forward model calculations based on prismatic bodies of given density contrast and thickness (Geolink. 1994). Profiles which cross the important **parts** of the residual anomaly features were selected (see Figure 5) and subjected to model calculations using the complete Bouguer anomaly as obsened values The geology of SLGP is described elsewhere (Tebar. et al, 1989; Leynes, et al. 1996) and is discussed herein only as **it** relates directly to the gravity anomalies. Gravity models presented here. while not unique. meet 2 distinctive qualities: (1) geologically reasonable and fit the constraints imposed by available geologic **data:** and (2) reasonable fit with the observed gravity data

5.1 Profile Line PO1

The best fit interpretation model is shonn in the bottom **part** of Figure 6. The model suggests that the broad long wavelength **gravity** anomaly reflects the effects **of** a shallow intrusion beneath Mt. Cabalian. The intrusive zone, which is approximately as large as the topographic expression of Mt. Cabalian in map view. appears to be rather bulbous at shallow levels and funnels out **with** increasing depth.

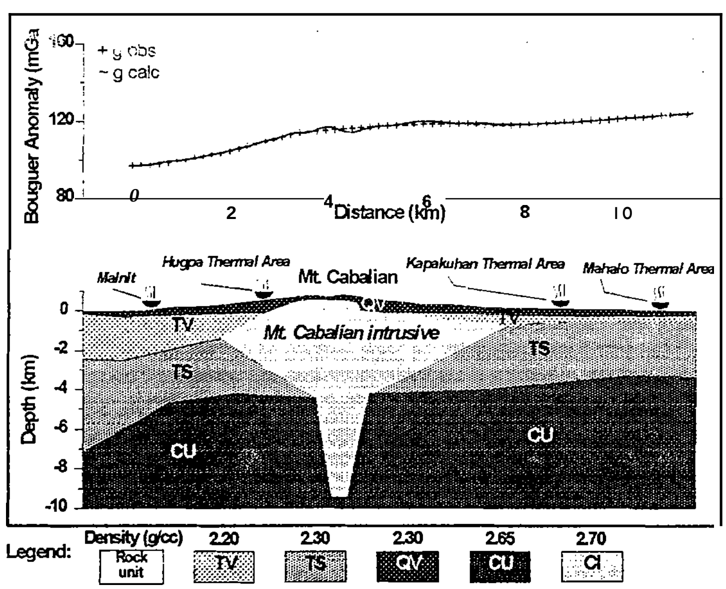

Figure ***6*.** Results of the gravity model for profile P01. The calculated and observed anomalies are shown at the top figure. Lithologies are as follows: Cretaceous ultramafics (CU), Tertiary sediments (TS), Tertiary volcanics (TV), Quaternary volcanics (QV), **and** Mt. Cabalian intrusive (CI)

5.2 Profile Line P02

The 2D gravity model depicts a multi-layered subsurface structure similar to that of profile P01. The overall positive gradient of the observed gravity profile maybe influenced by the relatively shallow depth to the ultramafic basement which. in some places. have risen to less than 2 km below the surface as a result of faulting and uplift. Short-wavelength peaks within the observed gravity profile are interpreted lo be caused by subvolcanic intrusions and subsurface faulting. The body on the northwest correlates closely with the area where a microdiorite body was observed while the body on the southeast represents a feeder dike of the Mt. Cabalian source vent.

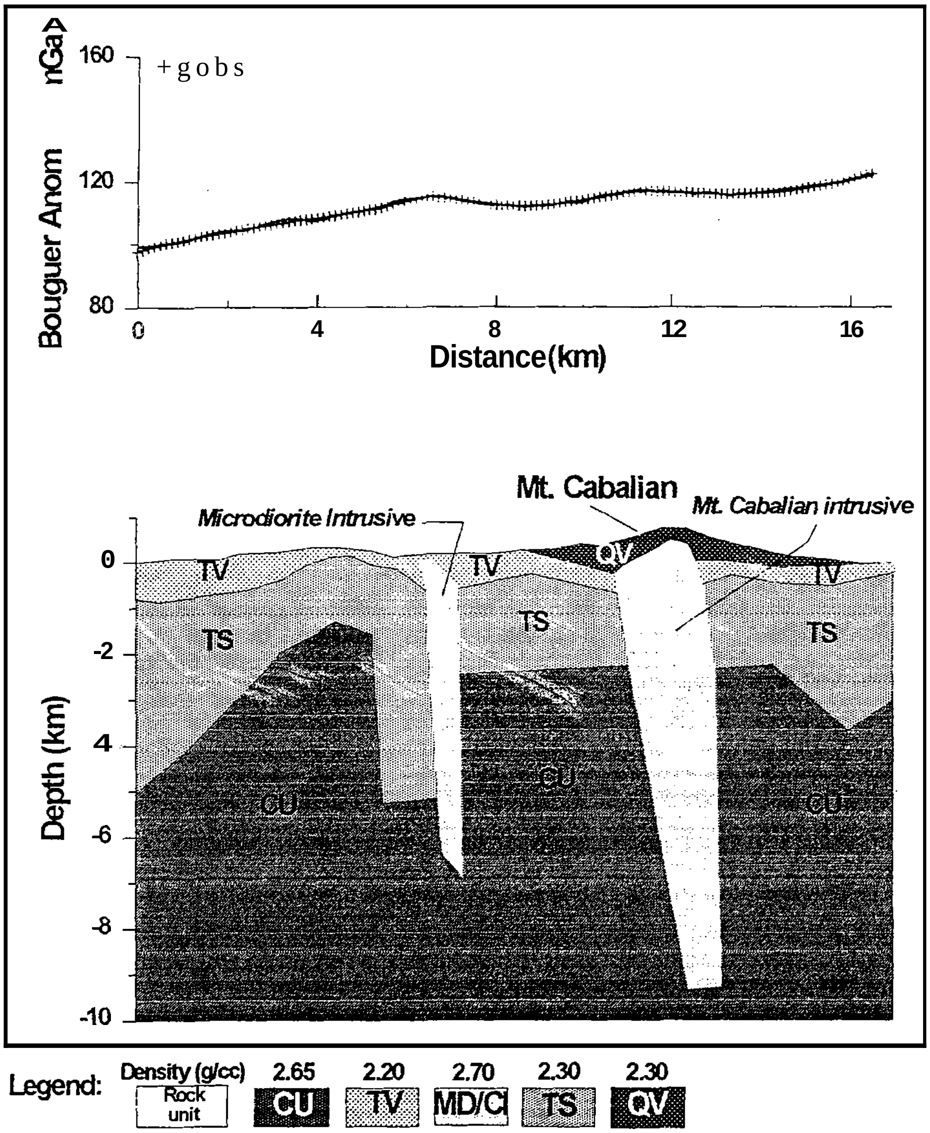

Figure 7. Gravity model for profile P02.

6.0 DISCUSSION

The gravity interpretation is, for most part, consistent with electrical cross section, where the **high** to intermediately resistive layer corresponds to ***the*** Quaternary Volcanics. This unit extends to depths between

100-200 m below the surface. The low resistivity bottom layer is interpreted *to* represent the Tertiary Volcanics. Although the vertical sounding measurements have **an** effective penetrating depth of about 400 meters. the resistivity measurements are unable to differentiate the Tertiary volcanics from the Tertiary clastics in places where the interface between the older volcanics and die underlying sediments is less than a km because both units have similar electrical properties. The gravity highs which were modeled as intrusive bodies correlate well with areas characterized by high apparent resistivity.

Density measurements hardly indicate a discernible difference in bulk density between the Tertiary volcanics and sediments as well as between the inferred intrusive body (microdiorite) **and** the underlying basement. Thus, a simple interpretation of the gravity field is that it reflects a generalized contrast between lowdensity old volcanics and sediments and the more dense intrusives and basement unit. Where the intrusive body or ultramafic basement is shallowest or crops out. the gravity effect will be most positive.

The gravity anomaly configuration over SLGP has an interesting implication in terms of the volcanic and structural evolution of the volcanic complex. The coincidence of the preferred elongation of the residual anomalies with the alignment of the volcanic centers and which parallels the **NW-SE** structural grain of the area suggests a genetic relationship between them. **As** the positive anomalies are modeled io be separate intrusive bodies. we speculate that they may have originated from a common source at depth. The gravity data. however. does not allow a more accurate modeling at greater depths because any densih- contrast within these levels is too small to observe.

7.0 SUMMARY AND CONCLUSIONS

A gravity investigation at the Southern Leyte geothemal prospect has revealed a Bouguer gravity anomaly with a strong regional component influenced by the combined effects of the underlying Tertiary sediments **and** Ultramafic basement. The residual gravity anomaly displays at **least 2** major positive anomalies separated by a gravih- low, all elongated in a northwest-southeast fashion. The main anomaly, which has an amplitude *of* about 2 mGal seems to delineate a large intrusion directly beneath Mt. Cabalian. Two smaller gravity highs mhich are superimposed on the main anomaly are initiially perceived to be small feeders nhich rise above the main intrusive body. The other gravity **high** situated southwest of the prospect **area** is attributed to the ultramafic basement which had risen to shallower levels due to faulting and uplift.

Two dimensional models to explain the local gravity anomalies indicate a subsurface structure of near horizontal sequences of recent and older volcanics overlying the Tertiary sediments which in turn are underlain by an ultramafic basement. The overall gravity field is dictated mainly by a density contrast between the dense intrusives and basement rocks and the less dense country rocks composed of altered volcanics and sediments. The heat source of the postulated hydrothermal system at SLGP is presumably derived from a shallow intrusive that has been emplaced locally within the volcanic edifice of Mt. Cabalian. Reservoir rocks are most probably made up of a thick sequence of old volcanics and sediments. ***Our*** gravity modeling constrains the depths to the interface between the basement rocks and overlying Tertiary Clastics between **3** to ***6*** km below the volcanic edifice of Mt. Cabalian.

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