INTERPRETATION OF GRAVITY SURVEYS AT TONGONAN GEOTHERMAL FIELD

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ABSTRACT

Residual gravity anomalies of the Tongonan Geothermal Field are interpreted to be the result of a positive density contrast between an intrusive diorite body and the surrounding volcanics. A possitive anomaly in the Mahiao, Sambaloran and Malitbog parts of the field, is associated with the occurrence of the Mahiao Plutonic Complex, as encountered in most deep wells. However, known plutonic bodies in the Mamban and Mahanagdong areas do not produce anomalously high gravity values because of overlying low density rocks. Another positive anomaly occurs in the nearby Bao valley. Interpretation of this anomaly suggests that it could be modelled by another plutonic body, which may originally have been related to the Nahiao Pluton, but has since been displaced by left lateral movement along the Philippine fault.

INTRODUCTION

Development of a 110 MWatt station in the Mahiao-Sambaloran sector of the Tongonan Geothermal Field is nearing completion, while a further 110 MW development in the Malitbog sector is proceeding and additional units in the Mahanagdong and Mahiao sectors are being considered.

In May 1981, precise gravity measurements on surveyed benchmarks were conducted in the Tongonan area to establish baseline gravity data for future repeat measurements that will assist calculations of mass-withdrawal, fluid re-distribution, reservoir performance, and recharge. This data together with additional measurements made outside the geothermal field, have been compiled to construct a Bouguer anomaly map of the Tongonan area.

The methods employed in this survey are summarized below, and a detailed interpretation of the Bouguer anomalies encountered near Tongonan is presented, along with some general comments on the regional gravity anomalies. A simple gravity anomaly map of Leyte, produced by the Philippine Bureau of Mines (from reduced data without terrain corrections) was used to help in the interpretation of the regional anomalies.

GEOLOGY

A gravity survey is a structural method and in this sense is simply an extension of geological mapping. However, some gravity anomalies, in geothermal areas, may be directly caused by the effect of the hydrothermal system on its host rock. Geothermal gravity anomalies are often associated with hydrothermal alteration and deposition, magmatic intrusions, structural features such as faults, calderas and basement structure, as well as metamorphism.

A knowledge of local geology is invaluable for the interpretation of gravity anomalies, to assist in the inter-active modelling process. No model solution is unique, but knowledge of formation densities and thicknesses from drill hole cores provide a constraint which can be used to deduce a realistic model that fits the observed data.

A detailed stratigraphy of Tongonan was given by Ablazo (1980). On the basis of contrasting bulk densities, three major rock formations are considered here. The oldest rock formation in the area (late Miocene to Upper Pliocene) is the Bao Formation. It is composed of hornblende andesite lavas and associated pyroclastics with intercalated conglomerates, thin beds of limestone, volcaniclastic siltstone, shale and breccias. The thickness of this formation varies from well to well, with the thickest sequence occurring in the Mamban and Mahanagdong area. The average density of the core samples taken from this formation was 2.62 gm/cc, however the true bulk density will be lower, if fractured zones (with low core recovery) are considered. There are no surface outcrops of the Bao formation.

Unconformably overlying the Bao Volcanics is the North Central Leyte Formation (NCLF) thought to be Pleistocene in age. It is composed of poorly sorted conglomerates with some intercalations of tuffaceous sediments, siltstones and lahars. The estimated thickness of this formation is 600 meters. Outcrops are found in the south - - - western part of the field, along the banks of the Bao river. Overlying the NCLF, on the flanks of Mt. Janagdan to the southeast, are the Janagdan Andesite lavas.

Intruding the Bao Formation is the Mahiao-Plutonic complex which is composed of diorite, quartz diorite, granodiorite and some granite. The variability of rock type and the presence of a complex zone of microdiorite apophys above the main body as well as a later stage of trachyte andesite dykes suggests a complicated history of multiple intrusion.

GRAVITY MEASUREMENTS

1. Field Procedure:

Measurements were made using the 'La Coste and Romberg' gravity meter belonging to the Geothermal Division of PNOC-EDC. Benchmark elevations were provided by the Philippine Coast and Geodetic Survey (BCGS); two altimeters (Paulin Precision), were used to determine the elevations of secondary gravity stations.

A looping method was adopted in the survey, with the base station being re-occupied four to six times daily. Altimeter observations were calibrated at the start of each day at a benchmark near the base station, where the base altimeter was left to monitor atmospheric pressure changes. Corrections for temperature and barometric pressure changes are applied to the readings from the roving altimeter. Some inaccuracies were noted because the two altimeters did not have identical responses to barometric pressure. Where discrepancies were excessive, the barometric correction was multiplied by the ratio of the final reading differences of the roving and base altimeters.

For the precise gravity survey, at least 2 readings were obtained at each benchmark; only one measurement was taken at each regional station. Drift curves were plotted from base station values and reading differences from repeated stations fitted to the curves. Suspect readings were repeated to improve reliability.

2. Density Measurements:

Density measurements were made on selected core samples, representing the various major rock types encountered. Wet densities (samples saturated under vacuum) of the NCLF, Bao Volcanics and the Mahiao plutonic complex are given in Table 1. It can be seen that there is a density contrast of about 0.17 between the Plutonic and Bao Volcanic formations.

TABLE 1 DENSITY OF ROCKS IN TONGONAN

Formation	Lithology	No. of Cores	Density (gm/cc)
N.C.L.F.	Shales, Tuff Sediments	-	2.30 estimated
Bao Volcanic Complex (Deep Wells)	Andesite	12	2.50
	" Breccia	11	2.52
	Volcaniclastic	2	2.6
	Tuff	2	2.63
Bao Volcanic (TGE Wells)	Andesite	18	2.60
	Tuff	2	2.33
Mahiao Plutonic Complex	Microdiorite	6	2.72
	Diorite	15	2.72
	Granodiorite	4	2.67
	Dacite Dikes	1	2.74

3. Data Reduction:

Data processing and interpretation was greatly assisted by the use of a micro-computer. The observed gravity values were adjusted for instrument corrections, tidal acceleration, terrain, Bouguer plate, free-air and latitude corrections. The Longman's method (1959) for computing tidal acceleration was adopted for the earth tide correction. The computed vertical components of the tide, (expressed as a function of time for any given station) when compared with the observed drift curves showed that the effect of instrument drift was negligible.

All corrections made for elevation, Bouguer plate and latitude were computed relative to the Ormoc reference station, (Ormoc Church) which has an elevation of 3 m. The 1967 Geodetic Reference System formula was adopted for the latitude correction. For terrain corrections, an average density of 2.67 gm/cc was assumed, based on average measured densities of core samples.

Plots of computed bouguer gravity values against station elevations show a random scatter, indicating that computed anomalies are not artificial functions of elevation caused by an inaccurate choice of average terrain density. Terrain corrections for Hammer zones B to D were calculated from elevation estimates made in the field. Zones E to M (170 m to 22 km) were estimated using a graticule overlay on 1:50,000 scale maps with 20 m contour intervals.

REGIONAL GRAVITY ANOMALIES

The regional gravity anomaly map (Fig. 1) of Northern Leyte includes the following features: a large positive anomaly west of Carigara; negative anomalies at Kananga, Jaro and Ormoc Bay (mostly peripheral to the positive anomalies); two distinct positive anomalies in the Tongonan Geothermal Field; and a small positive anomaly west of Lake Imelda. A profile drawn from Ormoc to Lemon (Fig. 2) shows a gently sloping regional gravity gradient of 0.4 mgals per kilometer, increasing to the north, A second profile (Fig. 3) parallel to the first and running through Jaro towards Carigara, also shows the same gently sloping regional gradient near Jaro. A third profile (Fig. 4) drawn across the geothermal field, shows a broad positive anomaly near the central part of the island, caused by a large, dense mass (probably a deep pluton) Fig. 5. The regional gravity map is dominated by anomalies trending from southeast to the northwest, approximately aligned along the Philippine fault zone.

RESIDUAL GRAVITY ANOMALY INTERPRETATIONS

The following assumptions were made to assist interpretation of the residual anomalies in Tongonan.

1. The density of the Mahiao Plutonic Complex, at depth, is probably greater than the measured densities of core samples. However, uniform density contrast was assumed.

2. The density of the NCLF is 2.3 gm/cc, which is considered average for sedimentary rocks.

3. The regional gravity can be approximated by a plane passing through Northern Leyte with a gradient of 0.4 mgal per kilometer, increasing to the north.

4. The plutonic rocks encountered in Mahiao, Malitbog, Mamban and Mahanagdong can be grouped into one body of uniform density.

Cross-sections of the bouguer anomaly (Fig. 6) were prepared, and the regional gradient (assumed here to be linear) removed, to enable the residual anomalies to be interpreted in terms of 2-dimensional models. This involves the use of an interactive computer program which allows the operator to enter and display several bodies of arbitrary shape, depth and density contrast, and then compare the computed gravity anomaly profile with the observed profile. Corrections can be made to improve the fit. The computer program does a line integral around the boundary of each body, computes the vertical gravitational force at each surface location, and sums these forces if there are two or more bodies.

Two local positive anomalies dominate the residual gravity anomaly pattern in Tongonan.

A. The Mahiao-Malitbog Anomaly:

The elongated northwest trending anomaly in the Mahiao area is clearly related to the Mahiao plutonic complex. A steep gradient in gravity to the southwest and northeast could be explained by the steepness of the boundary of the pluton with the surrounding volcanics. The southwest boundary coincides with the trace of the Central Philippine Fault. The peak in the anomaly suggests that the location of a root of the plutonic complex lies between wells 208 and 501 (MB-1). The isolated anomaly near well 407 may be due to local densification of the rocks through deposition of alteration minerals, variations within the complex itself, or another root.

The anomaly does not extend to the southeast, towards Mamban and Mahanagdong areas, although a pluton was penetrated by wells drilled in these areas. The most plausible explanation for this discrepancy is that, here, there is a thick sequence of low density volcanclastic sediments and tuff breccias overlying the pluton. Also, in Mahanagdong, many total loss circulation zones were encountered, while drilling the overlying volcanics, which implies that they are heavily fractured, and so their bulk density is further reduced. Computer modelling, using a dense plutonic body, overlain by low density volcaniclastics and tuff breccias, shows that the gravity effects of these two features tend to balance each other out.

Two dimensional models, along sections both parallel and perpendicular to the Mahiao-Malitbog anomaly, suggest that the plutonic complex has a lapolith-like shape along the NW-SE axis (figs. 7 and 8).

B. The Bao Anomaly:

The interpretation of the Bao anomaly assumes that the density model used for the Mahiao-Malitbog area can also be applied to the Bao Valley. There are no deep wells in the area to confirm this. The Bao anomaly is interpreted to be caused by a smaller pluton, which may also be dioritic in composition (fig. 9). This feature is elongated parallel to the Mahiao-Malitbog anomaly and to the Philippine Fault. It is also steeply bounded to the southwest. These similarities should not be dismissed as merely coincidental. The Bao Anomaly is bounded by two branches of the Philippine Fault (see map). It is possible then that the pluton, causing the Bao anomaly, could have been part of the Mahiao-Sambaloran pluton but has since been displaced horizontally 4 km to the south-east by left-lateral movement along the Central Philippine Fault.

CONCLUSIONS

A positive Bouguer anomaly in the Mahiao-Sambaloran-Malitbog sector can be modelled by a pluton with a density contrast of 0.17 gm/cc and flanking bodies of low-density near-surface volcanic sediments. The occurrence of a similar positive anomaly in the Bao Valley suggests that a plutonic body also underlies this area. There is no evidence? yet, for the age or present temperature of this pluton. However, the close proximity and similar form of these anomalies suggests that they originated from the same plutonic body. If this is correct, then their present distribution suggests that the body has been ruptured and off-set about 4 km horizontally by left lateral movement along the Central Philippine Fault. Relatively low gravity anomaly values in the Mamban-Mahanagdong area can be attributed to a thick sequence of low-density, near-surface material overlying the pluton.

A permeable zone directly above the Mahiao Plutonic Complex is known to be responsible for significant production of geothermal fluids. The elevation contours of this pluton coincide with subsurface temperature contours. Therefore, it is clear that the gravity method, when used to delineate a pluton (having similar contact permeability) can be a useful tool in geothermal exploration.

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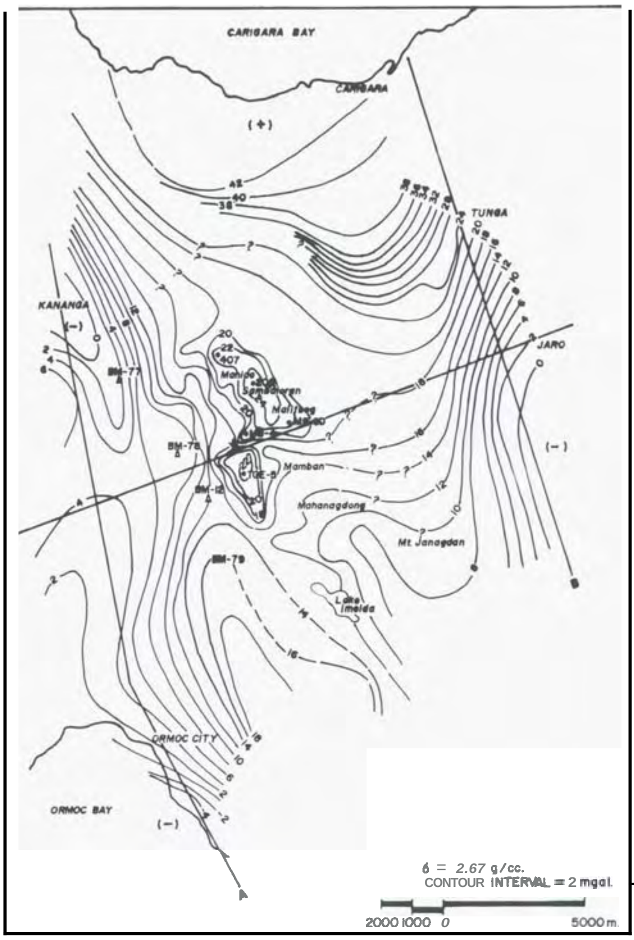


FIG.1 NORTHERN LEYTE BOUGUER ANOMALY MAP
L LYTE QEOTHERMAL PROJECT

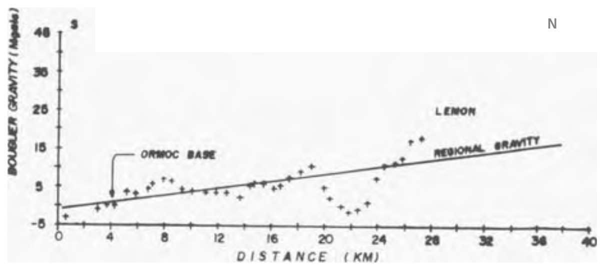


FIG. 2 REQIONAL GRAVITY PROFILE
(SECTION A)

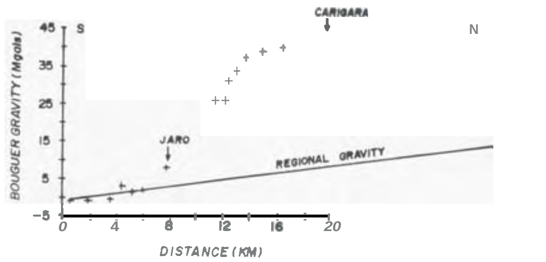


FIG. 3 REQIONAL QRAVITY MASKED BY A LARGE POSITIVE ANOMALY
(SECTION B)

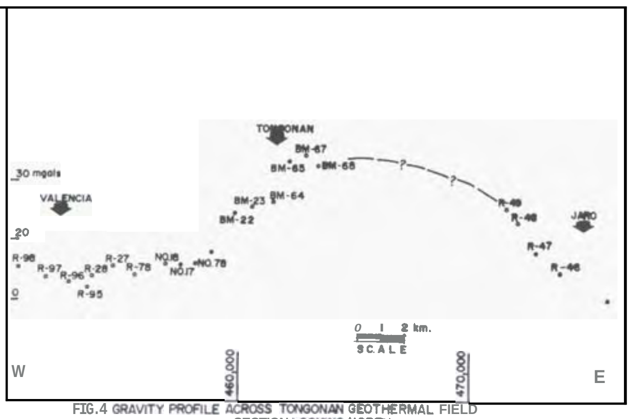


FIG.4 GRAVITY PROFILE ACROSS TONGONAN GEOTHERMAL FIELD
SECTION LOOKING NORTH
(SECTION C)

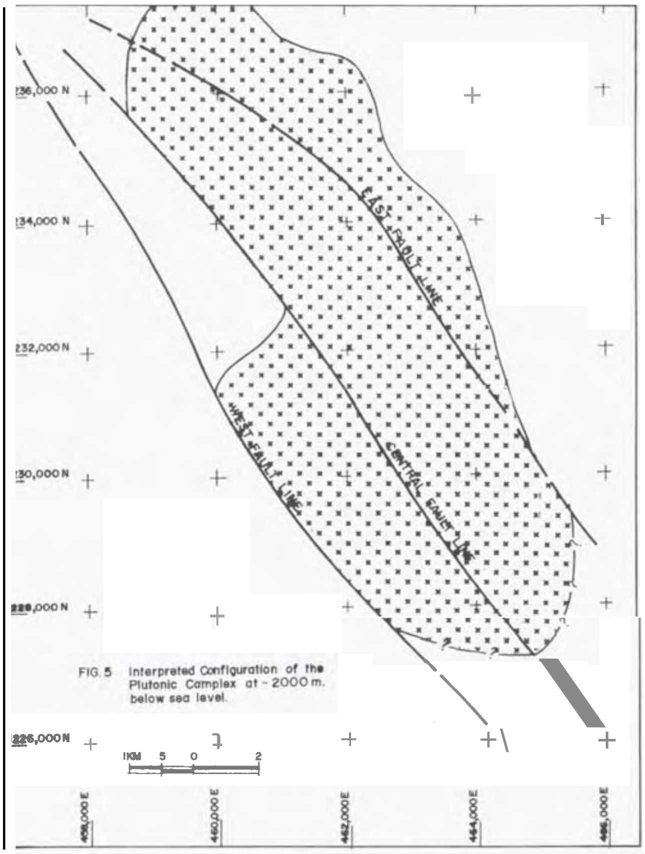


FIG. 5 Interpreted Configuration of the Plutonic Complex at ~2000 m. below sea level.

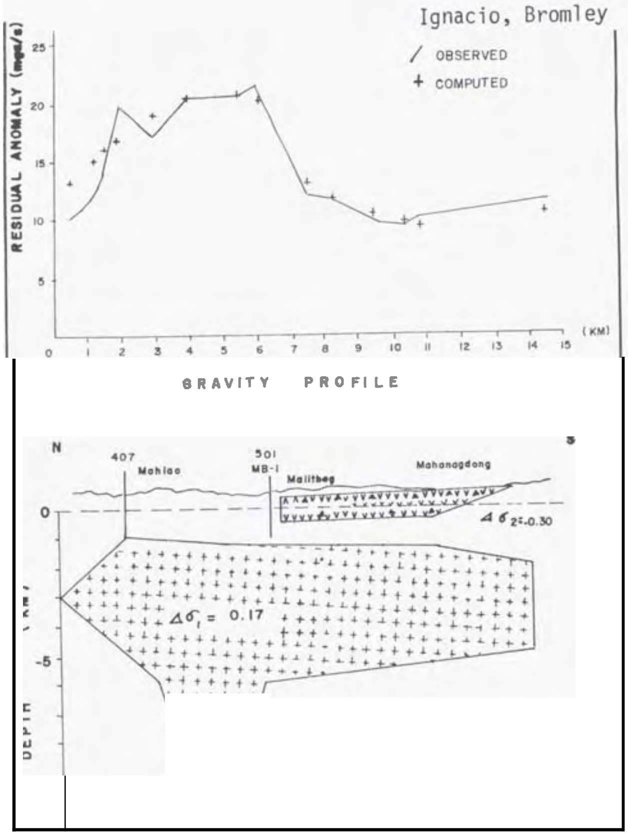


FIG. 7 INTERPRETED GRAVITY MODEL ACROSS MAHIAO, MALITBOG, MAMBAN AND MAHANAGDONG

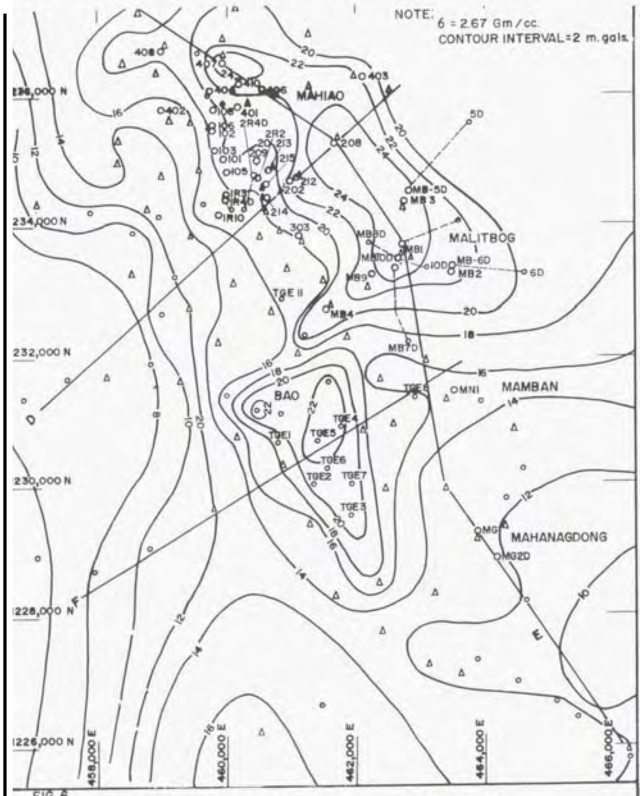


FIG 6
LEYTE GEOTHERMAL PROJECT
BOUGUER GRAVITY MAP

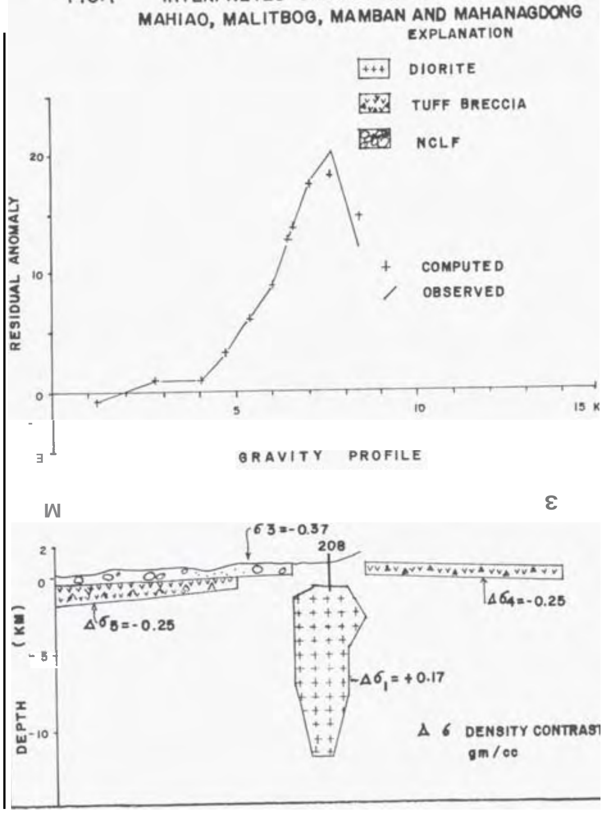
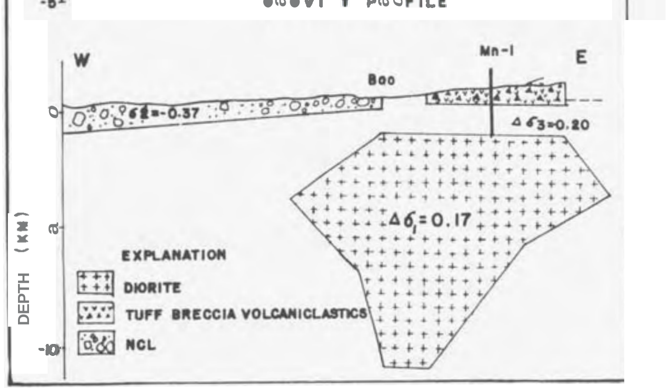


FIG. 8 INTERPRETED GRAVITY MODEL ACROSS THE TONGONAN GEOTHERMAL FIELD



W
E
Boo
Mn-1
$\Delta\sigma_3$=0.20
$\Delta\sigma_1$=0.17
-0.37
DEPTH (KM)
0
-10
EXPLANATION
DIORITE
TUFF BRECCIA VOLCANICLASTICS
NCL