GRAVITY AND ELEVATION CHANGES AT THE BULALO GEOTHERMAL FIELD, PHILIPPINES: INDEPENDENT CHECKS AND CONSTRAINTS ON NUMERICAL SIMULATION

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SUMMARY – Twelve precision gravity surveys have been carried out at the Bulalo Field since production began in 1979. Eight precision leveling surveys have been carried out over this same period to monitor elevation changes at the same benchmarks (BMs). The Bulalo Field has experienced a maximum free-air gravity (FAG) change of about –600 pgals. A maximum subsidence of about 0.5 m can also be observed in the area. Mass calculations based on the gravity data indicate a recharge from upflow and perimeter aquifers of about 42%. The gravity data has also been successfully used as an independent calibration constraint for the Bulalo reservoir simulation model.

1.0 INTRODUCTION

The Bulalo (also known as Mak-Ban) geothermal field is located about 70 km southeast of Manila (Fig. 1). The field is associated with Mt. Bulalo, a young dacite dome at the southeast flank of the Mt. Makiling andesitic stratovolcano. Gravity benchmarks were initially established at Bulalo in 1979 when the first two 55 MWe power plants were commissioned. Installed capacity was increased to 330 MWe by 1984. An additional 15.75 MWe of binary capacity was commissioned in 1994 while another 80 MWe (4 X 20 MWe modular units) were installed in 1996. Total installed capacity at Bulalo Field stands at 426 MWe, making it the second biggest operating geothermal field in the Philippines.

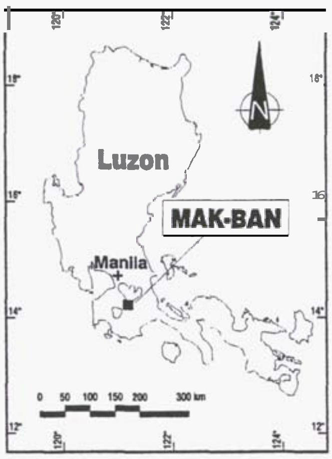

Figure 1. Location Map of Mak-Ban Geothermal Field

Repeat precision gravity surveys help in monitoring the temporal and spatial effects of production and injection in a geothermal field. The data can be utilized as an independent constraint and calibration for reservoir simulation models (Allis and Hunt, 1986; Atkinson and Pedersen, 1988). For Bulalo, this has lent confidence to simulation-based estimates of mass recharge to the reservoir and potential recoverable reserves (San Andres and Pedersen, 1993). Gravity changes can also provide qualitative analysis of reservoir processes, such as marginal recharge and steam cap formation.

Precision leveling surveys are undertaken primarily for the purpose of collecting elevation data used for reduction of precision gravity data. Precision gravity data cannot be meaningfully interpreted in the long-term without corrections for elevation changes. The resulting data can also be used to monitor subsidence although this has proved a minor concern at Bulalo.

2.0 GEOLOGY AND GEOCHEMISTRY

The Bulalo geothermal reservoir is characterized as a hot water-dominated, two-phase, neutral pH, low chloride (2,800 mg/kg) hydrothermal system (Sta. Maria et al., 1995). This geothermal system has a central core of relatively high permeability surrounded by hot, lower permeability rocks. The high permeability core consists of the semi-circular 6.2 km^2 area of commercial production area, which was also defined by low resistivity anomalies. Hot, lower Permeability rocks in the east and south and low-temperature rocks in the northeast and southwest bound this nearly circular production area (Clemente and Villadolid-Abrigo, **1993).** Non-condensible gas (NCG) content is generally low at 0.5 **wt.** % but the southeast portion of the field is characterized by **2-3 wt. % NCG** concentration in steam and relatively low reservoir permeability.

The reservoir is hosted by the Miocene to middle Pliocene Pre-Makiling Volcanics (PMV) that consist of intercalated lava flows and tuff horizons. The Bulalo reservoir is generally found within the PMV at depths of **450** m – **2,750** m below sea level (bsl). Capping the PMV and the Bulalo geothermal system is the Makiling Volcanics (MV), rocks extruded by Mt. Makiling northwest of the field. The upper portion of the MV is generally altered to smectite that provides a tight seal to **the** system and prevents convective heat loss. Pyroxene monzonite and dacitic dikes were found to intrude both the MV and PMV but no major plutonic masses or basement have yet been identified.

Geochemistry and measured high temperatures have delineated two upflow zones in Bulalo: a major upflow in the central part of the field and a minor one in the southeast. Constant chemistry in wells completed in these two upflow areas suggests vigorous basal recharge over time. Partially open boundaries or deep (>**1,220** m bsl) outflows have been inferred in the north and south but relatively shallow for the west (600 **-1,050** m bsl). These outflows are now avenues of recharge back into the reservoir.

3.0 METHODS

Precision gravity and precision leveling surveys were usually conducted every other year. Gravity surveys started in **1980** while leveling surveys started in **1979.** The surveys cover **an** area of approximately **36 km²** centered over the production area.

The gravity surveys were done with a LaCoste & Romberg Model D gravimeter. They were conducted over a fieldwide network of about **120** BMs. To ensure consistency between surveys the same gravity meter has been used for all of the surveys. Surveys were also scheduled during the *dry* season to minimize the impact of shallow groundwater changes related to rainfall.

The Wild **N3** spirit level was the equipment used for the leveling surveys. Surveys were done over a fieldwide network of about **150** BMs. More BM's are measured during the leveling survey to shorten the leveling circuit and to improve the network for the network adjustments.

Reduction of the gravity and leveling **data** were done using the loop misclosure corrections and least-squares network adjustments.

4.0 GRAVITY CHANGES

Figure **2** shows the cumulative free-air gravity (FAG) change from **1980** to **1999.** The most striking feature is the asymmetrical negative FAG anomaly centered over the production area. The maximum FAG changes have occurred near BM 66. BM **66** was not measured in **1980,** when precision gravity surveys were started, but **has** experienced a change of almost –600 pgals for the period **1981** to **1999.** BM **66** is located near the discovery well Bulalo-1 and the central portion of the production area, a sector interpreted **as** having high permeability and deep fluid recharge. This sector also coincides with the area of high excess steam indicating widespread on-going phase change fiom brine to steam.

The current conceptual model of the Bulalo geothermal field assumes that permeability trends in the reservoir change below **–1,220** m **(4,000')** bsl. Above this depth permeability trends are dominantly northeast and northwest-southeast. Below **this** depth north-south and east-west trends dominate. The long-term gravity changes show mostly northwest-southeast negative anomaly trends consistent with the shallower permeability trends. This is **as** expected because the gravity changes are most sensitive to density changes in the shallower portions of the reservoir. These density changes are due to saturation changes in the rock.

5.0 ELEVATION CHANGES

Figure 3 shows the cumulative elevation change fiom **1979** to **1999.** A roughly circular subsidence bowl coincident with the production area is observed. BM **66** (first measured **in** **1981)** exhibits the maximum cumulative negative elevation change **(-565** mm fiom **1981** to **1999) as** well **as** the highest long-term average rate of subsidence **(-32** mm/year). The magnitude and rate of subsidence are low compared with that of the Wairakei field where more than **14** meters of subsidence has occurred at several BMs (Allis et al., **1998).** Ground subsidence in Bulalo has not caused any adverse effects to the production facilities or local communities.

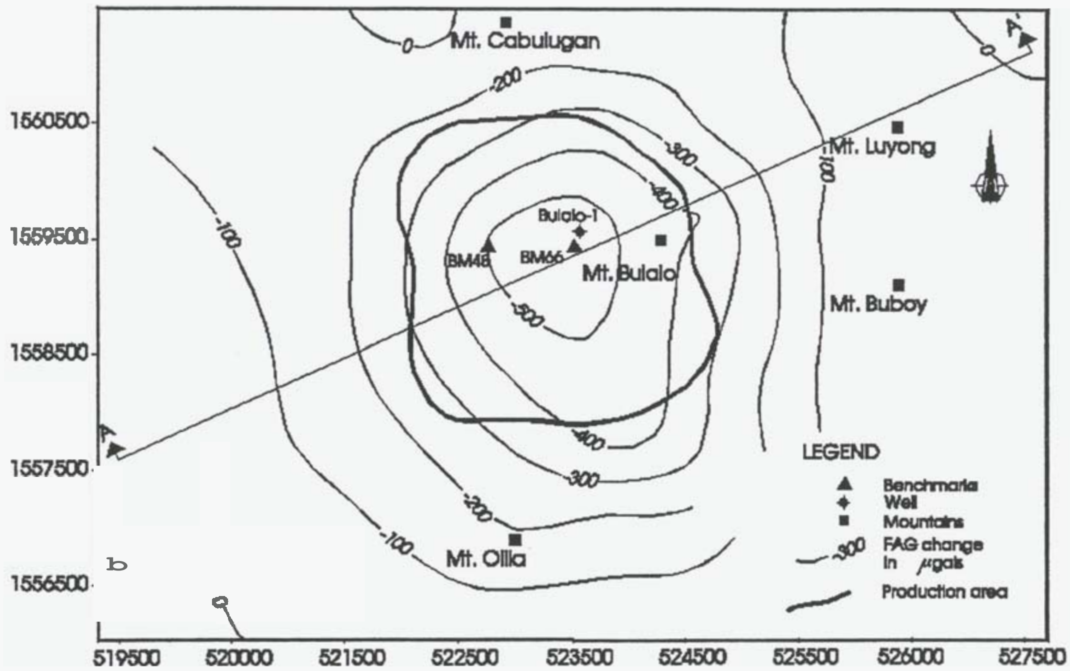

Figure 2. Free-Air Gravity **Change Map (1980 to 1999) with the locations** of BM66, BM48, Bulalo-1 and **profile A-A'.**

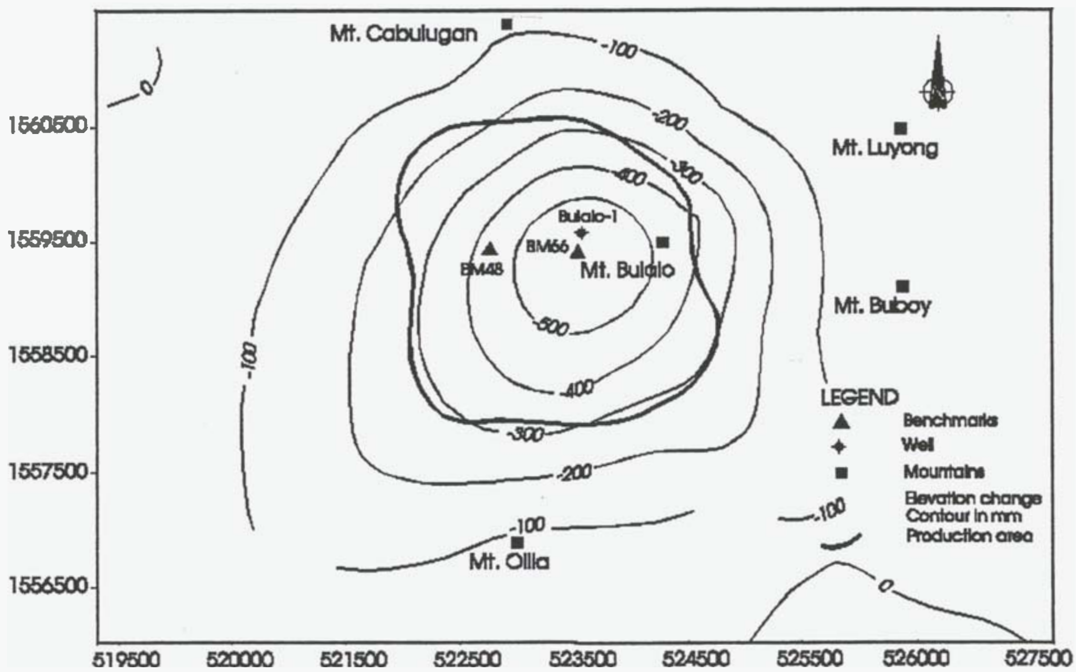

Figure 3. Elevation Change Map (1979 to 1999) with the locations of BM66, **BM48** and Bulalo-1.

The shape and location of the region with subsidence relative to the production area boundary indicates that the bulk of the subsidence is occuring due to compaction within the reservoir. The lack of subsidence in the rocks above the reservoir may be attributed to the well-sealed and strong geothermal reservoir roof that impedes shallow groundwater to geothermal reservoir interaction.

The most important function of these leveling surveys has been to provide elevation corrections for the gravity data. All the data have been corrected using the well known free-air correction factor of **0.3085** mgal/meter.

6.0 GRAVITY AS AN INDEPENDENT CONSTRAINT IN THE RESERVOIR SIMULATOR MODEL

The gravity data at Bulalo have been used on a regular basis as a check and constraint for the reservoir models (Atkinson and Pedersen, **1988;** San Andres and Pedersen, **1993).** A numerical simulation history match of the pressure and enthalpy that is consistent with the gravity data provides further confidence that the simulation model is correctly representing the key features of the reservoir and its response to production and injection. Checks of the observed and simulated gravity changes are made following each new gravity survey and after changes have been done on the simulation model.

During this past year, a significant effort has yielded an updated numerical simulation model of Bulalo that incorporates more geologic constraints. This resulted in a new orientation of the model's grid to better simulate key structures and refining of the grid for more detailed representation of the reservoir structure. The observed gravity data were used throughout the matching process to further constrain results and to add insight for the modeler.

The gravity data are used in two ways to check the match/consistency between the observed gravity response and the simulation results. The first and easiest to apply uses Gauss' Theorem. This provides an estimate of the net mass removed from the reservoir during a specified period (Hunt, **1970).**

$$M = \frac{1}{2\Pi G}\sum \Delta g \Delta s$$

(M = Mass Loss; G =Universal gravity constant; Ag = local gravity change associated with an areal element As)

Using this technique and the gravity data in Figure 2, a net mass loss of about 2 **15** teragrams **(Tg) is** calculated to have occurred for the period **1980** to **1999.** This compares favorably with the simulation model's prediction for the net mass withdrawal of about **227** Tg (Model **2** discussed below). The net mass produced from the field during this period was about **374** Tg (Total Mass Produced – Total Mass Injected) indicating a recharge of about **42%** has occurred from basal and lateral aquifers. The other check explicitly compares the observed gravity changes with those that would be predicted by the simulation model results. The three-dimensional gravity responses based on the simulation model are calculated using density changes in each of the simulation model's grid blocks. The density change in the blocks are due to phase changes in the rock and are a function of the saturation change, porosity and temperature. Matches to both the rate of gravity change and the total magnitude of gravity change are important. For example, Figure **4** shows the gravity changes for BM 66 and BM **48** and the results of two versions of the simulation models' match to those data. Both simulation models had reasonable history matches with the available enthalpy and pressure data but the gravity data show a preferred match with Model **2.** This better match of Model **2** with the observed gravity data is further illustrated on Figure **5.**

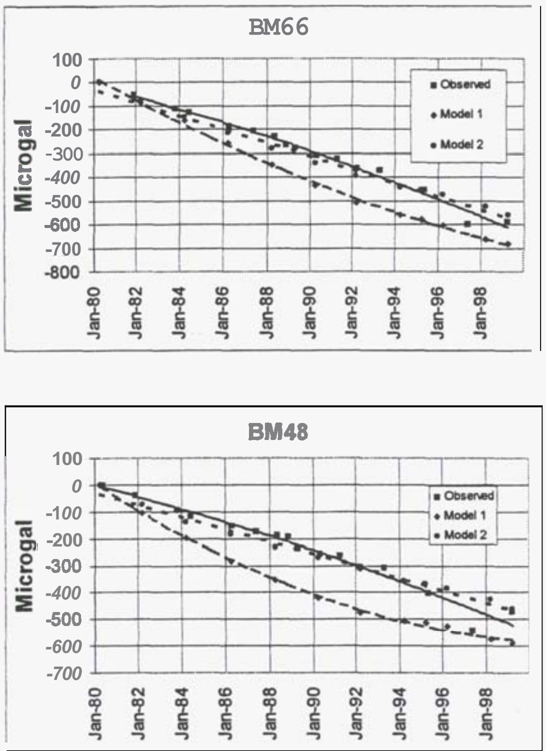

Figure 4. Comparison of observed and simulated rates of changes for gravity data.

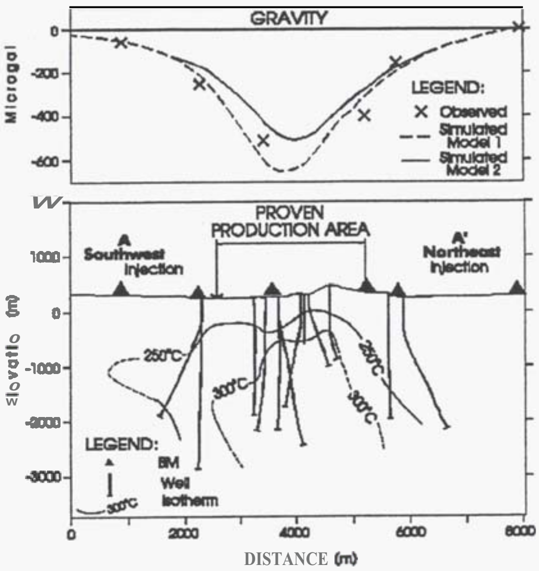

Figure 5. East-west profile showing match of simulated and observed gravity – 1980 to 1999.

7.0 CONCLUSIONS

Gravity monitoring at the Bulalo geothermal field for the past 20 years showed a continuous decrease of about 600 pgals near the center of the production area as a result of resource depletion. The negative gravity anomalies are primarily due to density/phase changes related to saturation changes in the rock in the shallow portion of the reservoir.

Subsidence delineated by precision leveling surveys had reached a maximum of a little over 0.5 m near the central part of the production area in the same period, with no adverse impact to the environment or operations.

Precision gravity data have played an important role in refining an update of the reservoir simulation model. By using the gravity data as an independent check and constraint, a simulation model that more accurately reflects natural recharge patterns was obtained for prediction of reserves and future reservoir performance.

8.0 ACKNOWLEDGEMENTS

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