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# REPEAT MICROGRAVITY AND LEVELING SURVEYS AT LEYTE GEOTHERMAL PRODUCTION FIELD, NORTH CENTRAL LEYTE, PHILIPPINES

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## ABSTRACT

Leyte Geothermal Production Field (LGPF) in North Central Leyte is the largest geothermal area in the Philippines. It is comprised of two independent hydrothermal systems: the Tongonan Geothermal Field (TGF) in the north and the Mahanagdong Geothermal Field (MGF) in the south.

The commissioning of additional power plants beginning 1996 to harness the full energy potential of the area led to a massive mass extraction from the field's reservoir, which to date has incurred a cumulative net mass loss of 291 Mt in TGF and 65 Mt in MGF. Microgravity measurements, in tandem with precise leveling survey were conducted over the area to determine the reservoir's response to exploitation by detecting the minute exploitation-induced changes in gravity over time. The most recent measurements were conducted in 2003.

Based on Gauss's Potential Theorem and mass balance equation, the negative gravity changes from 1997 to 2003 indicate that the system (LGPF) has incurred a net mass loss of about 244 Mt and a natural recharge of about 34 Mt or 12% of the total mass removed.

The measured decreases in gravity were associated with the mass loss from the reservoir. The data was also correlated with the pressure drawdown of about 4-4.5 MPa presently experienced over TGF and MGF.

## INTRODUCTION

The Leyte Geothermal Production Field (LGPF) is the largest geothermal area in the Philippines located along the northwest trending structures of the Philippine Fault in north central Leyte (Fig. 1). LGPF comprises six geographic sectors, namely, Mahiao, Sambaloran, Malitbog, Mamban, Mahanagdong and Bao valley. Two independent hydrothermal systems exist in LGPF: the Tongonan Geothermal Field (TGF) in the north and the Mahanagdong Geothermal Field (MGF) in the south.

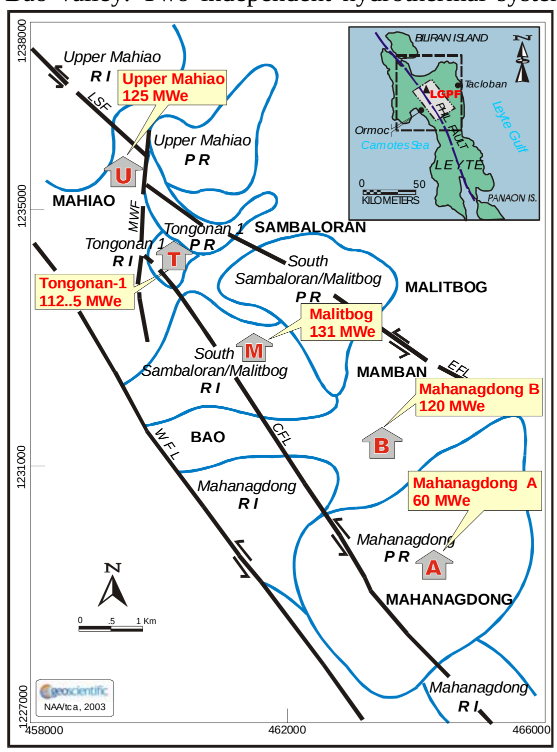



*Figure 1. Generalized sectoral location of LGPF production (PR) and reinjection (RI) areas.*

TGF occupies approximately 15 $km^2$ of rolling to rugged topography and has three production sectors, namely, Upper Mahiao (UM), Tongonan-1 (TGN-1) and Malitbog-South Sambaloran (MB-SS) (Fig. 1). TGN-1 in turn encompasses the Mahiao-Sambaloran production sector that supplies the first 112.5 MWe power plant that began in 1983. Full exploitation of TGF started in 1996 with the commissioning of additional 125 MWe Upper Mahiao power plant (1996), the 231 MWe Malitbog power plant (1996-

1997) and the 50 MWe SLI or steamline interconnection (2000). The SLI pipes the excess steam of TGF to the neighboring Mahanagdong geothermal field.

Initial extraction rate started at 0.5 to 1.1 Mt per month from 1983 to 1989 (Fig. 2). Of the total amount, about 0.1 to 0.5 Mt were injected back into deep wells. With the commissioning of the additional power plants, the monthly extraction rate increased abruptly from 1.3 Mt in 1995 to 4.5 Mt in 1998 and further rose to around 5 Mt when SLI was put online. The cumulative net mass loss from 1983 to present is about 291 Mt.

On the other hand, MGF, located 8 km south of TGF, is divided into two sectors: Mahanagdong-A (MG-A) and Mahanagdong-B (MG-B). MG-A constitutes the 120 MWe main plant and 12 the MWe topping cycle plant, while MG-B supplies 60 MWe to the main power plant and 6 MWe to the topping cycle plant. Commercial operation of MGF commenced in 1997. Since the full exploitation of MGF, the cumulative extraction started at 9 Mt in 1997 and increased to 192 Mt in May 2003 (Fig. 3b). Of the total amount, 127 Mt were injected back into deep wells incurring a net mass loss of about 65 Mt.

To date, both TGF and MGF experienced pressure drawdown. For twenty years of continuous fluid extraction, TGF has experienced pressure drawdown of 4 to 4.5 MPa affecting the Upper Mahiao and South Sambaloran production fields (Fig. 4). Consequently, various physical and chemical changes occurred in the reservoir mainly in response to field utilization. Such changes include the rise in enthalpy, the lowering of the water level, which resulted in the lateral and vertical expansion of the steam zone and the decline of brine discharge (Dacillo and Siega, 2003).

As early as 1998, pressure drawdown was detected in MGF as evidenced by declining reservoir chloride concentration, silica geothermometer and well output, which decreased from 192 to 135 MWe. This pressure drawdown induced the inflow of cooler peripheral waters that has swamped the reservoir (Herras and Siega, 2003). Downhole pressure measurements recorded the highest drawdown of about 4.5 MPa in the vicinity of MG-28D, -30D and -31D (Fig. 4).

Repeat gravity measurements in other part of the world have become a standard geophysical method in monitoring the response of geothermal reservoir with exploitation. This technique in tandem with precise leveling survey could yield valuable information on the causes of gravity change between surveys.

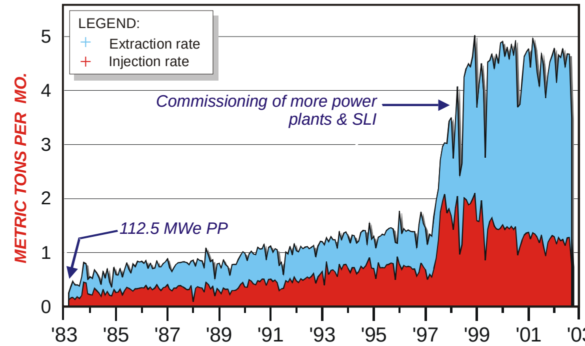
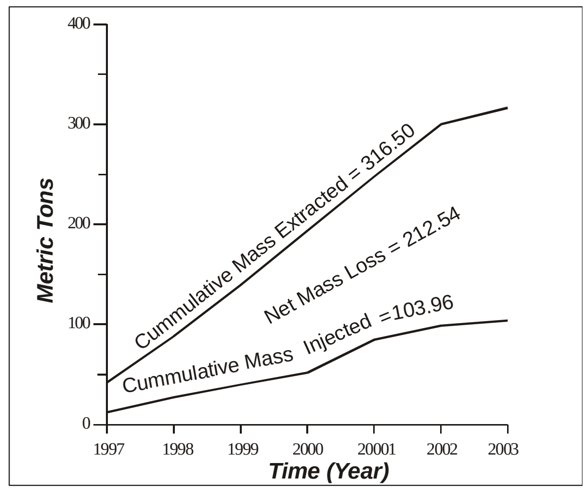
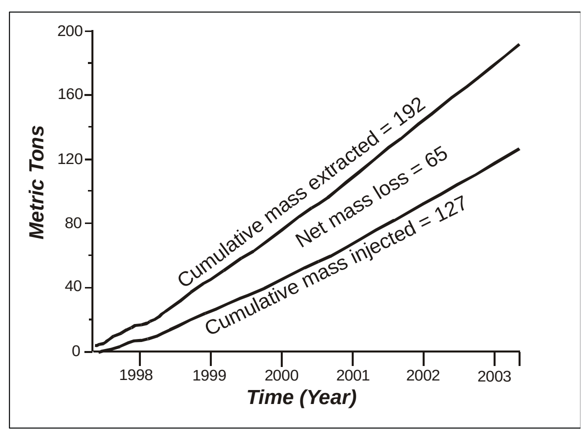



*Figure 2. LGPF cumulative monthly mass extraction rate from 1983 to 2003.*




a) Tongonan Geothermal Field




b) Mahanagdong Geothermal Field

*Figure 3. Cumulative mass extraction from 1997 to 2003; a) Tongonan Geothermal Field, b) Mahanagdong Geothermal Field.*

The purpose of the survey is to demonstrate the importance of repeat gravity survey with regard to the field management of geothermal reservoirs.

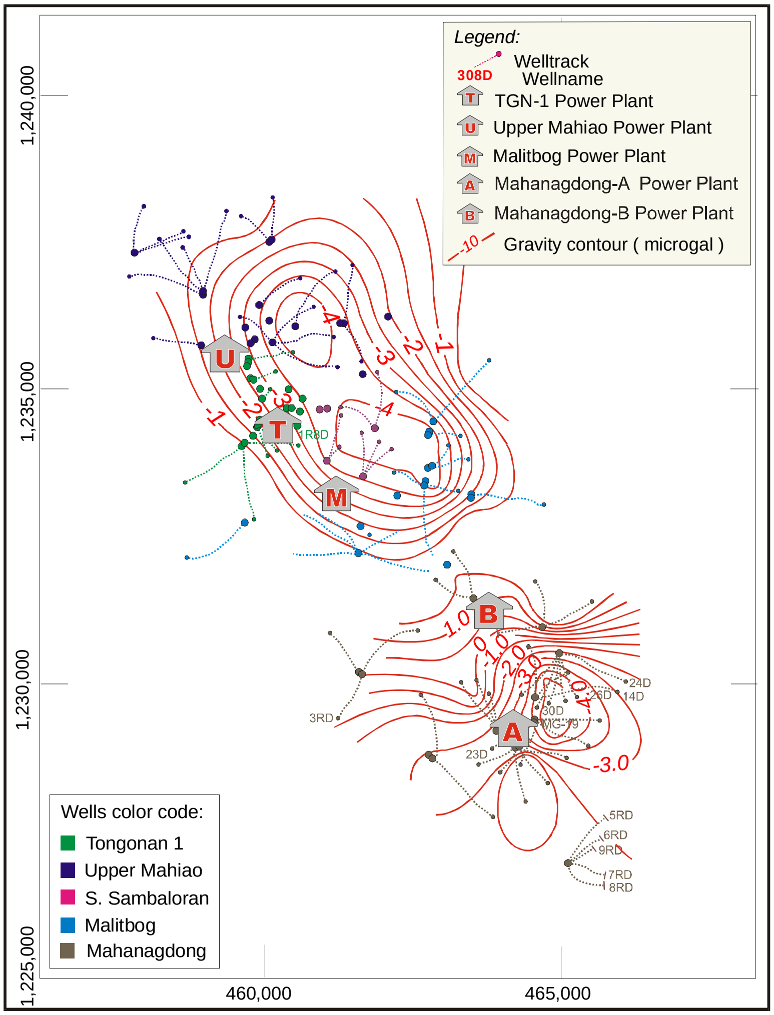



*Figure 4. Pressure drawdown from 1996 to 2002.*

## GRAVITY DIFFERENCES

The main causes of gravity differences at the same point between surveys are vertical ground movements and net mass loss from the geothermal field (Hunt, 1977). Other factors that affect gravity differences are: changes in ground water level, changes in saturation (soil moisture content) in the aeration zone, local topographic changes, horizontal ground movement and changes in gravity at the base station. Except for the change in ground water level and the changes in gravity at the base station, all other factors affecting gravity differences are negligible. Gravity values may also vary with time (in million years) as a result of deep seated regional mass movements (active volcanism) but because geothermal fields generally occupy a relatively small area, and the difference in time between surveys is short, the gravity effects of such movements are usually small and can be neglected.

The gravity effects of mass movements in the geothermal reservoir, called gravity changes, are obtained by correcting the measured gravity differences for the gravitational effects of vertical ground movements, changes in groundwater level and changes in base value.

For convention, a decrease in gravity is referred to as a negative change and an increase a positive change. Negative changes imply net mass loss and positive change imply net mass gain.

## DISCUSSION OF RESULTS

The uncorrected gravity changes between 1997 and 2003 (Fig. 5) indicate that there was a decrease in the value of gravity with a maximum difference of –160 µgal in the Upper Mahiao and TGN-1 sectors. The greatest decrease in gravity value occurred within the main TGF production field where it coincides with the location of the ≥ –100 µgal contours. Away from the production field, the gravity differences become smaller. Whilst in MGF, the production sector falls within the region where gravity generally decreased by about –40 µgals, which coherently centers on the

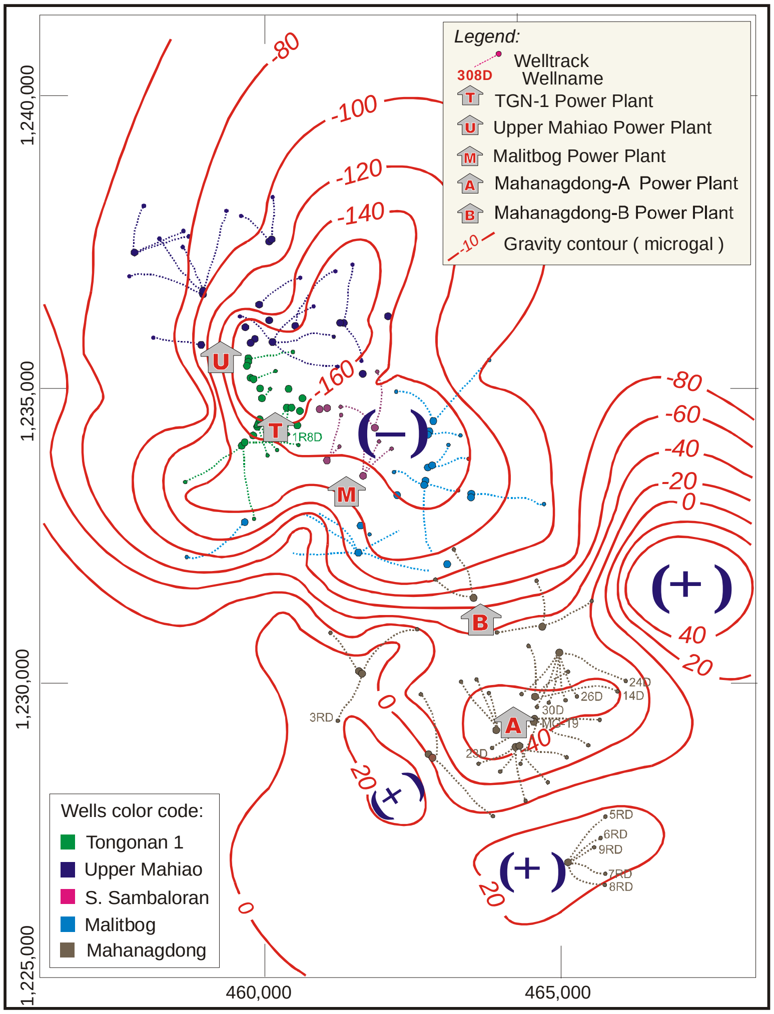



*Figure 5. Uncorrected gravity changes from 1997 to 2003.*

main production area, extending from MG-23D, -19, -30D, -28D, -26D, and -14D. A 20-µgal increase in gravity can also be seen in the southern reinjection area near wells MG-5RD, -6RD, -7RD, -8RD, and -9RD. The production area itself does not lie directly over the zone with the largest change in gravity, but rather, along the gradient where the gravity changes from 0 to –40 µgals. The centers of the largest gravity decrease form two separate "sinks", one at the southeastern and the other at the western fringes of the production boundary.

The gravity changes between 1997 and 2003 corrected for elevation and base changes are depicted in Figure 6. The values used for vertical gravity gradient in elevation correction and base correction are –298 µgal/m and 24 µgal, respectively. They show no significant differences in pattern with that of the uncorrected gravity changes. However, the gravity values of about –100 µgal are expectedly lower because they were corrected for elevation and base changes. From 1997 to 2003, TGF yielded a net mass loss of 212 Mt of geothermal fluids (Fig. 3a). Pressure drawdown contours from 1996 to 2002 (Fig. 4) indicate that the highest drop in pressure are located in Upper Mahiao and South Sambaloran (> 4.0 MPa) areas, which also coincide with the location of the highest negative gravity changes (≥ –100 µgals). Similarly, the depressurized 1 bar $PCO_2$ area has extended from Upper Mahiao to South Sambaloran sectors (Fig. 7), coinciding also with the –100 µgal contour. This depressurized zone, likewise, corresponds to the areas where production wells are already discharging dry steam.

Beginning 1997 when Mahanagdong became online for geothermal power production until 2003, the sector has lost a net total of 65 Mt of mass from the reservoir as a consequence of exploitation (Fig. 3b). The production sector this time is roughly defined by a decrease in gravity of 20 to 40 µgals (Fig. 6). Compared with the uncorrected data, the region where there is a decrease in gravity (negative values) is more extensive, and broadens out to include most

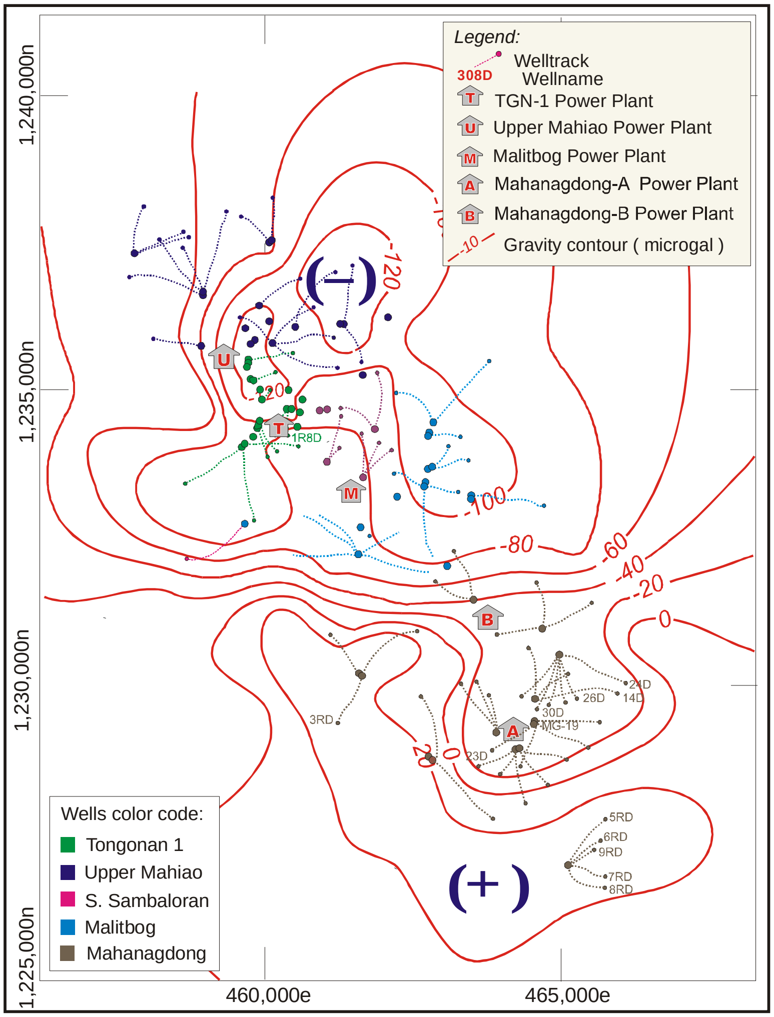



*Figure 6. Corrected gravity changes from 1997 to 2003.*

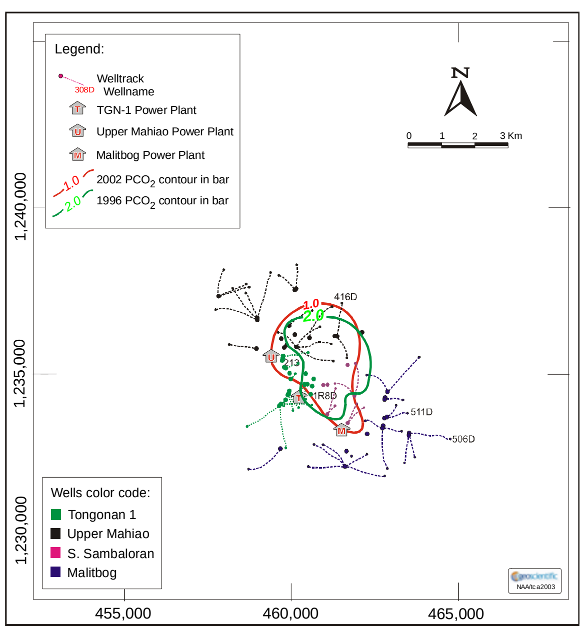



*Figure 7. PCO2 contour from 1996 to 2002.*

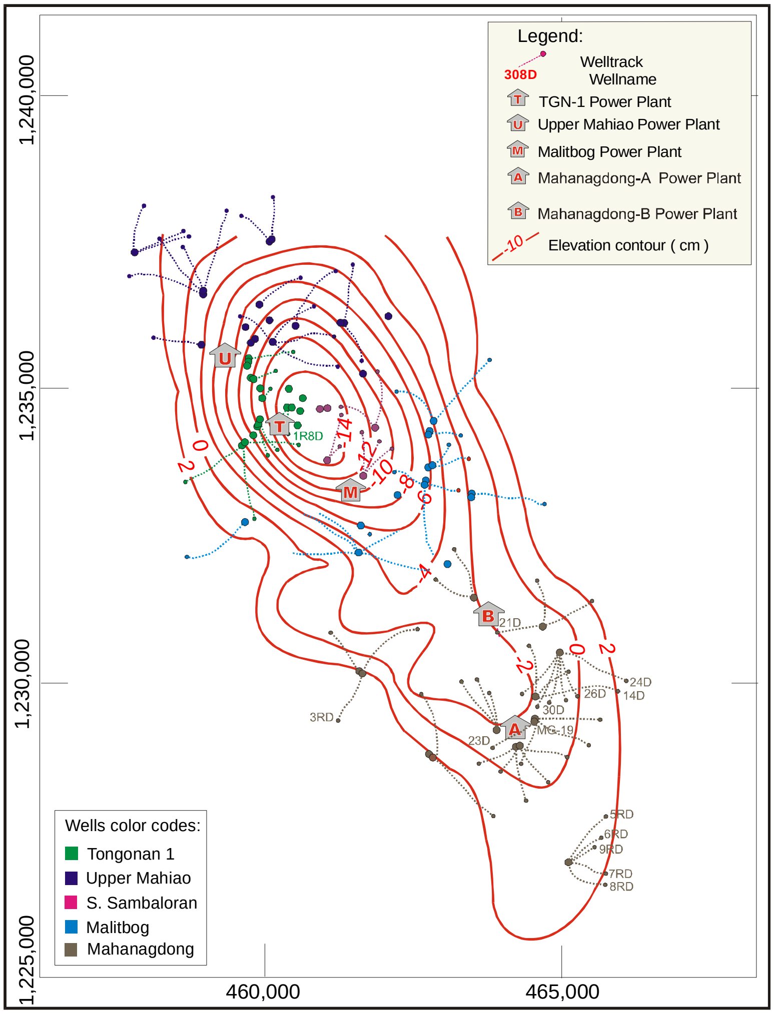



*Figure 8. Elevation changes from 1997 to 2003.*

of the eastern and the northeastern side of the production area. A well-defined 20-μgal increase in gravity encloses the southern and western reinjection areas.

The ground vertical movements (elevation differences) observed on the network from 1997 to 2003 were mostly negative (Fig. 8). The highest recorded subsidence (180 mm) occurred at TGN-1 production sector 1 km north of well 1R8D.

Generally, the amount of subsidence is relatively small since full exploitation of TGF commenced only in 1998, hence, no significant physical evidence on the surface could be found. Furthermore, the very small variance in elevation between 1997 and 2003 may be attributed to the zero-waste disposal scheme of the company, which reinjects back a substantial amount of mass into the reservoir.

In MGF, an apparent subsidence occurred between 1997 and 2003. The subsided region has a general northwest to southeast orientation and approximately follows the trace of the Philippine fault, which transects the area. The subsidence was minimal with only a maximum of about 20 mm and dips towards the northwest in the direction of TGF, where the magnitudes are relatively larger and are probably more significant.

## INTERPRETATION

Significant gravity differences at LGPF occurred at TGF during the survey period 1997 to 2003. The large negative gravity difference was primarily caused by the net mass loss of 212 Mt of fluid and steam (Fig. 3) from the geothermal reservoir due to exploitation. At present, the effect of vertical ground movement is still minimal. However, the effect of changes in shallow groundwater level cannot be discounted.

The large negative gravity changes at TGF correlate well with the liquid pressure drawdown from 1996 to 2002 (Fig. 4) with corresponding lateral and vertical

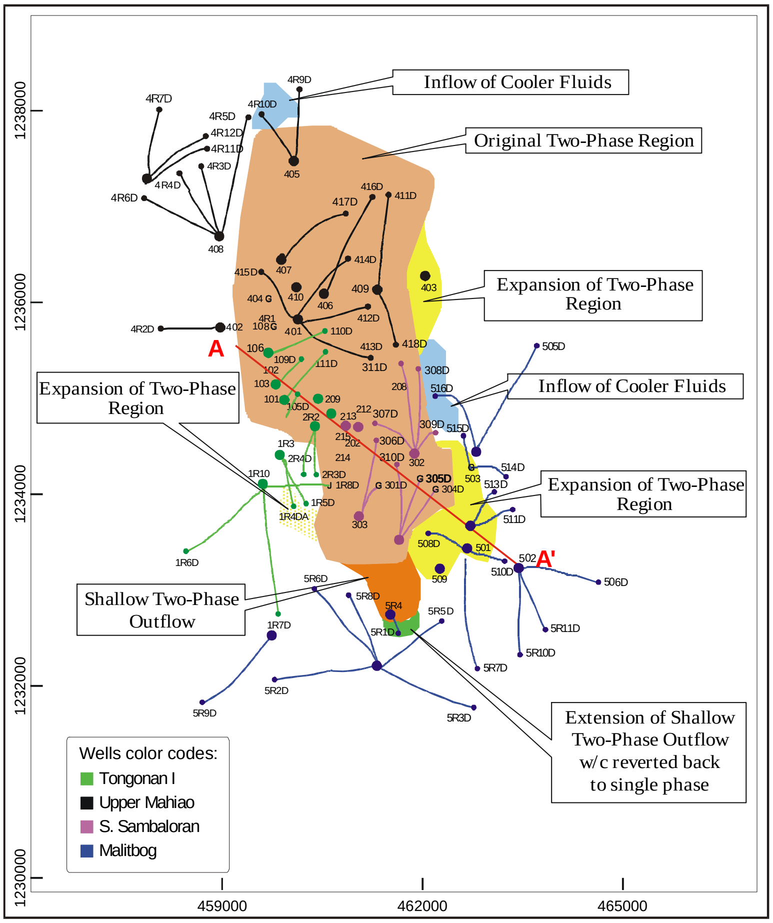



*Figure 9. Lateral expansion of the 2-phase zone (after Sta. Ana, 2002).*

expansion of the 2-phase zone (Figs. 9 and 10). Likewise, the depressurized 1 bar $PCO_2$ area where it extended from Upper Mahiao to South Sambaloran sector (Fig. 7) corresponding to the areas where production wells are discharging dry steam fall within the > -100 µgal contour. This also depicts the lateral expansion of the shallow steam cap towards South Sambaloran and the decline of the reservoir pressure (Dacillo and Siega, 2003).

The exploitation of MGF since 1997 has incurred pressure decline in the central part of the reservoir. This induced the inflow of cooler peripheral waters, particularly from the northwest and has presently swamped the reservoir thereby reducing the in-situ steam supply. Power output is now at about 135 MWe, which went from a high of 192 MWe in 1998 (Herras and Siega, 2003).

The pressure decline as a direct consequence of mass extraction is very apparent in the MGF. In the MG-DL area, for example, extensive drawdown since 1998 has resulted to a decline of almost 5 MPa in reservoir pressure in the central part of the production field. This decrease in subsurface mass is reflected in the microgravity measurements by a corresponding decrease in gravity values. As shown in Figure 6, up to greater than 20-µgal decrease in gravity was observed occurring at the central portion of the production sector since 1997. The area includes well MG-23D in the southwest, wells MG-30D and MG-28D at the central part, and well MG-24D in the northeast. Comparing this figure with the plot of pressure drawdown contours (Fig. 4), it is plain that the maximum drawdown was experienced roughly over the same area, which also borders around wells MG-30D and MG-28D.

On the other hand, the positive gravity change experienced in the vicinity of wells MG-5RD, -6RD, -7RD, -8RD, and -9RD, which was as high as about 20 µgal could possibly be due to reinjected fluids, with the area being a reinjection sink.

According to Gauss's Potential Theorem (Hammer 1945; Hunt 1970),

$$\Delta \mathbf{M} = \Sigma \Delta g \Delta s / 2\pi G$$

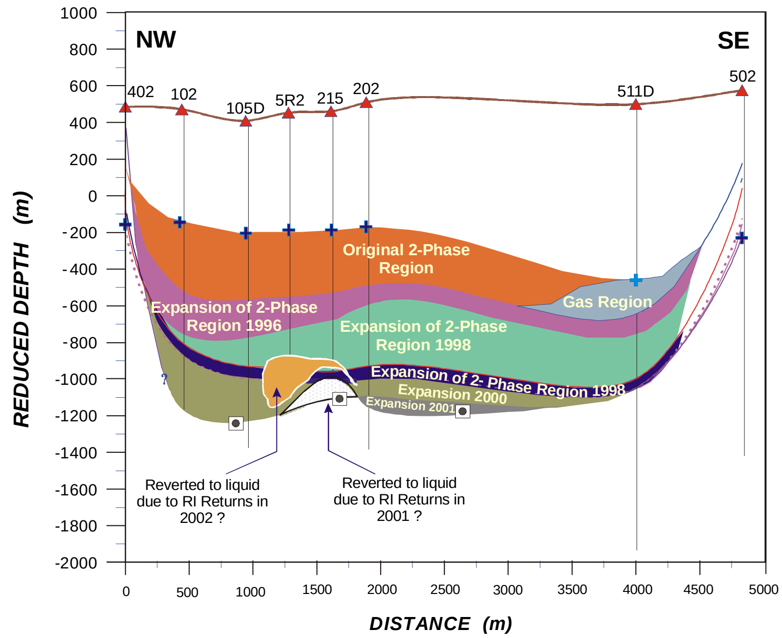



*Figure 10. Yearly vertical expansion of the 2-phase zone zone along line A-A'(after Sta. Ana, 2002).*

where: ΔM is the net mass loss from the system, Δg is the corrected gravity difference for area Δs, and G is the gravitational constant (6.67 x $10^{-11}$ N $m^2$ $kg^{-2}$). The integrated sum of the corrected gravity difference (ΣΔgΔs) between 1997 and 2003 obtained from the contours in Fig. 6 is about –10205 µgal $km^2$, hence, the resulting net mass loss from the system (ΔM) is about 244 Mt. Using the mass balance equation,

$$(\mathbf{Mw + Ds}) - (\mathbf{R + I}) = \mathbf{\Delta M}$$

where: Mw is the mass withdrawn from the wells, Ds is the surface discharge, R is the natural recharge, and I is the injected fluid. The natural recharge (R) is 34 Mt or 12 % of the total mass removed from the system.

Examination of the contour map of gravity changes (Fig. 6) shows that the gravity changes are generally negative, but the greatest is in TGF area. This is where the greatest degree of mass withdrawal compared with replacement is occurring, probably as a result of lateral and vertical expansion of the 2-phase zone (Figs 9 and 10). The negative gravity changes in the reinjection areas indicate that more fluid is still being withdrawn than being injected.

## CONCLUSIONS

Based on Gauss's Potential Theorem and mass balance equation, the negative gravity changes from 1997 to 2003 indicate that the system (LGPF) has incurred a net mass loss of about 244 Mt and a natural recharge of about 34 Mt or 12% of the total mass removed.

At TGF, the main causes of gravity changes resulting from mass changes in the reservoir are the liquid drawdown and the saturation changes in the 2-phase zone. This extraction, with a recharge deficit of about 212 Mt reflected a 4.5 MPa drawdown in reservoir pressure, which in turn induced the migration of cooler peripheral fluids towards the production reservoir, thereby lowering its steam capacity.

The pressure drawdown experienced in the MGF is a direct consequence of the massive mass withdrawal from the geothermal reservoir. Likewise, the field has lost a total of 65 Mt of water and steam to the atmosphere since its exploitation in 1997.

It was presented that the trends observed in the various reservoir monitoring methods were similarly attained using microgravity data. With several sets of microgravity data, trends can also be established that will allow tracking of the path taken by reinjected fluids within the reservoir. Reservoir properties, such as porosity and saturation can also be estimated using the method, and will be an invaluable aid in testing numerical models of the reservoir performance. Given the versatility, the microgravity method could be considered as an alternative if not a better method in monitoring reservoir processes.

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