

REPEAT GRAVITY MEASUREMENTS AT THE TONGONAN GEOTHERMAL FIELD, NORTH CENTRAL LEYTE, PHILIPPINES

Nilo A. Apuada and Rhoel Enrico R. Olivar

PNOG Energy Development Corporation, Merritt Road, Fort Bonifacio, Taguig, Philippines

ABSTRACT

Leyte Geothermal Production Field (LGPF) in North Central Leyte is the largest geothermal area in the Philippines. It is comprised by 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 Mtons in TGF. 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.

The greater than 100 μ gal decrease in gravity values since 1997 was recorded at TGF coinciding with the production field. This was accompanied by a corresponding ground subsidence, which had a maximum amplitude of about 18 cm, likewise occurring within the production sector of the geothermal field.

The measured decreases in gravity were associated with the mass loss from the reservoir. The data correlated well with the pressure drawdown of about 4-4.5 Mpa presently experienced over TGF.

1.0 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.

TGF occupies approximately 15 km² 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

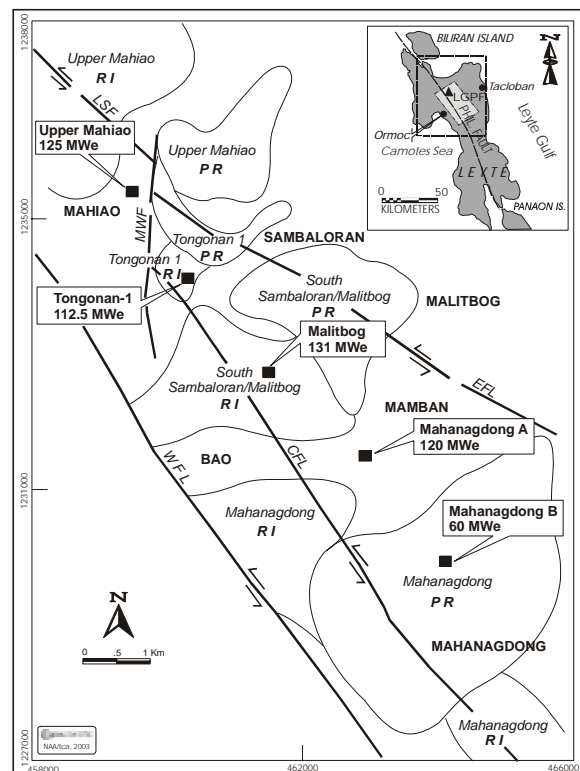


Figure 1. Generalized sectoral location of the LGPF showing approximate limits of production (PR) and reinjection areas. Heavy lines are major faults, WFL - West Faults Line; CFL - Central Fault Line; EFL - East Fault Line; MWF - Mahiao West Fault.

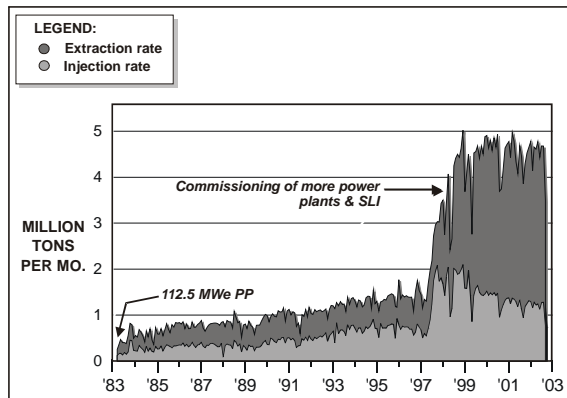


Figure 2. Cumulative mass extraction for the period 1983-2003.

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

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. 3). 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).

Repeat gravity measurements in other countries has 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 regarding the causes of gravity change between surveys. Experience in various geothermal fields in the world showed that the main causes of differences in gravity are: the net mass loss from the geothermal reservoir, subsidence or vertical ground movement and changes in shallow groundwater level.

This report aims to demonstrate the importance of repeat gravity survey with regard to the field management of geothermal reservoirs.

2.0 METHODOLOGY

PNOC-EDC started monitoring the gravity changes at LGPF in 1980. Since then, repeat gravity surveys were conducted in 1981, 1982, 1995, 1997 and 2003. The 1981, 1995, 1997, and 2003 data are most extensive and best documented. Originally, about 90 gravity benchmarks (GBM) were constructed for the baseline gravity survey in 1981. No corresponding leveling survey was performed during the first three years of microgravity measurements (1980, 1981 and 1982).

In 1995, additional 21 GBMs were constructed to cover areas outside of the production zones. After the construction, repeat gravity measurements were carried out in tandem with precise leveling survey. The leveling survey procedure and equipment employed at that time, however, was later established to be not suitable. It did not achieve the necessary level of precision to detect elevation changes that would properly account for its effect on gravity values. This set of data indicated that most of the GBMs in the production area appear to have risen by about 1 m, which were highly improbable since TGF was at the early stage of production.

Also, in 1995, Trevor Hunt introduced a new microgravity survey procedure and data reduction programs using the Woodward and Carman (1984) method and DS4Phil that helped improve data quality. It was in this survey that the vertical gravity gradient in LGPF was determined in seven locations over vertical intervals of 1.5 to 10.7 m. A mean value of $-298 \pm 9 \mu\text{gals/m}$ was obtained.

Starting in 1997, the leveling survey employed the correct procedure and the appropriate equipment. The elevation differences obtained

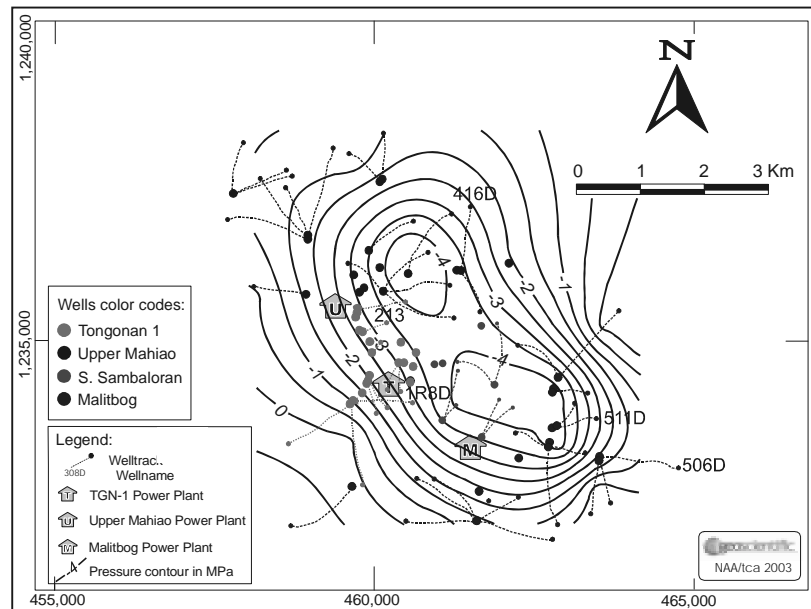


Figure 3. Pressure drawdown difference from 1996-2002 (after Sta. Ana, 2002).

for the survey period 1997 to 2003 ranged from +80 to -180mm. The average traverse loop length was about 68 km, and the average closure error was 14 mm, which was well below the allowable limit for the whole network of about 40 mm.

3.0 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.

4.0 DISCUSSION OF RESULTS

Figure 4 shows the results of the 2003 repeat gravity survey. The uncorrected gravity changes between 1997 and 2003 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 (Fig. 4a). The greatest decrease in gravity value occurred within the main TGF production field where it coincides with the location of the $\geq -100 \mu\text{gal}$ contours. Away from the production field, the gravity differences become smaller.

The gravity changes between 1997 and 2003 corrected for elevation changes are depicted in Figure 4b. They show no significant differences in pattern with that of the uncorrected gravity changes. However, the gravity values of about -140 μgal are expectedly lower because they were corrected for elevation. In the southeastern

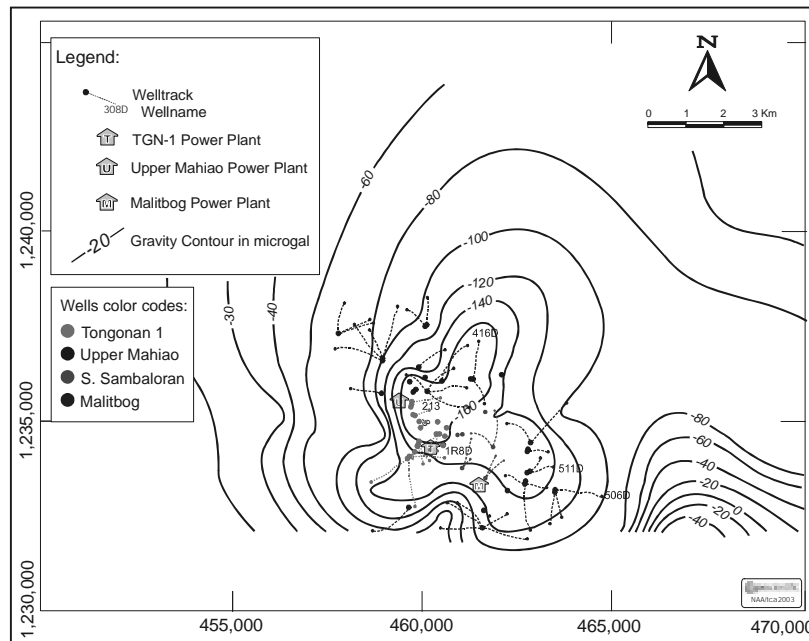


Figure 4a. Gravity difference for the period 1997-2003 (uncorrected for elevation).

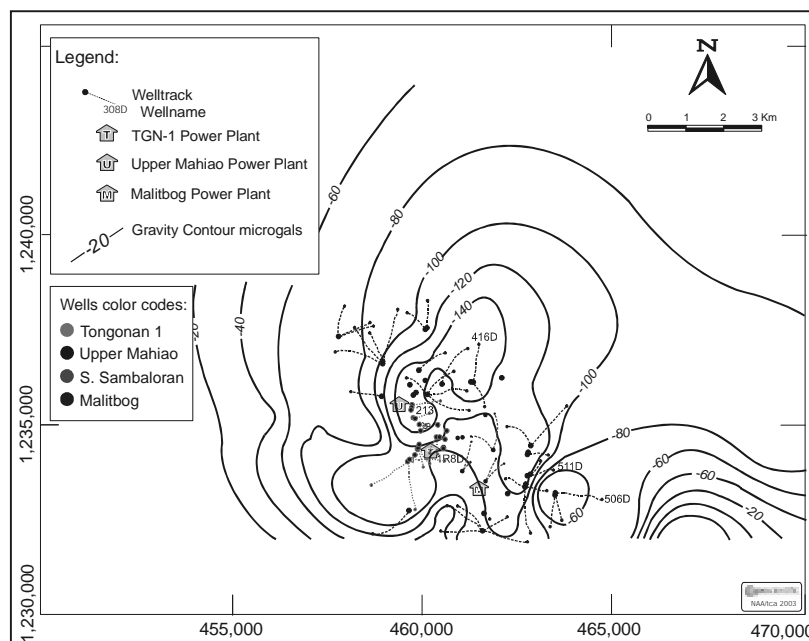


Figure 4b. Gravity difference for the period 1997-2003 (corrected for elevation).

part, the $-100 \mu\text{gal}$ contour shrink back from well 506D to 511D and elongates on a southerly direction. From 1997 to 2003, TGF yielded a net mass loss of 212 million tons of geothermal fluids (Fig. 5). Pressure drawdown contours from 1996 to 2002 (Fig. 3) indicate that the highest

drop in pressure are located in Upper Mahiao and South Sambaloran ($> 4.0 \text{ MPa}$) areas, which also coincide with the location of the highest negative gravity changes ($\geq -100 \mu\text{gal}$). Similarly, the depressurized 1 bar PCO_2 area extends from Upper Mahiao to South

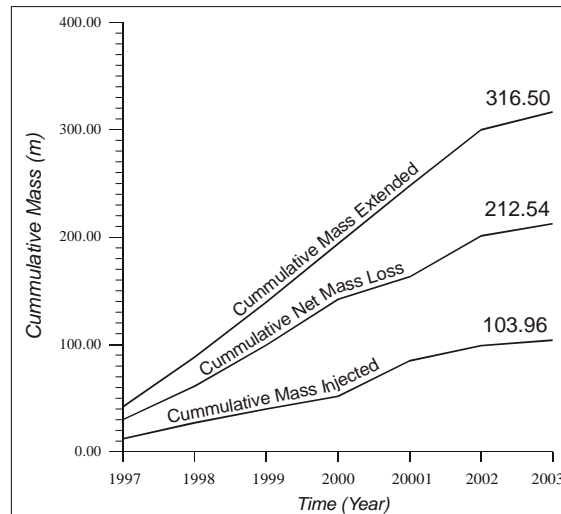


Figure 5. Cumulative mass extraction for the period 1997-2003.

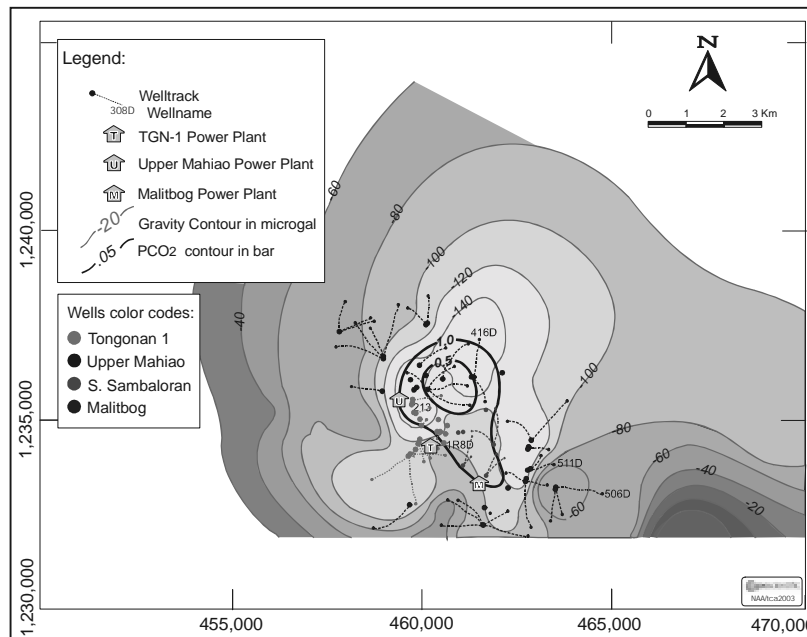


Figure 6. Gravity difference for the period 1997-2003 vs 2003 PCO2 contour.

Sambaloran sectors (Fig. 6), coinciding also with the -100 μgal contour. This depressurized zone, likewise, corresponds to the areas where production wells are already discharging dry steam.

The ground vertical movements (elevation differences) observed on the network from 1997 to 2003 were mostly negative (Fig. 7). The highest recorded subsidence (180 mm) occurred

at TGN-1 production sector, in the vicinity 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 maybe attributed to the zero-waste disposal scheme of the company, which reinjects back a substantial amount of mass into the reservoir.

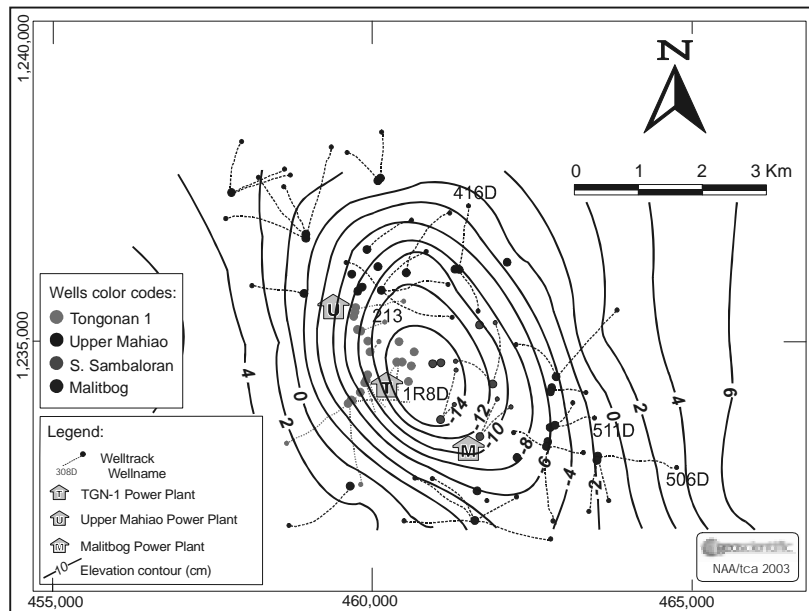


Figure 7. Elevation differences for the period 1997-2003.

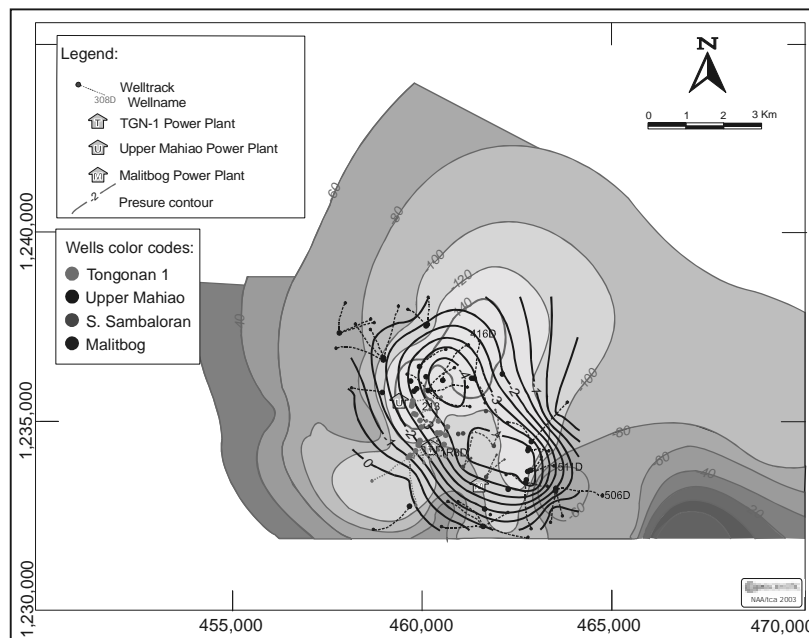


Figure 8. Gravity difference for the period 1997-2003 (corrected for elevation vs. pressure drawdown).

5.0 INTERPRETATION

Significant gravity differences at TGF occurred during the survey period 1997 to 2003. The large negative gravity difference was primarily caused by the net mass loss of 212 million tons of fluid and steam (Fig. 5) 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. 8) with corresponding lateral and vertical expansion of the 2-phase

zone (Figs. 9 and 10). Likewise, the depressurized 1 bar PCO₂ area where it extended from Upper Mahiao to South Sambaloran sector (Fig. 6) 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).

Experience in other water dominated geothermal fields in the world such as Wairakei (Allis and Hunt, 1986) and Ohaaki in New Zeland, Hatchubaru in Japan (Kasagi *et al.*, 1996), and Bulalo (San Andres and Pedersen, 1993) and Tiwi (San Andres, 1992) in the Philippines had shown that saturation change in the steam zone causes gravity changes. A pressure decrease by up to 1 MPa and a temperature decrease of 20° – 30°C could either be due to steam loss, which would cause the steam zone to dry out, or to cooling and condensation from the invading groundwater. With the former, the saturation gradually decreases with steam loss as immobile water boils due to pressure decrease. Cooling and condensation cause the saturation to increase. Similarly, in TGF, the above conditions have been experienced except for the temperature decrease since there were no temperature repeat measurements that have been conducted due to blockages on most of the production wells. However, the invasion of cooler injected fluids and the encroachment of cooler peripheral waters will certainly lower the temperature in the 2-phase zone. Hence, saturation may have contributed in obtaining negative gravity changes in TGF.

6.0 CONCLUSIONS AND RECOMMENDATIONS

Repeat gravity observations, in conjunction with measurements of subsidence can provide important information on the response of water-dominated geothermal systems to exploitation.

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. Another factor that needs to be considered is the changes in deep-liquid density due to temperature changes though this effect needs to be quantified.

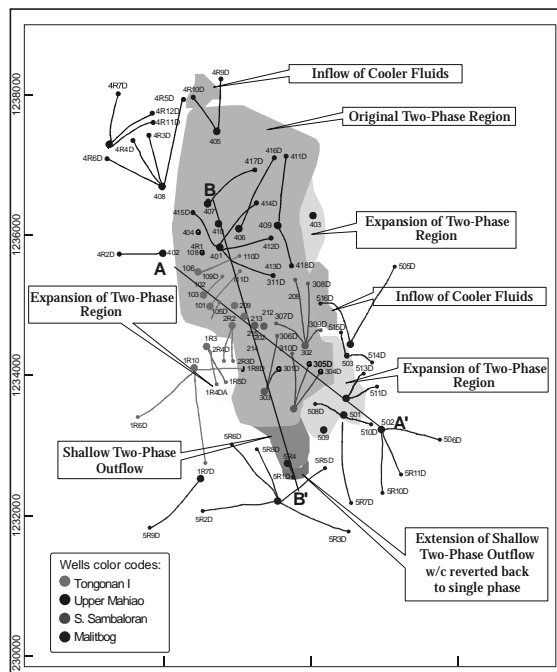


Figure 9. Lateral expansion of the 2-phase zone (after Sta. Ana, 2002).

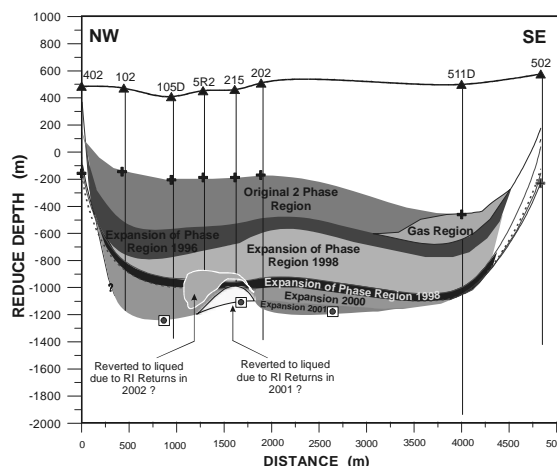


Figure 10. Vertical expansion of the 2-phase zone (after Sta. Ana, 2002).

A quantified correlation between subsurface mass movements and gravity can be produced through refined measurements, taking into account the distribution of gravity and elevation changes. Interpretation can also be enhanced if data on the variation of groundwater level is available, since it is among the major factors influencing gravity changes which can induce a change of 5-10 µgal per meter of variation (Allis, *et al.*, 2000).

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 a valuable 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 and could pinpoint possible drilling or reinjection sites in areas devoid of subsurface and well data.

To further appreciate the usefulness of repeat micro-gravity survey, a one-dimensional modeling may be performed to validate the correct value of saturation used in the simulation of the reservoir. Saturation is not measurable, hence, heat calculation using correct gravity value could yield a correct saturation value.

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