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Repeat Microgravity and Precise Leveling Response to Production in EDC Geothermal Fields, Philippines

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ABSTRACT

The Energy Development Corporation (EDC) conducted repeat microgravity and precise leveling surveys from 2016 to 2018 in two of its geothermal fields, namely Tongonan and Mahanagdong in Leyte Geothermal Project (LGP) and Palinpinon in Southern Negros Geothermal Project (SNGP). This is to determine the changes in microgravity and elevation values that may be correlated with more than 10 years of production relative the last gravity and elevation surveys. Negative gravity and elevation changes were observed within the production area of each field (i.e. PAL-1 and PAL-2 in SNGP and Mahiao, Tongonan, Malitbog-Sambaloran and Mahanagdong sectors in LGP) while positive gravity and elevation changes were noted in the reinjection areas. However, negative anomalies were also observed to extend even in reinjection areas. This could be attributed to contraction of mass due to inflow of cooler fluids and also the sum of regional tectonics in the area.

Other observed correlation between the gravity and elevation data with reservoir data included the delineation of the extent of the resource and possible expansion areas of the fields.

1. INTRODUCTION

The Energy Development Corporation (EDC) has renewed its microgravity survey campaign over its producing geothermal fields in 2016. The surveys' main objective is to determine minute gravity changes that may be correlated to the exploitation of the field. A precise leveling survey was also conducted in tandem with microgravity to determine the corresponding elevation changes. The plan is to conduct repeat surveys in 1 of EDC's 4 main fields every 5 to 10 years depending on the impact of the field production to gravity changes. Two of these surveys that have already been completed, namely from the Southern Negros Geothermal Project (SNGP) and Tongonan, Leyte (LGP). The results of these surveys will be presented here.

2. INSTRUMENTATION, SURVEY AND DATA PROCESSING PROCEDURE

Prior to the actual survey, a reconnaissance survey was conducted to determine the status of all the gravity benchmarks (GBM) in the respective fields. This is to determine whether the GBMs are still present as these may have already been demolished because of civil works or natural calamities such as landslides. It was found out that a number of GBMs were either missing or destroyed on both sites that new GBMs were constructed to replace these. Additional GBMs were also constructed to include areas that were not previously considered for monitoring and to cover possible expansion areas.

2.1 Microgravity

A LaCoste and Romberg G-526 gravimeter was used for the survey (Figure 1a). Before data acquisition, conformance tests on the LaCoste and Romberg G-526 gravimeter were performed for three consecutive days to evaluate the gravimeter's performance. This test is done by measuring the gravimeter readings at a static location at 30 minute interval for a day.

For the survey proper, a near random loop network design was applied. A typical gravity loop contains two or more survey points occupied the previous day. This is done to improve the network linkage between successive day's observations when reducing the meter readings to gravity values. To demonstrate the loop design and measurement, an example is presented in Figure 1b. Loop 1 corresponding to Day 1 measurement will follow the loop design (blue arrows and numbers): Base station → A → B → C → D → B → Base station. On the other hand, Day 2 measurement will follow the loop design (orange arrows and numbers): Base station → E → F → G → D → C → H → G → Base station. Note that stations D and C (green circles) were occupied in Day 1 and were reoccupied in Day 2 for network linkage improvement. When the microgravity survey is completed, all GBMs should have been occupied at least thrice.

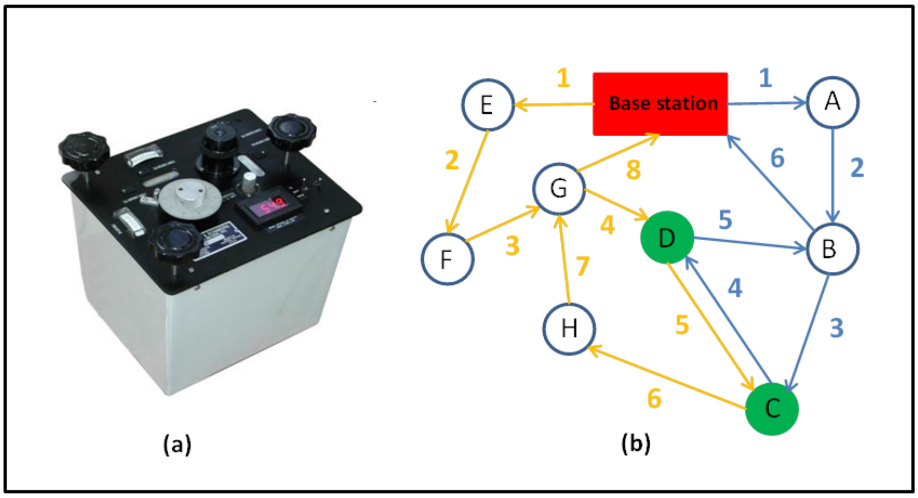

Figure 1: a) Lacoste and Romberg G-526 meter b) Illustration of gravity loop applied

The gravity data were processed using the Python-based GSolve software developed by Jack McCubbine and Grant O'Brie (2016). This included gravity network adjustment calculations via least squares. Loops of good quality data should have drift rate ≤ 0.05 mgal/day and standard errors of gravity benchmarks should be ≤ 20 microgals.

2.2 Leveling

The precise leveling survey used 2 sets of Leica™ digital level, Invar rods/staves with bar-coded graduations and leveling struts (Figure 2a). The equipment is calibrated every morning before the daily survey starts in order to adjust the collimation error of the digital level which depends on the general weather condition for that day.

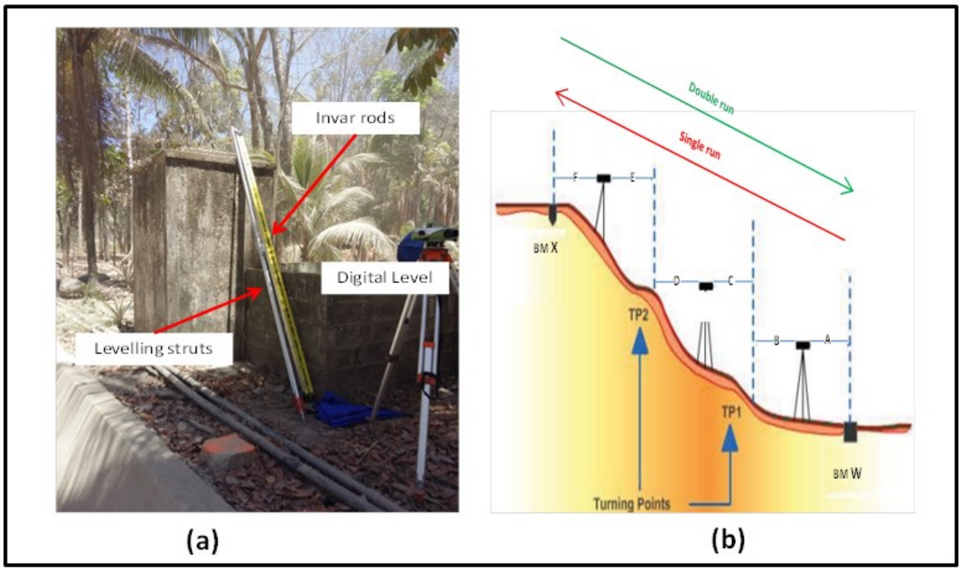

Figure 2: a) Precise leveling equipment includes digital level, invar rods and levelling struts b.) Double run set up to measure from BM W to BM X then back to close the loop

Data acquisition is conducted using a double run measurement method. In this method, a single run is performed along a certain leveling line which measurement set up involves a digital level in between two points to be measured. The measurement first starts at the backsight which can either be a permanent or a temporary benchmark then faces in the opposite direction to measure the foresight. After this, the digital level moves forward and measures the backsight and foresight of different points in between until the last point to be measured is reached which also either can be a permanent or a temporary benchmark (Figure 2b).

3. Survey results

Results of two microgravity surveys will be presented, one from Palinpinon, Southern Negros Geothermal Project and another in Tongonan, Leyte Geothermal Project.

3.1 Palinpinon, SNGP

The baseline microgravity and precise leveling survey which occupied 85 GBMs was conducted in SNGP in 1997. A repeat survey was conducted in 2007 which occupied the 85 original GBMs plus four additional GBMs for a total of 89 GBMs. The latest survey was conducted from March to September 2016 wherein a total of 98 GBMs including five new GBMs in the Lagunao sector were occupied. As for the leveling survey, 3 GBMs (81, 83 and 84) located in San Jose and Amlan were not occupied in 2007, because of its considerable distance that makes it impractical to be occupied. These GBMs were also not measured last 2016, so a total of only 95 GBMs were covered. A summary of these survey campaigns is depicted in Figure 3.

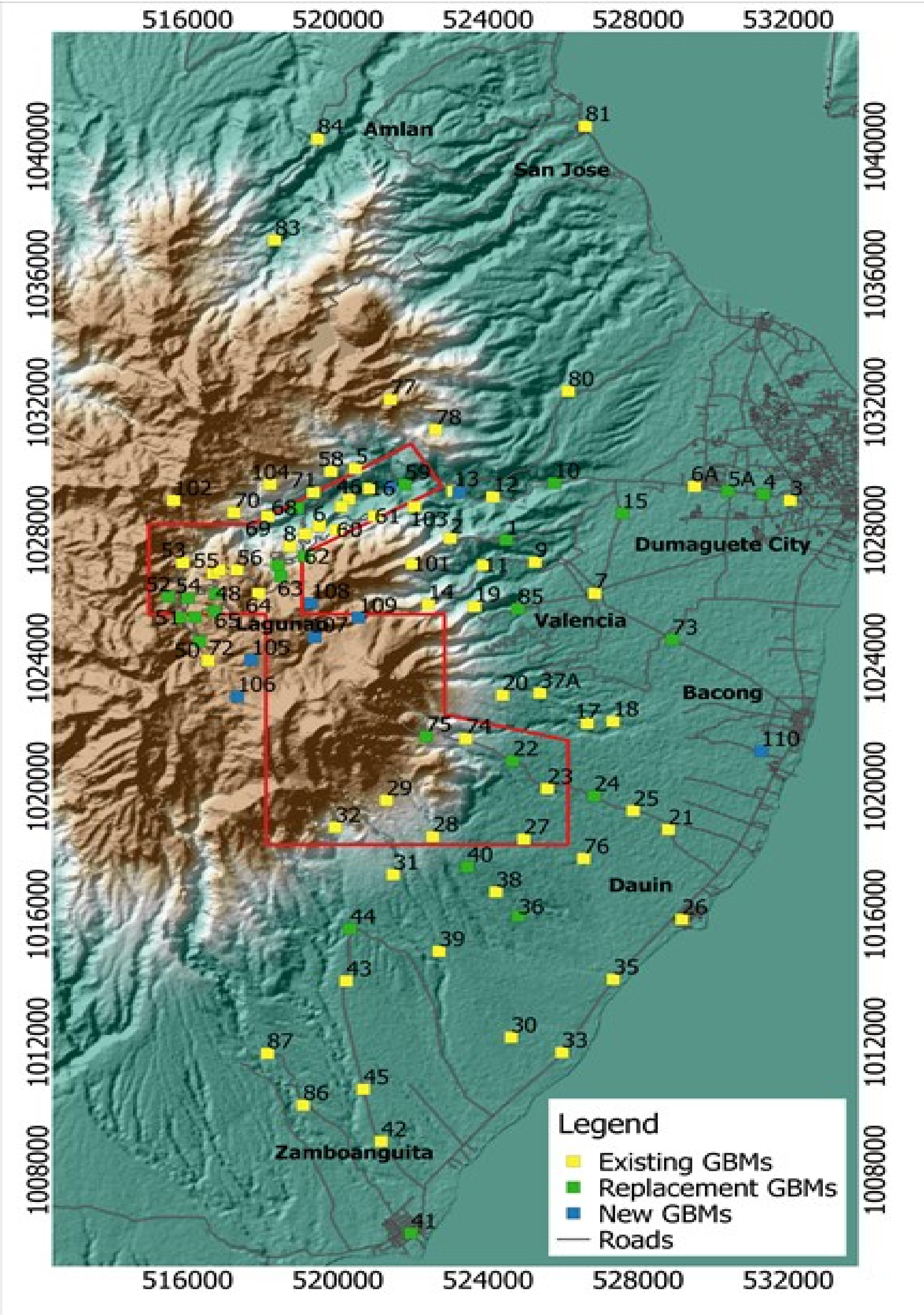

Figure 3: Location map of gravity benchmarks (GBM) in SNGP

3.1.1 Microgravity changes

Gravity changes for periods 1997-2007, and 1997-2016 were determined by getting the differences between FAG values of GBMs obtained for each period. Plotting the calculated gravity values show negative gravity contours are generally concentrated within the production field and positive gravity contours are generally found north, east and southeast of the production field (Figure 4). A prominent gravity change is seen in the area of Puhagan RI wells (at the center of the field) wherein it was at first negative for the period 1997-2007 (Figure 4a) then turned positive for 1997-2016 (Figure 4b). This is interpreted to be due to the addition of reinjection fluids from RI wells. There is uncertainty in the gravity contours south and southeast of the production field as there were no gravity values calculated in that area because GBMs there have just been established in 2016. Also note that in the western portion of the production field, the gravity contours are open because no GBMs are present there.

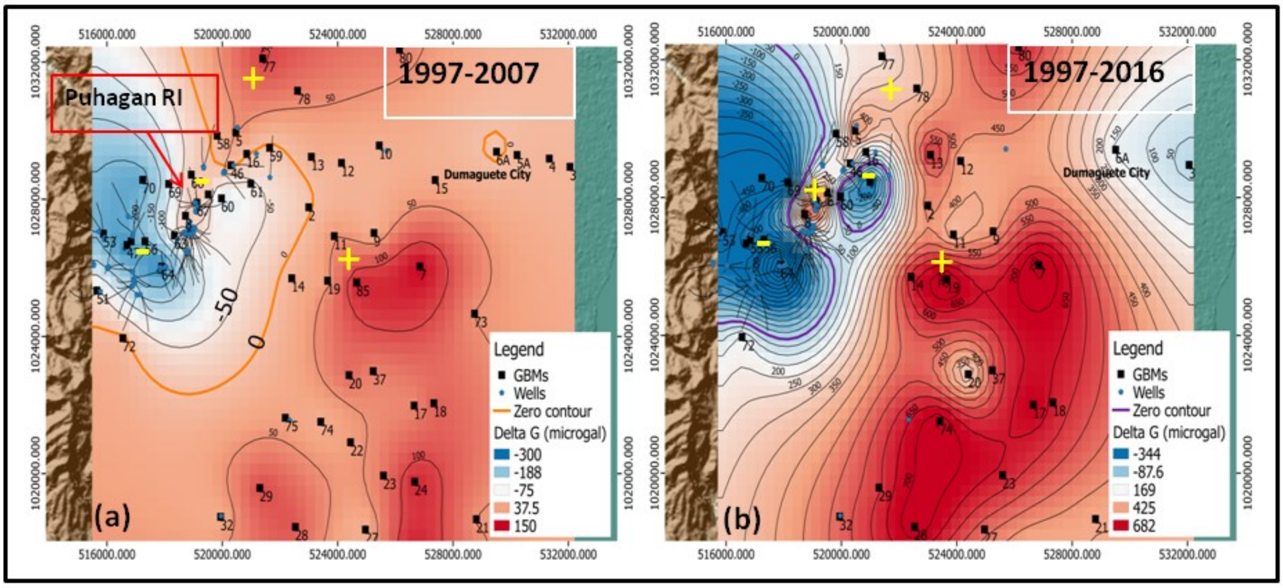

Figure 4: Plots of gravity changes in SNGP for (a) 1997-2007 and (b) 1997-2016 (from Monasterial et al., 2016)

3.1.2 Elevation changes

As what was done for the gravity changes, differences in elevation values for periods 1997-2007 and 1997-2016 were also plotted and shown in Figure 5. Negative elevation contours are notably concentrated within the production field which extends toward the east. Positive elevation contours are generally found north near reinjection wells and southeast of the production field. Similar to the gravity contours, there is uncertainty in the elevation contours south and southeast of the production field as no elevation values was calculated because GBMs there were just established in 2016. Also note that in the west of the production field, the contours are open since no GBMs were established there.

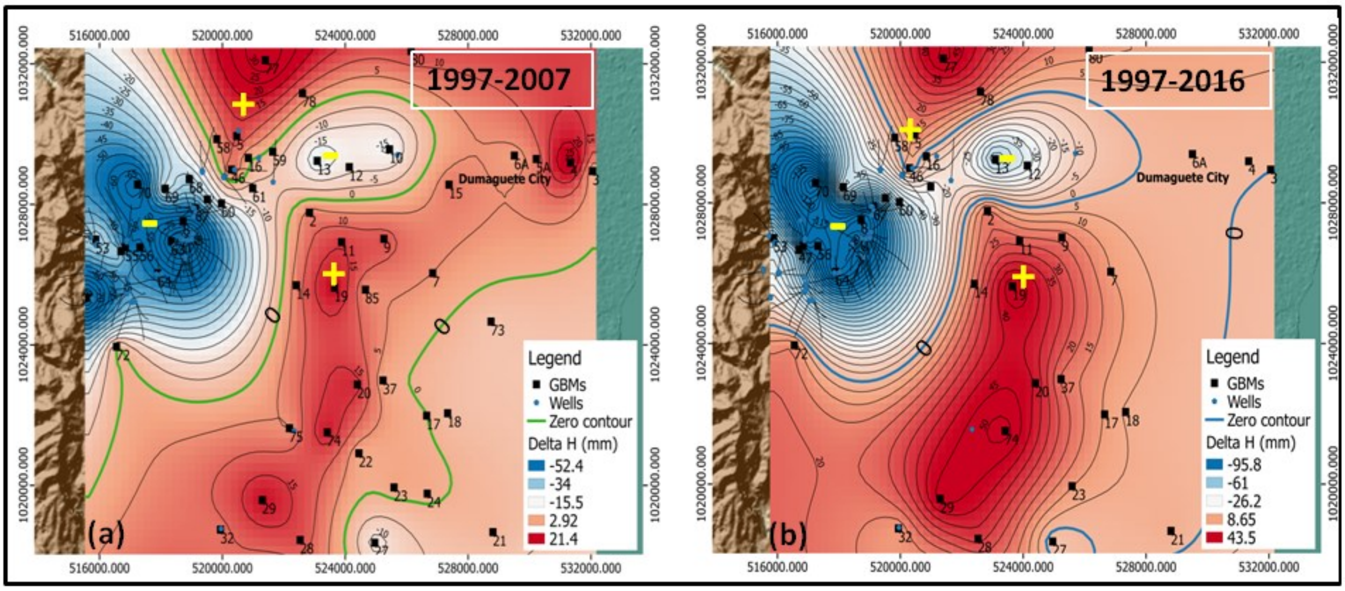

Figure 5: Plots of elevation changes in SNGP for (a) 1997-2007 and (b) 1997-2016 (from Monasterial et al., 2016)

3.1.3 Discussion of results

According to Hunt (1997), the main cause of gravity differences at the same point in a geothermal field is the vertical ground movement brought about by net mass loss or gain from extracting or injecting mass. Figure 6 shows a summary of cumulative mass extraction and mass injection of the whole SNGP field from 1983 to 2016 (EDC, 2016). Total mass produced was 835,283.80 x 10^3 Tons and total mass injected was 373,099.08 x 10^3 Tons, as of July 2016, giving a mass deficit of 462,184.72 x 10^3 Tons. This would easily explain for the areas with negative gravity and elevation changes which generally coincided with the production zones of SNGP. Plots of selected GBMs (64 and 53) that are affected by Pal-1 and Pal-2 production zones are seen in Figure 7.

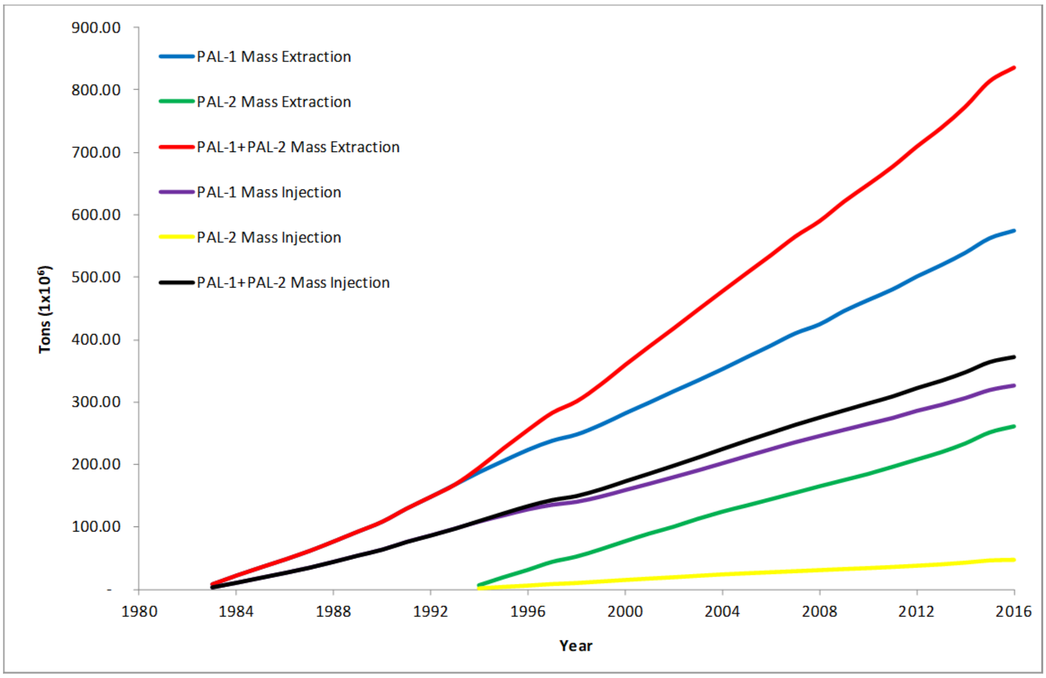

Figure 6: Summary of cumulative mass extraction and injection of Pal-1 and Pal-2 (SNGP) from 1983 to 2016 (EDC, 2016)

Reinjection wells inject brine fluid back to the earth replenishing geothermal fluid to counter the effect of continuous mass extraction by production wells. Continuous injection can result to mass gain and saturation underneath as indicated by positive gravity and elevation anomalies observed in GBMs nearby reinjection wells such as GBMs 5 and 77 in the northern portion of the field (Figure 8). However, some benchmarks such as GBMs 61 and 70, which are located in Ticala and northwest of Puhagan, exhibit negative elevation and negative gravity changes despite being located near reinjection wells (Figure 9). This means that the effect of mass extraction in these areas is greater than the effect of mass injection leading to subsidence and negative mass changes. Also, a possible explanation is that the injected fluids are displaced laterally within the rocks near the reinjection wells (Hunt, 1997) and flow towards the middle of the production field which increase saturation in the area resulting to positive gravity changes or mass gain.

There are also areas where GBMs exhibited positive gravity changes but negative elevation changes such as GBMs 6 and 67 (Figure 10) located in the central portion. This could be explained by the movement of fluid from the reinjection wells in the northern portion of the Nasuji area towards the middle thru Nasuwa Fault (Figure 11) and from reinjection in Ticala sector going to its east. Another possible explanation is that fluids from reinjection wells in Puhagan and Ticala sectors goes back into this area channeled through the Ticala and Odlumon Faults as seen in Figure 11 (Malate and Aqui, 2010). The mass gain or anomaly experienced at the center of the production field is due to increase of density caused by additional fluids and subsidence is due to the cooling contraction effects of cooler reinjection fluids (Diaz et al., 2015). Furthermore, reinjection into a two-phase zone can result in a “bulls eye” gravity change anomaly of several hundred microgal amplitude, extending radially for several kilometers from the reinjection well(s). Such an anomaly indicates that the horizontal permeability in the zone is isotropic. However, the shape of the anomaly may be distorted, similar to what is seen at the center of the field in Figure 11, by anisotropic horizontal permeability or by lateral movement of the reinjectate towards a region of low pressure such as the production zone (Hunt, 2005).

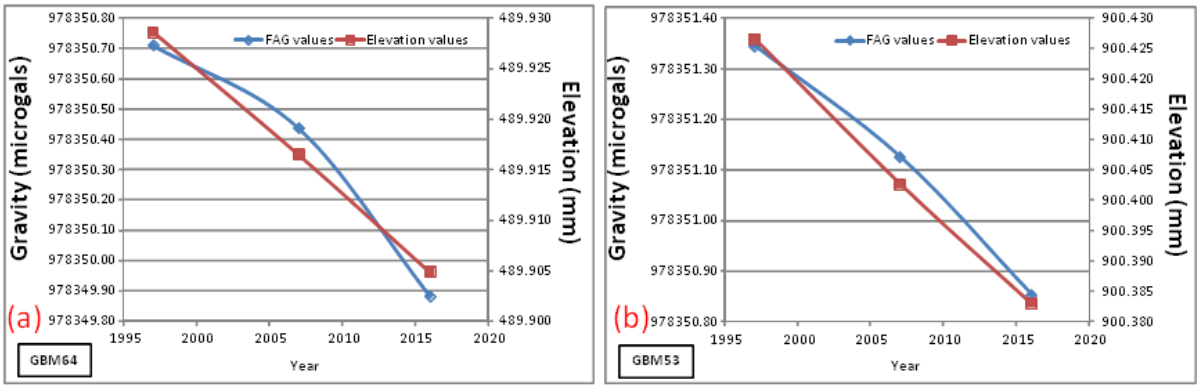

Figure 7: Plots of decreasing gravity and elevation values for (a) GBM 64 and (b) GBM 53 affected by Pal-1 and Pal-2 production zones

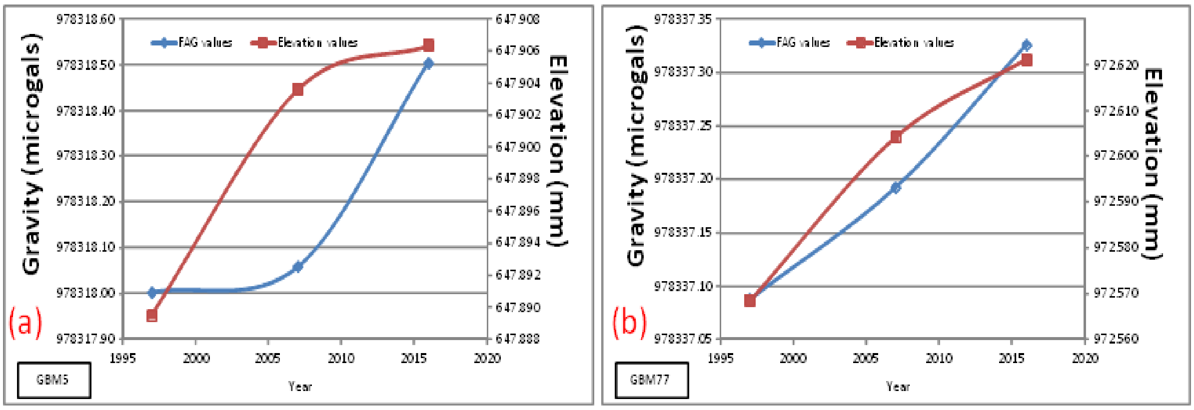

Figure 8: Plots of increasing gravity and elevation values for (a) GBM 5 and (b) GBM 77 in reinjection zones

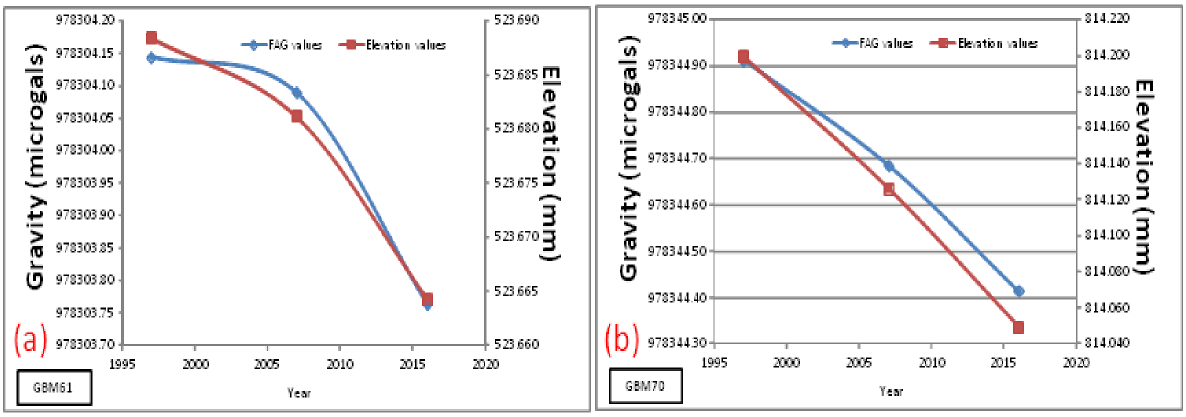

Figure 9: Plots of decreasing gravity and elevation values for (a) GBM 61 and (b) GBM 70 in reinjection zones

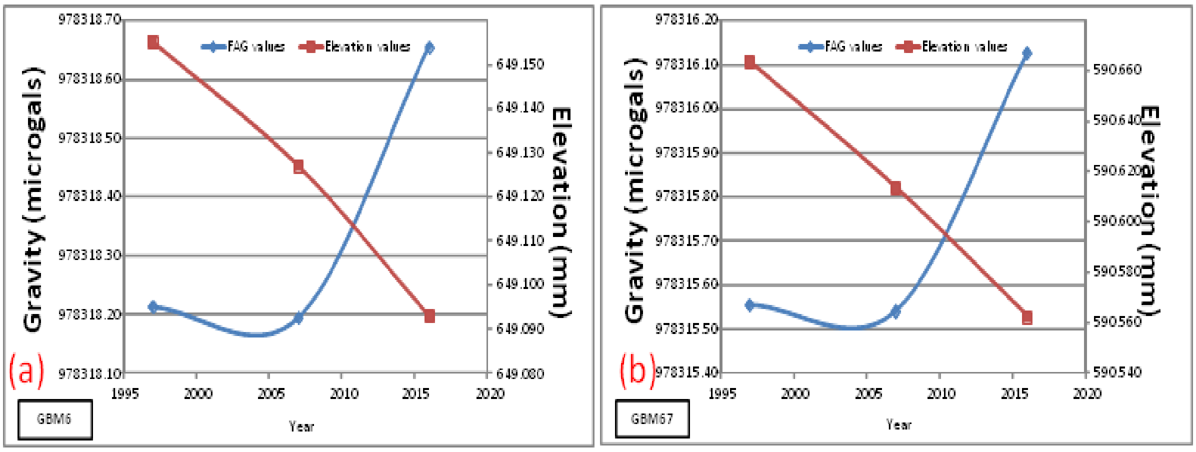

Figure 10: Plots of increasing gravity and decreasing elevation values for (a) GBM 6 and (b) GBM 67

The negative gravity anomaly is observed to extend towards south-southeast of the Lagunao Dome. It is then interpreted that the reservoir extends farther to this sector and that this is a potential site for expansion.

The computed average gravity change within SNGP decreases at a rate of about -24.11 microgals/yr while the average subsidence rate is about -2.71 mm/yr.

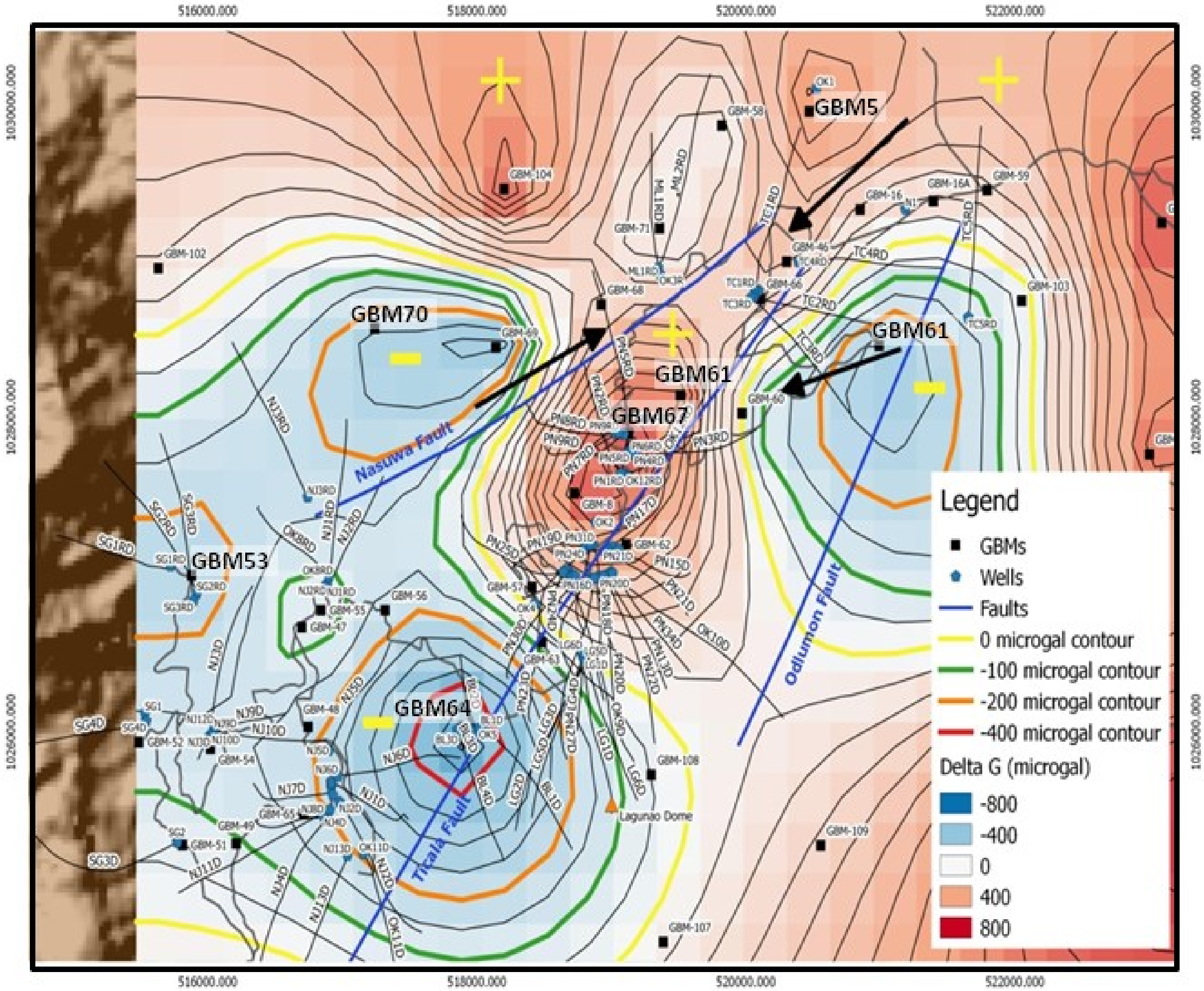

Figure 11: Gravity contour map with structures as possible flow paths

3.2 Tongonan, LGP

The considered baseline data for the microgravity and precise levelling surveys in LGP was the dataset obtained in 1997. Earlier data obtained were deemed inaccurate because of observational or reduction errors. Succeeding microgravity surveys were conducted in 2003 and the latest one in 2018. For the period 2003-1997, 85 GBMs were compared for free-air gravity and elevation differences while for 2018-1997, only 51 GBMs were used for comparison as the other GBMs were either destroyed or missing. Additional 32 GBMs were however, constructed in 2018 to completed future repeat surveys

3.2.1 Microgravity changes

The resulting gravity anomalies for the periods 1997-2003 and 1997-2018 are shown in Figures 12a and 13a, respectively. For the period 1997-2003, a notable feature would be the circular negative gravity anomaly in the middle area of Mahiao, Tongonan and Malibog-South Sambaloran sectors. For the 1997-2018 period, it can be observed that the LGP area, from Upper Mahiao-Tongonan-Malitbog-South Sambaloran sectors, is covered mostly by a negative gravity anomaly with the largest gravity decrease (about >900 microgals), located in the Upper Mahiao and Tongonan sectors. Only minimal contours were made for Mahanagdong sector because of lack of data as the GBMs were either missing or destroyed. But a negative anomaly can also be seen on the southern portion of Mahanagdong. It can also be observed that the anomalies are less negative along the fringes of the producing sectors.

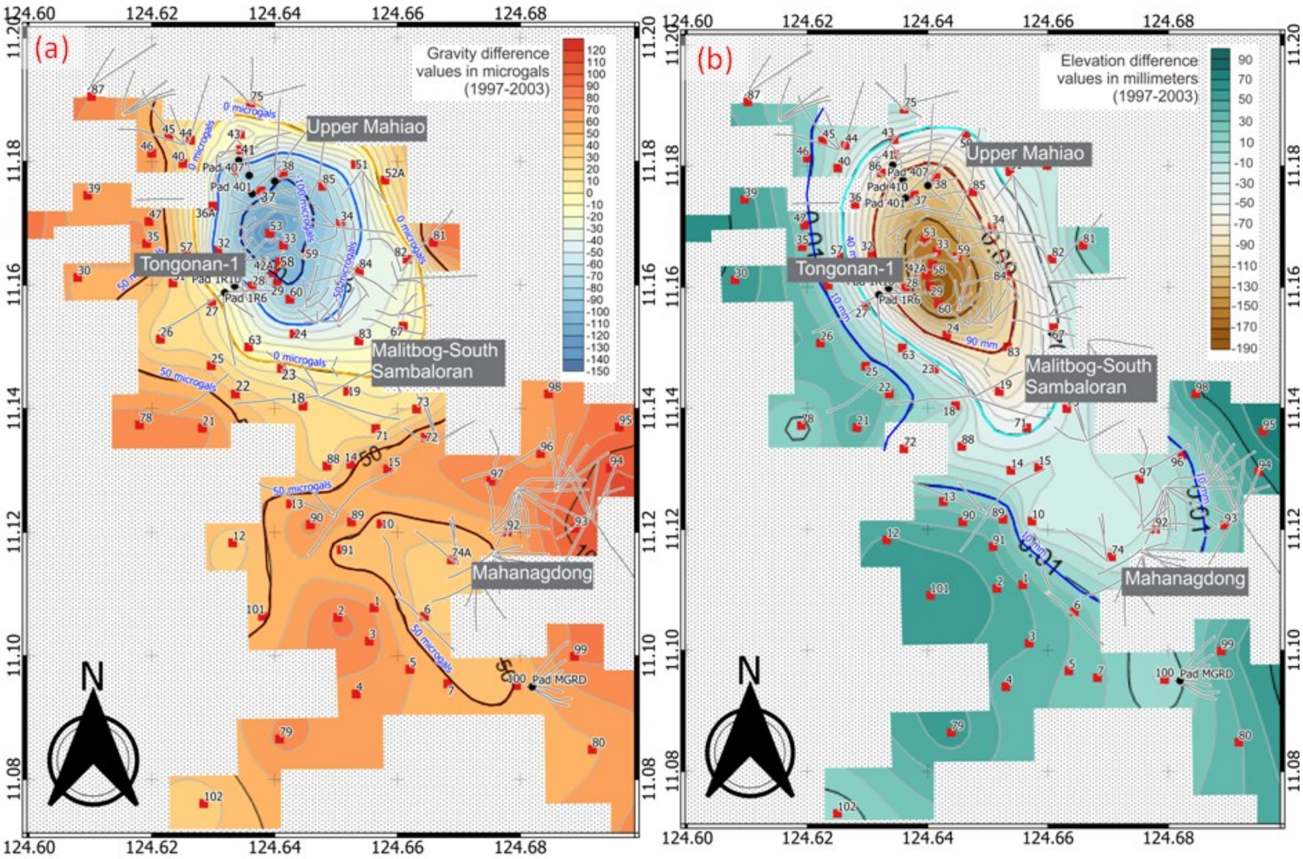

Figure 12: Map showing (a) gravity and (b) elevation anomalies in LGP from 1997-2003 (from Marteja et al, 2018)

3.2.2 Elevation changes

The observed elevation anomalies for the periods 1997-2003 and 1997-2018 are shown in Figures 12b and 13b, respectively. For the 1997-2003 period, it can also be observed that there is an elongated negative elevation anomaly (light blue to brown shaded area) located at the central area of Mahiao, Tongonan, Malibog-South Sambaloran sector down to Mahanagdong sector. This is also exhibited all the way from the Upper Mahiao in the north to Mahanagdong in the south for the period of 1997-2018. Values are more negative towards the production field and become less in the fringes.

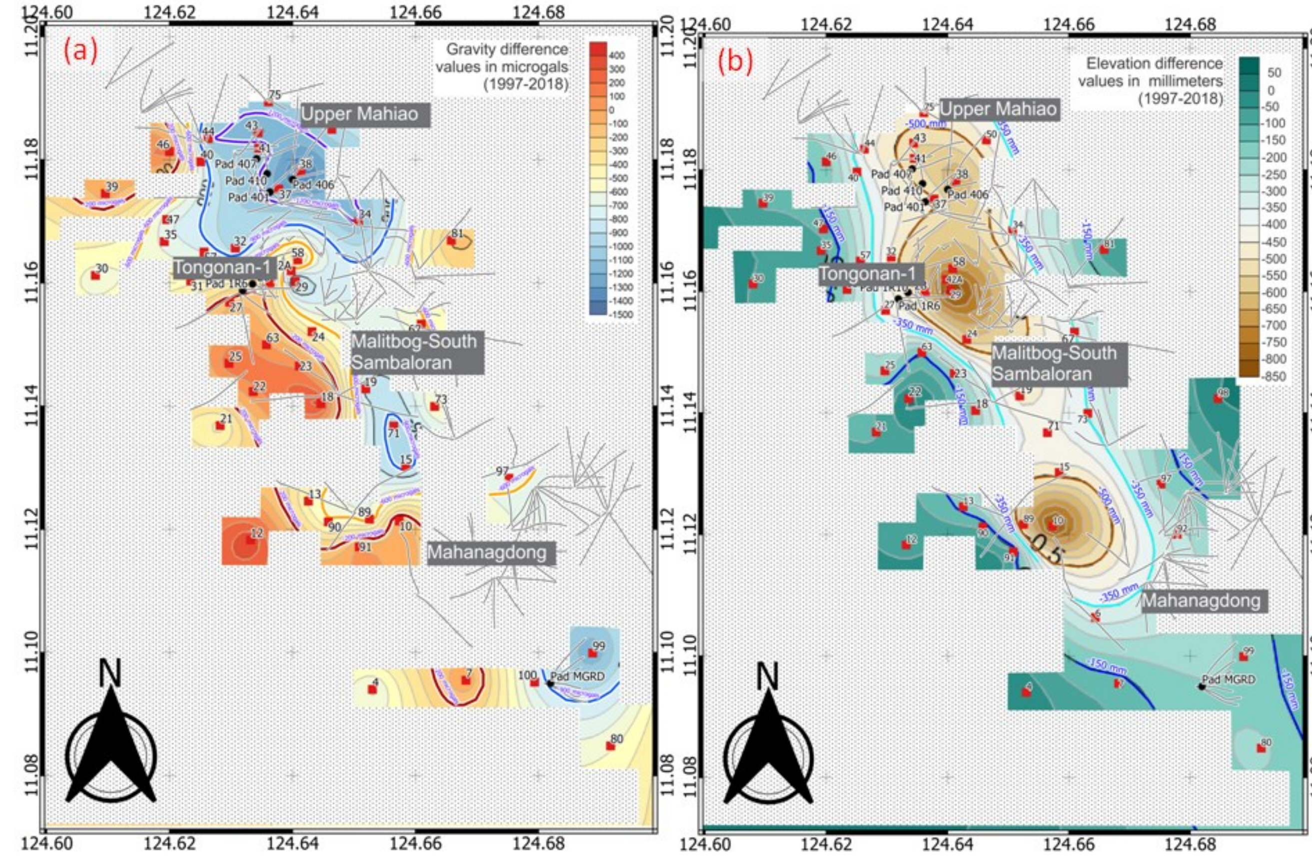

Figure 13: Map showing (a) gravity and (b) elevation anomalies in LGP from 1997-2018 (from Marteja et al, 2018)

3.2.3 Discussion of results

As mentioned in the previous section, gravity and elevation changes are mainly affected by reservoir operations in the field, which include mass extraction and mass injection of fluids. To explain the general observation in gravity and elevation changes in LGP, a an overview of the production history of LGP field is shown in Figure 14. LGP has been in commercial production since 1983, with the commissioning of the 112.5 MW NPC Tongonan Geothermal Power Plant (TGPP). Additional power plants of Upper Mahiao (116 MWe) and Malitbog-South Sambaloran (225 MWe) were commissioned in 1996-97. Mass extracted from the field from 1983 prior to the additional plants was about 1 million tons per month with about 50% injection rate. This significantly increased to about 5 million tons per month after 1997 with about 40% injection rate after 1997. The total field mass produced in LGP from March 1983 to June 2018 was about 1,848,874,295 tons while mass injected was 889,365, 601 tons or only about 48% of the mass extracted giving a mass deficit of about 959,508,694 tons (EDC, 2018). The significant mass deficit over the years is already an indication on why negative gravity and elevation differences were observed throughout the field. To explain further, correlations of significant observations with field activities are discussed.

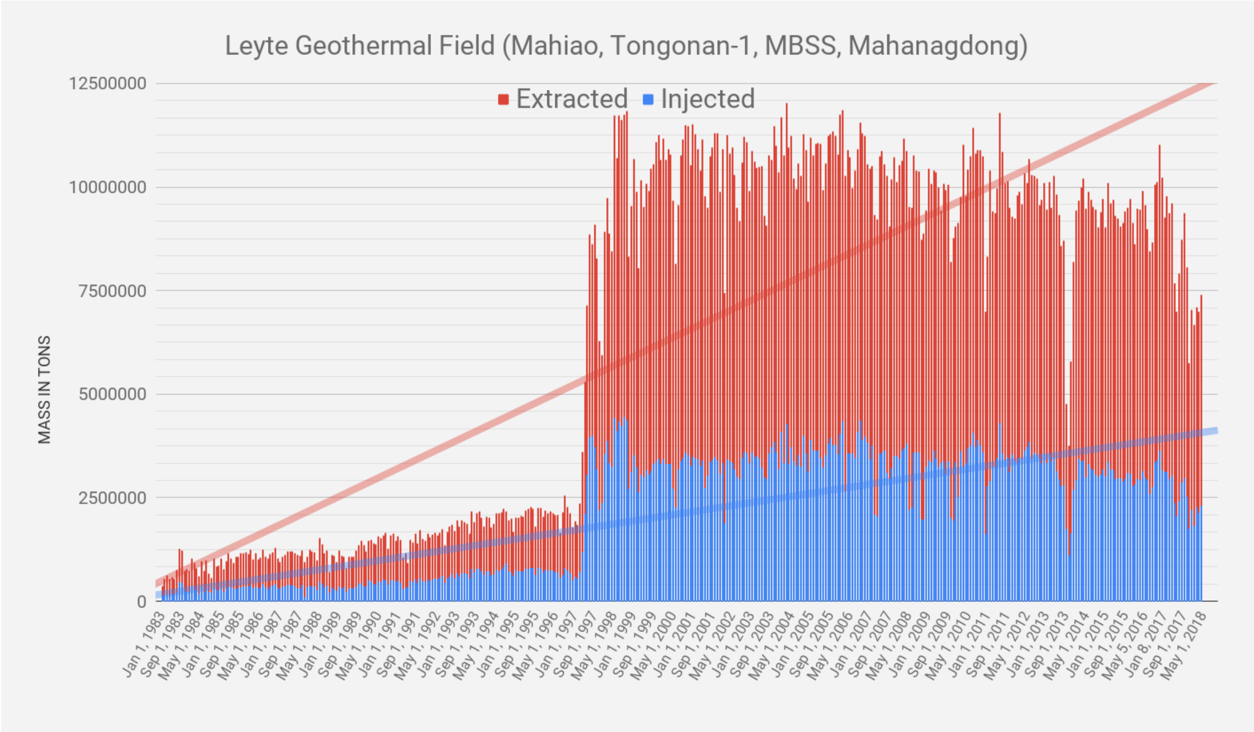

Figure 14: Production history of LGP from 1983-2018 (EDC, 2018)

In the Upper Mahiao Sector, located in the northern portion of LGP, the radial negative gravity anomaly is observed within the production well pads (i.e 406, 410, 407, 401). This is indicated by the >1200 microgal contour and accompanied by an elevation decline of about 0.5 m as observed in GBMs such as 37, 38, 41 and 43 (Figure 15). A gravity increase of about 160 microgals was also observed in the northwestern portion, where the reinjection wells in that sector are directed. If there were GBMs present in the later well pads in the northeastern portion (i.e. 4RC and 4RD), it would be expected that these should also register positive gravity anomalies. The lowermost portion of the negative circular anomaly extends towards the Tongonan sector. A finger shaped of lesser negative gravity anomaly (as measured in GBM's 28 and 58) is observed to be encroaching on the western portion of this sector. This coincides with the region identified as affected by brine returns related to injection of fluids in well 1R9D in the western portion (Herras et al., 2005)). It can be shown that GBM's 28 and 58 have a lesser degree of decrease in gravity values compared to other GBMs in Tongonan sector (Figure 16). Further south in the Malitbog-South Sambaloran sector, there is a notable lack of GBMs but the area is generally enclosed by a negative gravity anomaly (i.e. GBMs 19, 71) which peaked at about -900 microgals on the southern portion . The the production wells are located in the central portion of this sector. Slightly positive gravity anomalies are found on the western portion (GBMs 18, 22, 23) coinciding where the reinjection wells are sited. Plots of gravity and elevation differences of GBMs 18, 19, 22, 23 and 67 are shown in Figure 17. Further south in the Mahanagdong area, only a number of GBMs are present but the notable features include a 0.5m elevation subsidence near the central portion and a more positive gravity anomaly towards the west, which is attributed to the reinjection wells and also the inflow from Paril. Another significant observation in Mahanagdong is the large negative gravity anomaly on the southern portion (>1000 microgals), which would be contrary to what should have been observed as this is a reinjection area. It is hypothesized that this is caused by enhanced permeability over the long period of injection that there is less mass reflected in the gravity values measured in the latest survey due to faster rates of mass transfer which can be attributed to enhanced permeability. It is surmised that at the time of gravity measurement in 1997, gravity values reflected mass contained within the injected sink. However, continuous injection at Pad MGRD enhanced the permeability in the area resulting to relatively faster rates of mass transfer to the production wells. The mechanism by which the permeability values were enhanced is partly governed by thermal fracturing mechanisms wherein injected cold water down the host rock causes considerable shrinkage of the material and thus potentially increasing local stresses that may potentially lead to the formation of cooling related fractures (Imaro et al., 2017). This mechanism is believed to have resulted to the unexpected negative gravity values observed at the MGRD injection area. This anomaly in Mahanagdong will be verified once another repeat microgravity survey is conducted with more GBMs in this sector measured.

It can also be observed that the gravity anomaly extends in the northern portion of LGP (Mahiao sector). This could be a potential site for expansion.

As LGP is located within a segment of the active Philippine Fault Zone, it cannot be discounted that elevation changes may also be a function of regional movements caused by earthquakes.

The calculated average gravity change within LGP decreases at a rate of about -37.59 microgals/yr while the average subsidence rate is about -15.78 mm/yr.

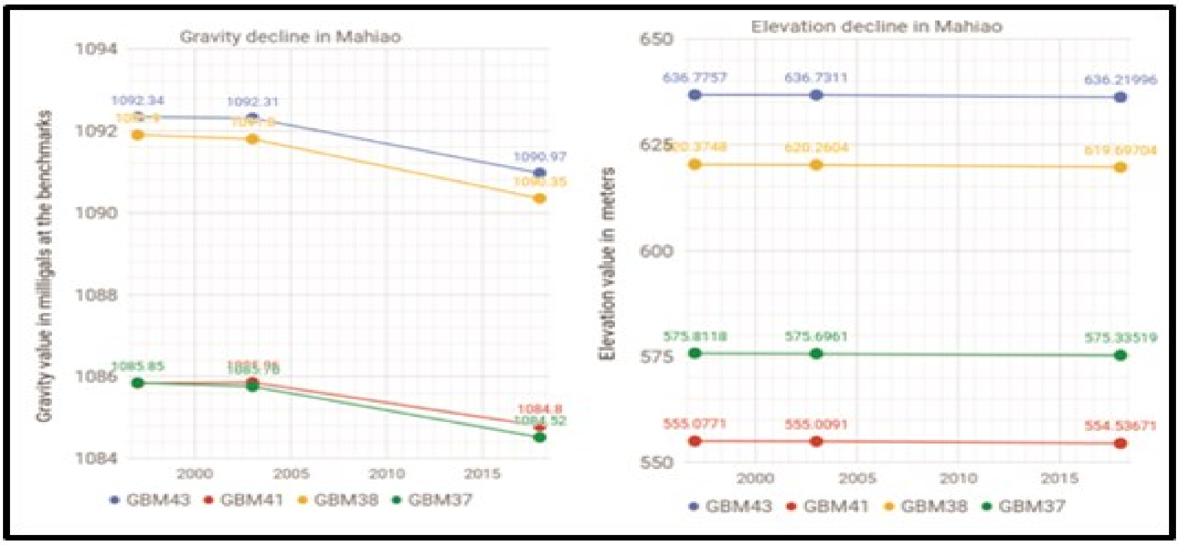

Figure 13: Plots of selected GBMS in Upper Mahiao sector, LGP

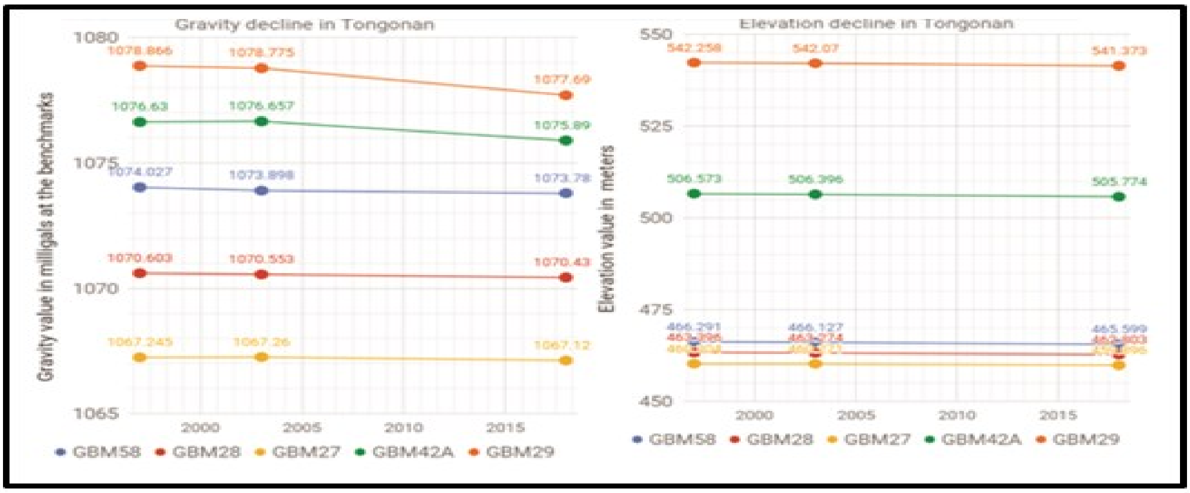

Figure 14: Plots of selected GBMS in Tongonan sector, LGP

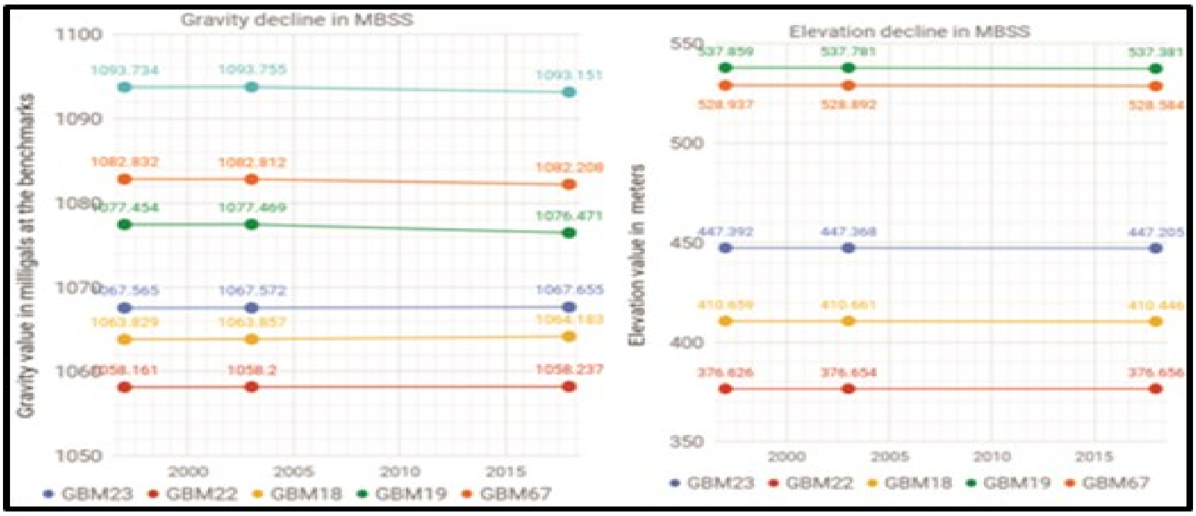

Figure 17: Plots of selected GBMS in Malitbog-Sambaloran sector, LGP

3. SUMMARY

In general, results from the microgravity surveys conducted at two EDC geothermal fields show that negative gravity and elevation changes were measured in both the production zones of SNGP (Palinpinon 1 and 2) and LGP (Upper Mahiao, Tongonan, Malitbog-Sambaloran, Mahanagdong), which can be interpreted as mass loss and subsidence, respectively, brought about by mass extraction from the reservoir. As expected, the negative anomalies in LGP are broader and more extensive as the production rate in LGP is very much larger relative to SNGP. On the other hand, positive gravity and elevation anomalies are mainly observed in the reinjection zones and are interpreted as mass gain and inflation due to reinjection of fluids. This was observed within the reinjection sites on the northern portion of SNGP and the western portion of LGP.

Positive gravity anomalies but with negative elevation changes have also been observed within the production zones. This has been correlated with mass gain due to reinjection returns (i.e. Ticala, SNGP and Tongonan, LGP). The positive gravity anomaly is due to the increase of density caused by additional fluids while the negative elevation change (subsidence) can be associated with the contraction effects brought about by cooler reinjection fluids.

It has also been observed that a negative gravity anomaly is present within a reinjection zone in (Mahanagdong) LGP, contrary to what was expected. This is believed to be caused by enhanced permeability over the long period of injection that there is less mass reflected in the gravity values measured due to faster rates of mass transfer.

As the main production zone of the geothermal field coincides with the negative gravity anomaly, it is thought that the anomaly may indicate the extent of the geothermal resource. Potential expansion areas would be south-southeast of Lagunao Dome in SNGP and the northern portion of Mahiao, in LGP.

The subsidence observed in the geothermal fields may also be related to regional movements caused by earthquakes, particularly in Leyte where the field is located within a segment of the active Philippine Fault zone.

The calculated average gravity change within SNGP decreases at a rate of about -24.11 microgals/yr while the average subsidence rate is about -2.71 mm/yr. Computed values for LGP are much larger given that the average gravity and elevation changes are 37.59 microgals/yr and 15.78 mm/yr, respectively.

Future repeat microgravity surveys will confirm the gravity changes particularly on areas wherein additional GBMs have been constructed. This will also substantiate the unexpected findings in Mahanagdong sector.

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