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PRELIMINARY MICROGRAVITY MEASUREMENT OF PAKA GEOTHERMAL PROSPECT

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ABSTRACT

Microgravity surveys together with the GPS data are normally used as a base of information to monitor land elevation and gravity changes caused by seismicity, volcanism and exploitation of geothermal fields. Precision gravity measurements have been conducted to monitor changes in fluid mass within a geothermal reservoir related to production, reinjection or phase changes. In Kenya, repeat microgravity surveys have been performed only in Olkaria geothermal field which is a producing geothermal field. Most geothermal fields in Kenya are magmatic in nature and magma movement is not only indicated by occurrence of seismic events but must also be supported by other data sets from microgravity and DGPS analysis. Consequently, GDC has put in place monitoring system that includes microgravity and differential GPS measurement. The goal of this paper is to showcase the data collected and the technique used for analysis to set baseline information for deformation monitoring of Paka geothermal prospect, which is one of the geothermal projects earmarked for development by Geothermal Development Company Limited. Data collected will be used for as a basis for future monitoring of geothermal systems. The outcome of this survey are computed gravity difference values between designated benchmarks that will be used as baseline data for future regular repeat investigations to monitor positive or negative changes from which information on surface deformations related to Paka volcano can be inferred.

1.0 INTRODUCTION

Paka geothermal prospect has been targeted for accelerated geothermal development by Kenya Government through Geothermal Development Company, GDC. The prospect is magmatic in nature hence the reason to undertake deformation monitoring campaigns to assess ground distortions around the area before embarking on geothermal exploitation activities. Information obtained from these campaigns will enhance donor confidence in partnering with GDC in terms of funding geothermal development in the region. GDC has recently put in place deformation monitoring system in Paka geothermal prospect that includes precise microgravity survey and differential GPS measurements with a view to acquiring information on surface deformations or assessment ground deformation related to magmatic movement.

Microgravity monitoring involves measurements of small changes with time in the value of gravity at a network of stations with respect to a permanent base. Microgravity is recognized as an effective tool for the monitoring of volcanic activity and prospecting for geothermal energy. Since the 1950s, microgravity surveys have proven invaluable for measuring the subsurface mass and/or density changes that take place on various temporal scales preceding volcanic eruptions (Yokoyama, 1957).
Synchronized Gravity and GPS measurements have been demonstrated to be a powerful combination for detecting subsurface mass or density changes long before eruption precursors appear. Due to preliminary signatures that signify a magmatic active zone in Paka, necessity to conduct regular monitoring campaigns as part of the wider scope of determining the inherent geological changes was

vital. In general, time-based gravity changes on volcanoes are caused by mass redistributions and the free-air effect of elevation changes (Charco et al, 2007). In this way, repeated microgravity surveys have the potential to provide information on both surface displacements related to inflation or deflation cycles and subsurface mass changes. This can be caused by a variety of processes which include the filling and draining of magma reservoirs, surface and subsurface magma movement, changes in the density of magma bodies, and changes in surface and groundwater reservoirs. Nevertheless, the capability of microgravity data to detect subsurface mass movement is greatly enhanced if gravity data are analysed and modelled conjointly with DGPS data. Figure 8 shows the basic relationship between microgravity and DGPS data. The chart shows that repeated or continuous deformation and gravity measurements can provide information on how the gravity and height relationship evolves and the associated spatiotemporal changes of mass and magma chamber volume within the medium (Charco M. A., 2009).

This lead to the justification of constructing a network of survey control benchmarks for purpose of conducting periodical differential GPS and microgravity measurements. The baseline and subsequent monitoring of Paka geothermal prospect will aid in resolution of the arising issues associated with progressive work over time. Micro-gravity monitoring was done using a Scintrex CG5 gravimeter on the same location as the GPS geodesy monitoring sites and is expected to be repeated after every six months. This will enhance future integration and collocation of outcome from both methods on the same location.

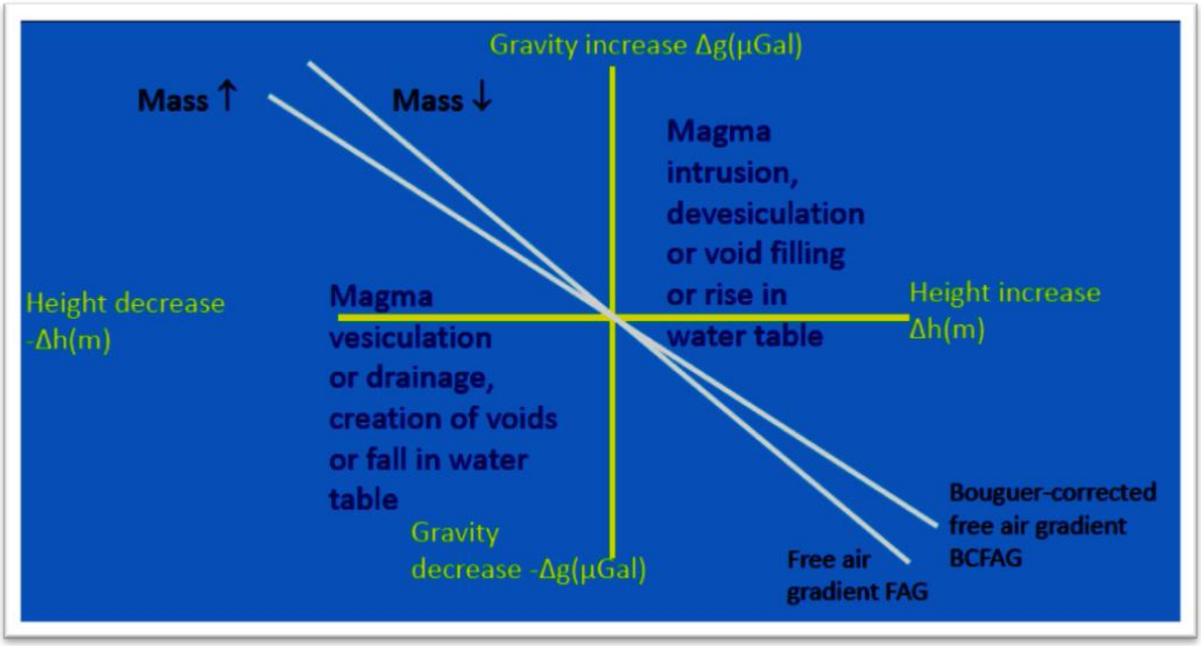

Figure 1: Basic relations between microgravimetry and deformation (Rymer, N, 1996), Scarpa and Tilling (1996

Microgravity monitoring method has been used for a variety of subsurface survey projects. In Kenya, the method was used to Olkaria geothermal field to monitor gravity changes as a result of geothermal fluid withdrawal, (Mariita, 2000). Mariita, a geophysicist with KenGen, analyzed microgravity data collected since 1983 and detected in the area of Olkaria under exploitation relative changes of the order a few tens of microgals per year. Below are some of the results that were presented

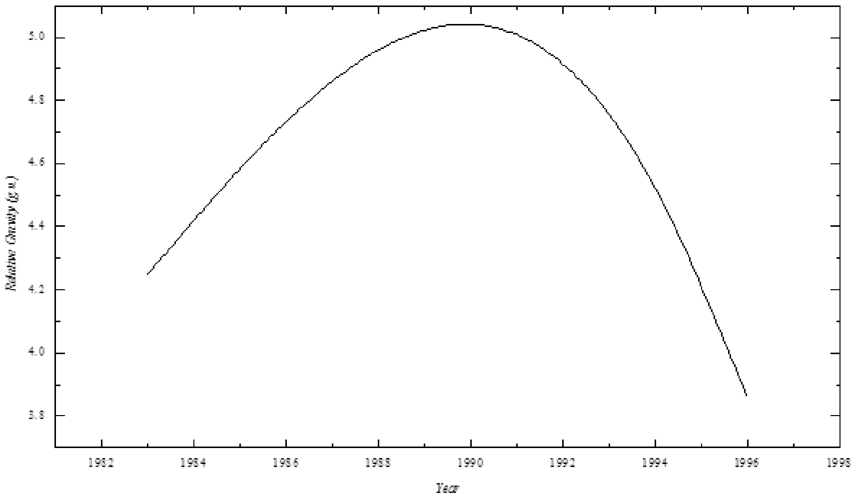

Figure 2: Gravity change over Benchmark G5 with respect to BM9 between 1983 -1996. (Mariita, 2000)

Majority of the benchmarks show gravity increments between 1983 and 1988. This trend was reversed after 1988. Figure 1 is a typical example of such gravity change over one of the benchmarks.

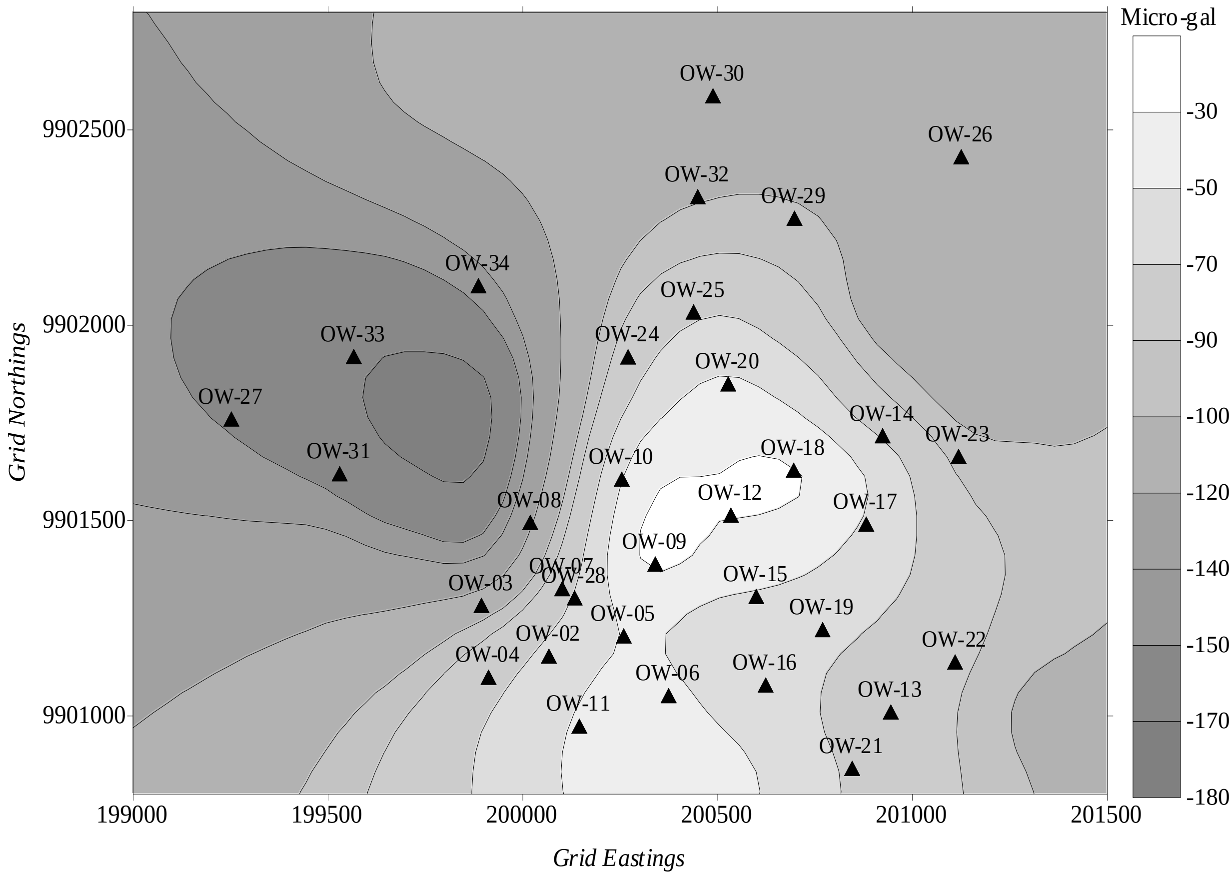

Figure 3: Gravity changes between 1988 to 1996 (Mariita, 2000).

From Figure 3 it can be seen that between 1988 and 1996 gravity decreases were observed for most parts of Olkaria. Decreases down to -180 μgals were observed on benchmarks to the west and northwest of the power station, i.e., the centre of this activity shifted westwards. This was supported by the observation of average yearly mass flow from wells on this part of the field. They show a steep decline of average yearly mass discharge between 1988 and 1996. Mariita (2000) explained this as a sudden subsidence occurring around 1988 when the level of recharge fluid inflow could not keep up with the level of extraction. Some of the studies done using gravity method include: Precise gravity measurements for mass change monitoring at Olkaria (Mwangi, 1983). (Rymer, 1998), came up with an integrated approach, involving microgravity and geodetic precise leveling, GPS, and InSAR studies, in order to attain perception of the deeper processes controlling volcanic activity in Krafla geothermal field, Iceland.

2.0 BACKGROUND OF PROJECT AREA

Paka geothermal prospect is situated in the Kenya Rift 20 km NNE of Lake Bogoria (Figure 4). Manifestations of a geothermal system at Paka are well displayed by the widespread fumarolic activity, hot grounds and hydro thermally altered rocks. The summit elevation is about 1697m above sea level and raises about 600 to 700 m above the rift floor. The volcano is dominated by a caldera with a diameter of 1.5 km. Its volcanic rocks cover an area of ~280 km^2 and are composed of trachytic and basaltic lava flows and pyroclastic deposits. The volcanic complex is dotted with a number of smaller satellite volcanic centers, which are linked to the main volcano by linear zones of basalt and trachyte cones and eruptive fissures, (Mutonga, 2013). Geothermal activity manifestations are present at the summit caldera and northern flank.

3.0 MICROGRAVITY SURVEY: METHOD

This section outlines the approaches used during microgravity data collection and initial processing. The first stage of this project entailed acquisition of microgravity and GPS data in the period between June and July 2015. The main equipment used was the Autograv Scintrex CG-5 gravity meter and dual frequency Differential GPS. In Paka geothermal prospect area, microgravity monitoring has never been done before with a view to acquiring information on surface deformations related to Paka volcano´s. Henceforth, Geothermal Development Company found it necessary to start a monitoring system in order to gain more information that will facilitate the viability of geothermal development in the area.

3.1 Field Procedures:

Field surveys conducted in Paka geothermal prospect consisted of one relative-gravity base station and from one to 16 relative-gravity stations. During a field survey with the CG–5 gravimeter, the first station measured was defined as the base station. The remaining relative-gravity stations were then measured to create a closed loop. The relative-survey loop, starting with the base station, was repeated in the same order from one to three times (a total of as many as four loops) during a field survey to ensure measurement repeatability and to help assess measurement accuracy. The microgravity network uses Tokol station (Figure 5) as reference, because it is located outside the main zone of deformation (Rymer et al., 1998). In most cases, the survey base station was occupied at least four times during the survey period to ensure measurement repeatability. Each gravity station occupation consisted of three 60-second measurements during which data were continuously collected at a 6-hertz sample rate. These three measurements were averaged to obtain the tide-corrected gravity value for a given station occupation, which was later processed to remove instrument drift.

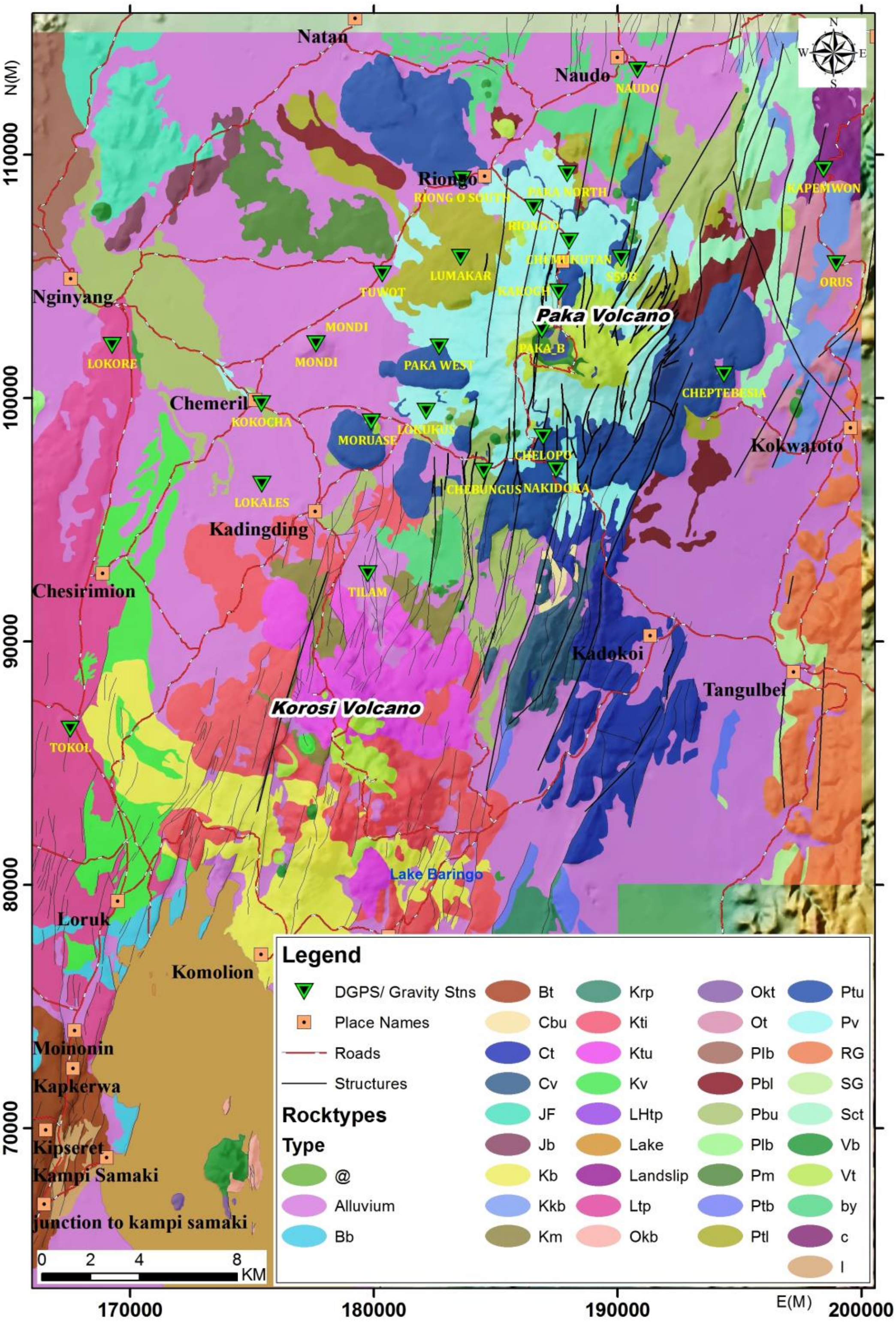

Figure 4: Geological Map of Paka geothermal prospect

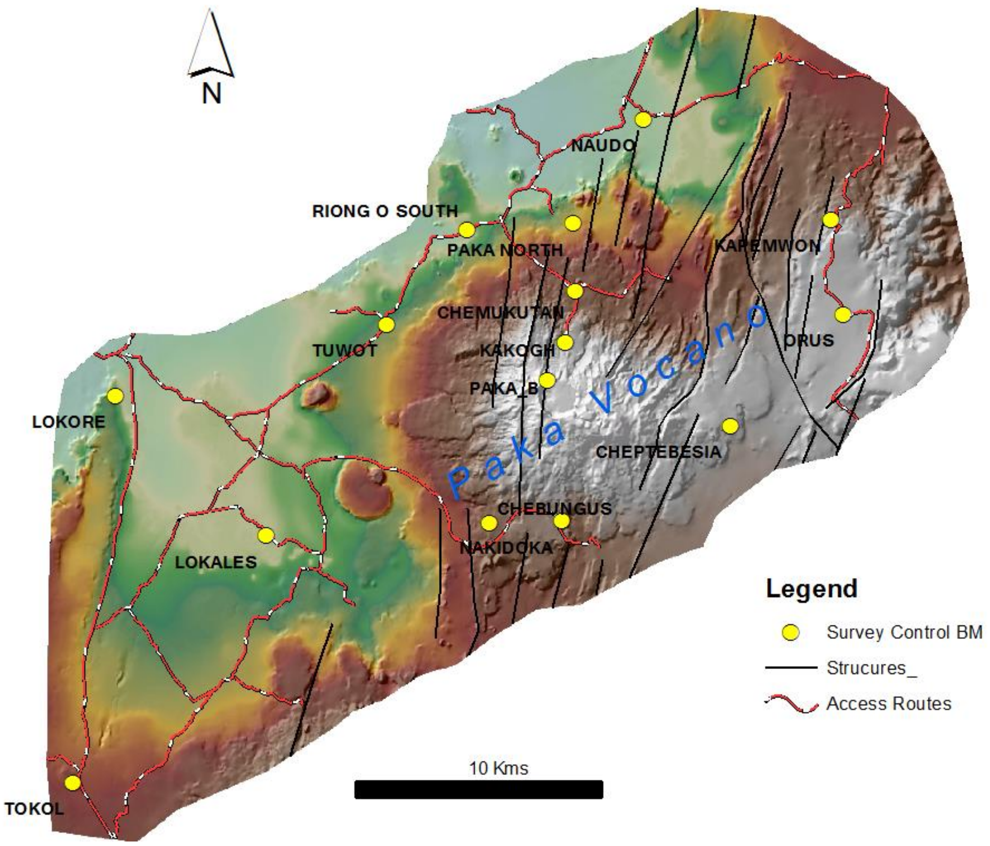

Figure 5: Survey Ground Controls on a DEM of Paka geothermal prospect

The CG–5 Autograv meter was carried in the passenger seat of a vehicle, open to the ambient air temperature, and buckled firmly in place with a seatbelt. Special care was taken to evade juddering the Autograv meter while in transit and also while moving it from the vehicle to the monitoring station. The CG–5 gravimeter was stabilized for about 5 minutes at the survey station before gravity measurements were made. The gravity meter is positioned precisely on a predetermined survey point and values of gravity are measured repeatedly to produce an average value and standard deviation. This procedure ensured the consistency of relative-gravity measurements and lessened measurement errors. One gravity meter was used to cover the whole area of Paka prospect by making a series of measurements on the network of benchmarks and comparing the value of gravity with the value at a reference point. The whole survey is supposed to be repeated some time later and any changes in gravity difference between the reference point and the places of interest are noted. The effects of solid earth tides, instrumental drift and calibration, and atmospheric and elevation changes of the ground are removed and then the residual gravity changes can be interpreted in terms of subsurface mass or density changes (Carbone, 1999).

Topographic monitoring of gravity benchmarks, based on a differential-mode, dual frequency GPS, started in 2014 on Paka geothermal prospect. Measurements of gravity changes started in 2015 after a regional network around the prospect was established (Figure 6). In order to enable the determination of mass changes between the campaigns the height control was provided by parallel GPS measurements. In all, the network consists of 16 benchmarks. Main objective of the project is to acquire information on the nature of surface deformations related to Paka geothermal prospect's magmatic movement. The stations are distributed on the flanks of the volcano and several stations on the plains. Dual frequency geodetic receivers (Trimble and Leica) were used in the GPS campaign mounted on surveying tripods

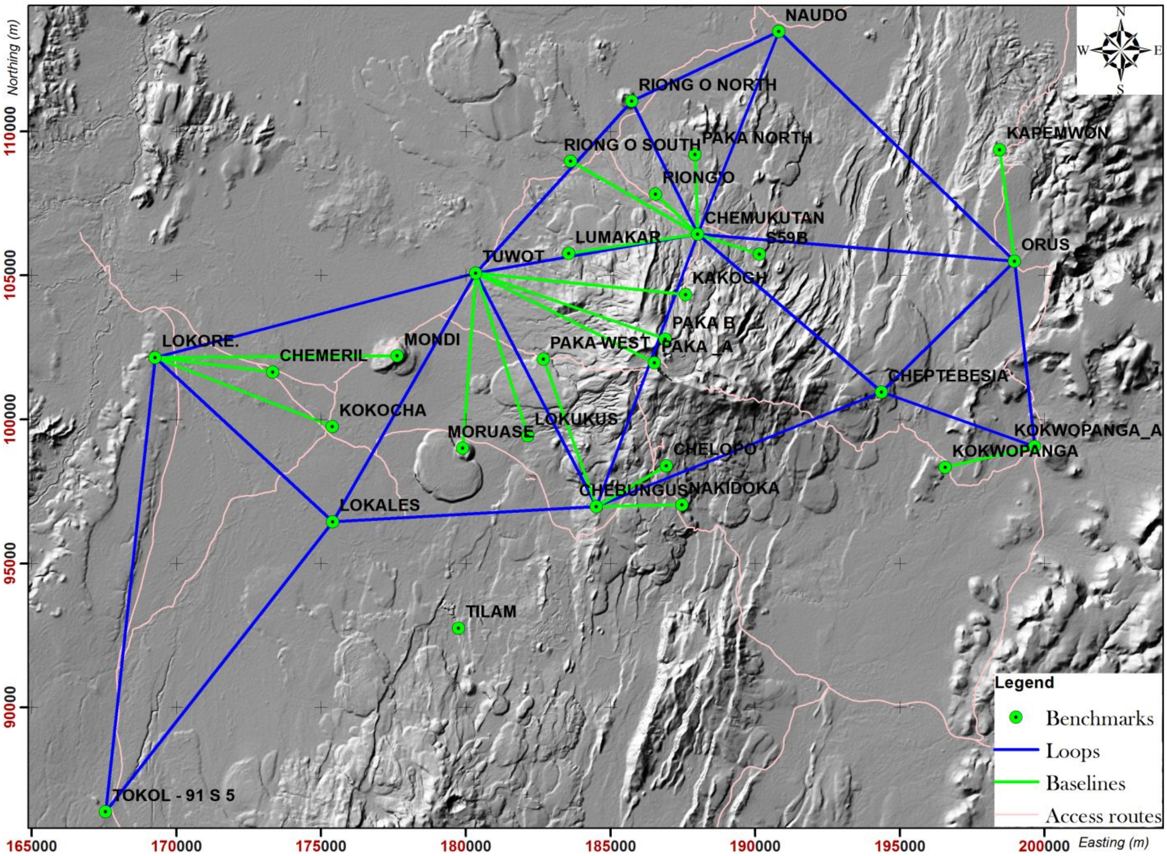

Figure 6: Gravity Network of Control Benchmarks around Paka area.

4.0 DATA PROCESSING

Gravity measurements require use of corrections to compensate for background effects such as Earth tides, instrument drift, latitude effects, elevation and local topography. The most important aspect in the interpretation of microgravity surveys is the relative variations in the local gravitational field. Consequently, the data do not need to be corrected to the absolute gravity. The latitude correction was ignored due to the small dimensions of the survey area. The most important steps of the incomplete Bouguer anomaly evaluation were the free air and the planar Bouguer slab corrections. Microgravity data was recorded on site which included accurate position and elevation measurements for each station. Use of CG5 gravimeter enabled automatic corrections of Earth tides, tilts of the meter, temperature variations and long period drift, (Scintrex Operation Manual, 2014).

Figure 7 shows six (6) interconnected loops of microgravity network benchmarks completed within two hours in relation to Tokol (reference). The sum total for each loop is zero (0) which indicates absence of error in loop at closure, further interpreted to mean insignificant mass change in the subsurface over the benchmarks.

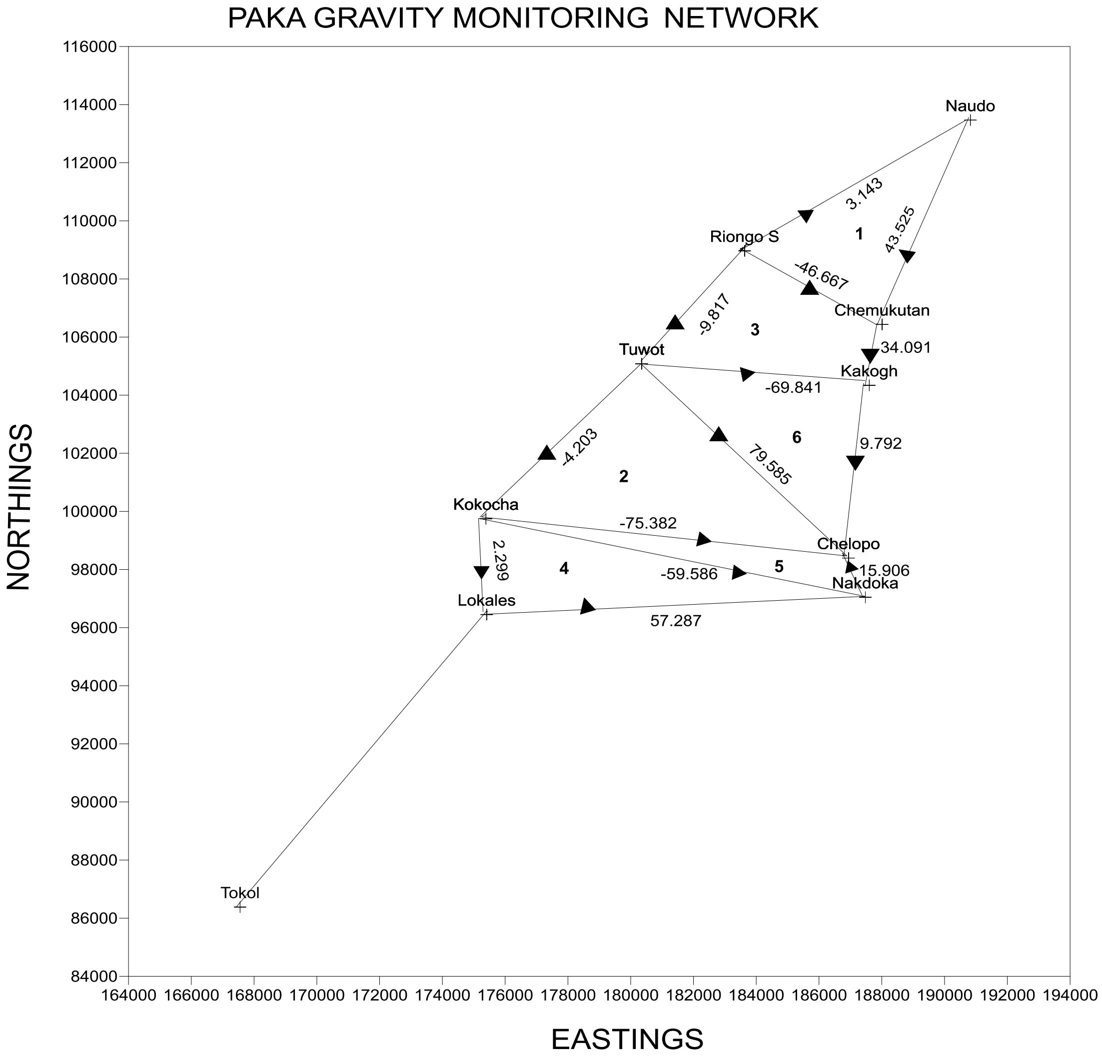

Figure 7: Gravity Network Loops with computed gravity differences.

A geodetic GPS network (Fig. 1) consisting of 30 stations was established in the broader area of Paka Volcano and included a reference station in the North Western part of the volcano. All Differential GPS measurements were made in the static mode using tripods above the benchmarks. Geodetic, dual frequency Trimble and Leica receivers (R8 and GS10) were employed for all the measurements. The "connecting stations" were occupied more than once in some cases. Post-processing was performed using Trimble Business Center software, together with post-computed satellite orbits (available through the International GPS Service). This was in order to improve the error estimation to an accuracy of 2 to 3mm in the horizontal component and 4 to 6 mm in the vertical was achieved. The horizontal and vertical precision acceptance criteria used for the DGPS data collection and post processing was 0.050 m + 1.000 ppm and 0.100 m + 1.000 ppm respectively. The adjusted results of all campaigns are presented in the following tables showing the grid Differential GPS post processed co-ordinates of all the baseline stations observed. The baseline vectors of the data collected in June 2016 differential GPS surveys were computed by using Trimble Business Centre scientific software. Previous baseline results for (September 2014 and September 2015) were also incorporated in the analysis. As an improvement from the previous analysis approach, precise ephemerides were used instead of broadcast ephemerides to resolve the residual ionospheric and tropospheric biases which were considered negligible after data double differencing and use of dual-frequency observations in the previous surveys (The precise ephemerides were obtained from the International GPS Service website). This was in order to improve the error estimation to an accuracy of 2 to 3mm in the horizontal component and 4 to 6 mm in the vertical was achieved. The horizontal and vertical precision acceptance criteria used for the DGPS data collection and post processing was 0.050 m + 1.000 ppm and 0.100 m + 1.000 ppm respectively. In processing the baselines, most of the cycle ambiguities of the phase observations were successfully resolved.

The standard deviations of GPS-derived relative errors of the computed baseline vectors were typically in the order of several mm for Easting (E), Northing (N) and Orthometric Height (H) components with recorded outliers in Tokol-Lokales and Chemukutan-Orus baselines (Figure 8).

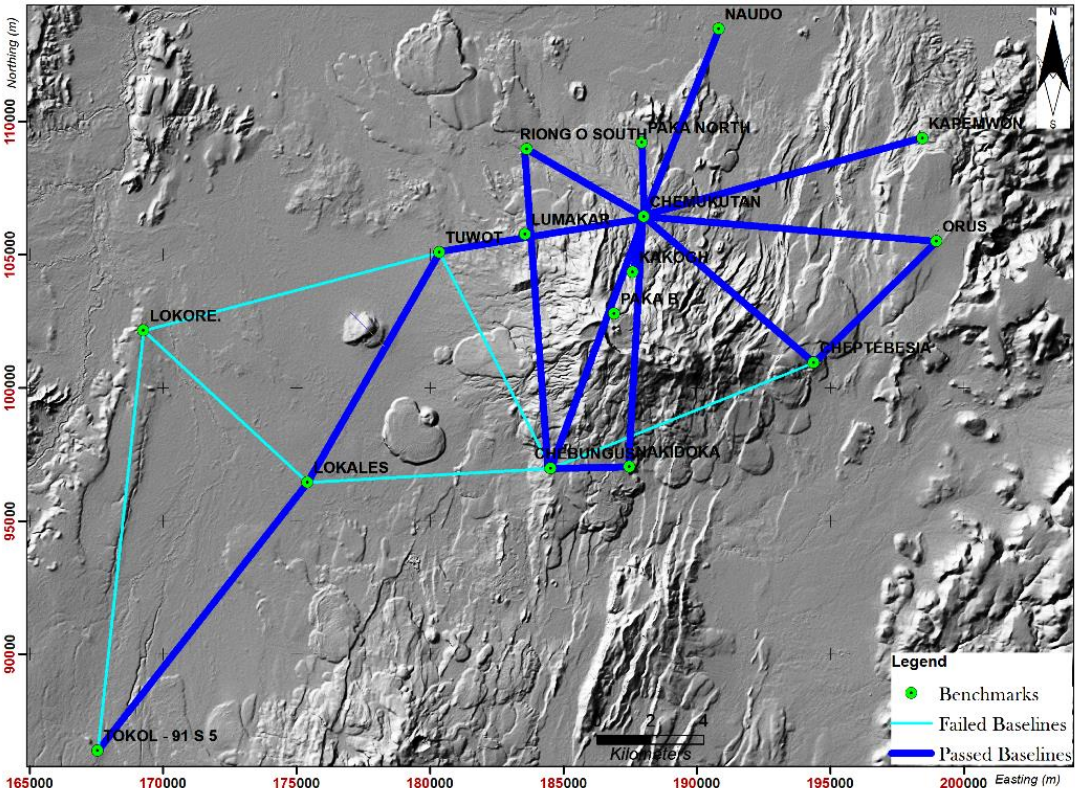

Figure 8: DGPS baseline Vectors.

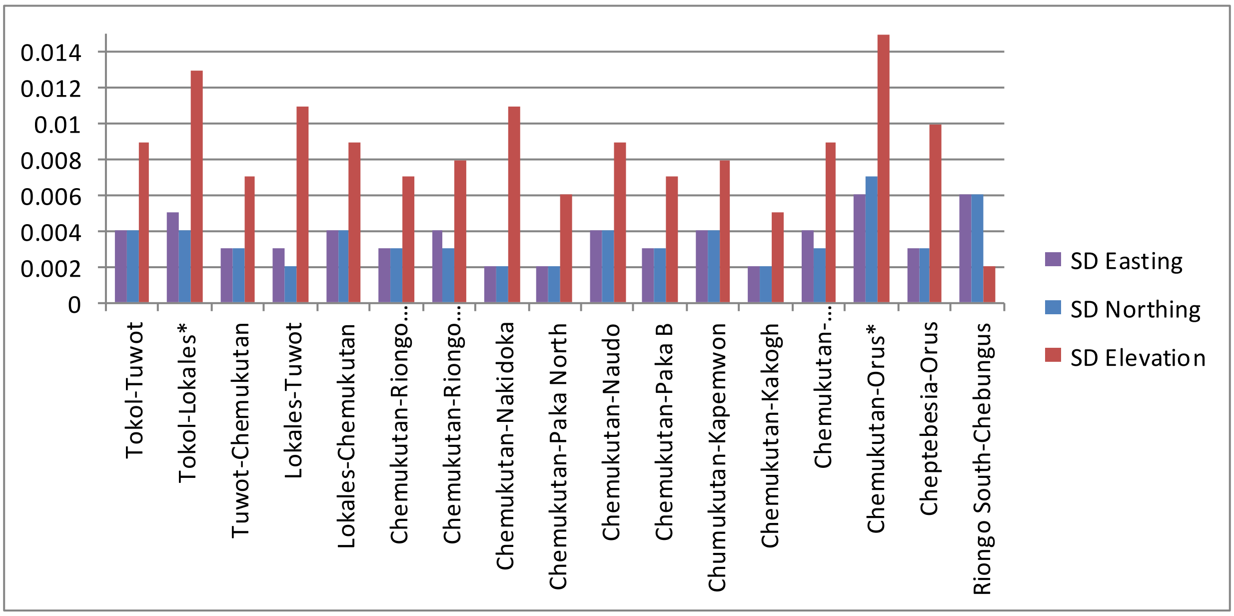

Figure 9: Graphical representation of change in Easting, Northing and Elevation.

5.0 RESULTS AND DISCUSSION

Results of microgravity survey produced gravity differences between predetermined benchmarks as shown in Table 1. Gravity differences were computed between adjacent ground controls belonging to the same loop. Reduction was done using standard loop misclosure method where algebraic sum of the closed loop is expected to be zero. If the algebraic sum of the gravity difference between the stations in a loop is not equal to zero, the difference is distributed equally to the stations that make the loop to settle the final sum to zero.

Table 1: Gravity differences between Benchmarks in Paka

Traverses	G-Diff
Kokocha - Lokales	2.299
Kokocha - Nakidoka	59.586
Lokales - Nakidoka	57.287
Tuwot - Kokocha	4.203
Tuwot - Chelopo	79.585
Kokocha - Chelopo	75.382
Tuwot - Kakogh	69.841
Tuwot - Riongo S	9.817
Riongo S - Chemukutan	46.667
Chemukutan - Kakogh	34.091
Kakogh - Chelopo	9.792
Nakidoka - Chelopo	15.906
Riongo S - Naudo	3.143
Naudo - Chemukutan	43.526

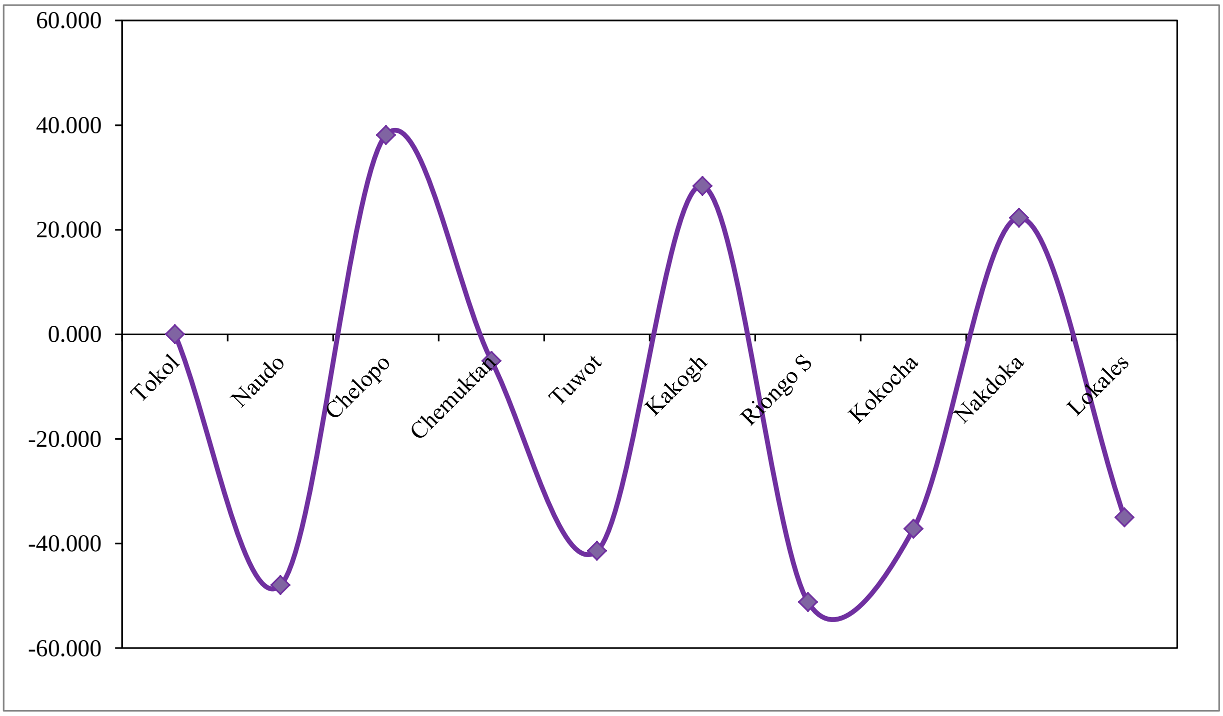

Figure 10: Gravity changes over benchmarks in with respect to Tokol base station

The graphical presentation in Figure 10 of gravity change over the benchmarks in relation to the reference point (Tokol) will be used henceforth in future monitoring surveys for comparison. The negative value indicates the measured gravity at the benchmark is greater than at reference and positive value means less than reference point. But the actual gravity difference is a scalar and not a vector. From this analysis gravity value (51.176 mGal) is highest at Riongo south benchmark and lowest by (38.118 mGal) at Chelopo. High density benchmarks are Naudo, Riongo south, Tuwot, Kokocha and lokales while Chelopo, Kakogh and Nakdoka are low density benchmarks. Most of the high density stations are located close to Paka massif probably influenced by dense subsurface magmatic intrusions unlike all the less dense stations located in the sedimentary deposit environment that could have influenced their reduced gravity value. The reference point and chemukutan benchmarks are closely related in terms of density influence inferred from gravity value both built in stable but highly faulted areas.

In using GPS surveys method, the Easting, Northing and Elevation changes ΔdEij , ΔdNij and ΔdHij and their rate vΔdEij , vΔdNij and vΔdHij for each baseline are derived using the following relation:

$\Delta dEij = \Delta dEj - \Delta dEi$, $\Delta dNij = \Delta dNj - \Delta dNi$, $\Delta dHij = \Delta dHj - \Delta dHi$ --------(*Eqn. 1*)

$v\Delta dEij = \Delta dEij /(tj - ti)$, $v\Delta dNij = \Delta dNij /(tj - ti)$, $v\Delta dHij = \Delta dHij /(tj - ti)$-----(*Eqn. 2*)

where ΔdEij , ΔdNij and ΔdHij) are the relative baseline changes in Easting, Northing and Elevation heights with respect to Tokol (91 S 5), obtained from the ith and jth GPS surveys. Uplift or subsidence is represented by a positive or negative value of Δdhij respectively while a strike-slip movement is represented by positive or negative values of ΔdEij and ΔdNij respectively. In order to statistically check the significance of the estimated uplift, subsidence or lateral movement values, we applied a general linear hypothesis test (King, 2004) to the changes in Easting, Northing and Elevation parameters. The null hypothesis of the test is that the estimated relative changes in Easting, Northing and Elevation at epoch j equal the estimated relative values of the previous epoch i, i.e. there is no uplift, subsidence or lateral movement that has occurred.

Therefore,

Null hypothesis $H_o : \Delta dE_{ij} = \Delta dNij = \Delta dHij_{,} = 0$--------------(*Eqn.3*)

Alternative hypothesis $H_a : \Delta dE_{ij} \neq \Delta dNij \neq \Delta dHij_{,} \neq 0$---------------(*Eqn.4*)

The test statistics for this test is,

$t = \Delta dE_{ij} / \sigma(\Delta dE_{ij}$ $t = \Delta dN_{ij} / \sigma(\Delta dN_{ij)}$ $t = \Delta dH_{ij} / \sigma(\Delta dH_{ij)}$-----------------------(*Eqn.5*)

This has the customary Student's t-distribution if Ho is true. The null hypothesis is rejected if

$| t | > t_{df,\alpha/2}$,

Where df is the degrees of freedom and α is the significance level used for the test. In this case, for GPS baselines derived using 24min to greater than 4 hours of GPS data with 5 seconds data interval, then df → ∞ (infinity). Note that a t-distribution with infinite degree of freedom is identical to a normal distribution. If a confidence level of 99% (i.e. α=1%) is used, then the critical value $t_{\infty,0.005}$ is equal to 2.576 (Wolf and Gilani, 1997). The common baselines for the period Sept 2014-June 2016 and Sept 2015-June 2016 showed changes in the vectors and standard errors when subjected to the congruency test in order to statistically check the significance of the displacements derived, the congruency test, was performed based on the following equations: $\delta dij = (dEij^2 + dNij^2 + dHij^2)^{1/2}$ .Where δdij is the displacement of baseline vectors from epoch i to j. The null and alternative hypotheses for the statistical test (equations 3 and 4) results have been outlined in Table 3 for the considered time periods. This result qualifies the alternative hypothesis but all the changes are within the limits of the accuracy criteria of the GPS measurements. This is further subjected to the congruency test .Therefore: Null hypothesis $H_{o.}$: $\delta dij = 0$, Alternative hypothesis $H_{a.}$: $\delta dij \neq 0$. The test statistics for this test is: T = δdij / (σ of δdij), this has a Student's t-distribution if Ho is true. The region where the null hypothesis is rejected is $| T | > t_{df,\alpha/2.}$ In this study, uplift or subsidence are obtained by differencing the baseline vectors of GPS baselines obtained from two consecutive surveys. In this case, the obtained baseline vector differences (ΔdE_{ij} , $\Delta dNij$ and $\Delta dHij$) along with their standard deviations. Analysis was done for common baselines observed in: September 2014 and June 2016, and September 2015 and June 2016. And the results subjected to hypothesis and congruency testing. For the June 2016 GPS campaign, a total of 17 baselines were observed. The common baselines are 6 for the June 2016-Sept 2014 period and 5 for the June 2016-Sept 2014 period. These are outlined in Table 2.

Table 2: Common Baseline Observed 2016 & 2015

	Baseline Vectors			Standard Errors (Vector Errors)		
Baseline	**ΔEasting**	**ΔNorthing**	**ΔElevation**	**σ ΔEasting**	**σ ΔNorthing**	**σ ΔElevation**
Tokol-Tuwot	12801.326	18701.285	-92.226	0.049	0.031	0.066
Tokol-Lokales	7864	10066.232	-114.11	0.031	0.02	0.042
Tuwot-Chemukutan	7667.559	1346.41	172.564	0.004	0.003	0.009
Chemukutan-Kakogh	-413.323	-2089.832	154.205	0.001	0.001	0.003
Chemukutan-Naudo	2807.282	7039.017	-205.736	0.003	0.002	0.005

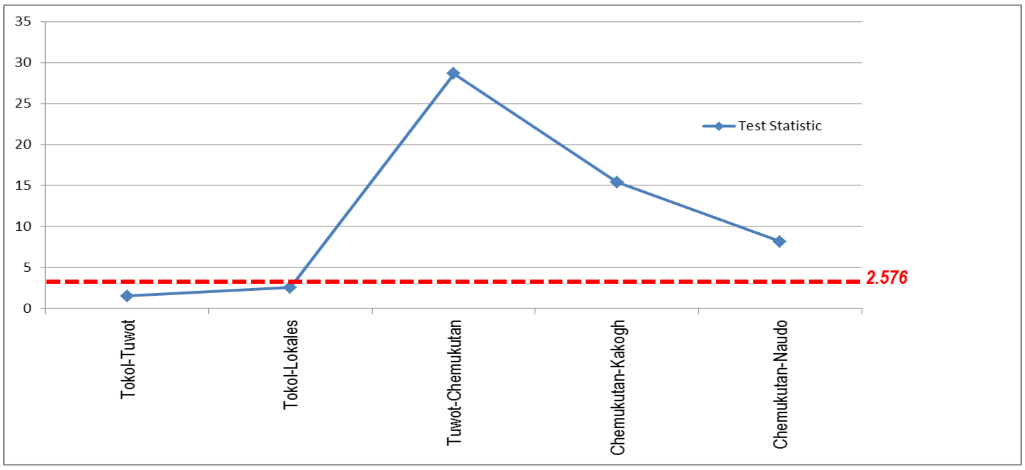

Figure 10: Test statistic for congruence test for Sept 2015 to June 2016

For the two time periods, three baselines are in the re-join where the alternate hypothesis is accepted that there is significant displacement. But based on the changes recorded, these changes are within the error limit of the GPS surveys. Therefore from both the statistical test and congruency test, displacements are recorded but at an insignificant margin as per Table 3.

Table 3: summary of congruency test of GPS derived displacements

Baseline	**δdij (m)**	**s of δdij**	**T**	**Insignificant Displacement**
Tokol-Tuwot	0.1186002	0.077479	1.53073896	YES
Tokol-Lokales	0.1073359	0.042107	2.54912258	YES
Tuwot-Chemukutan	0.0640391	0.0022361	28.6391341	YES
Chemukutan-Kakogh	0.0377094	0.0024495	15.3948043	YES
Chemukutan-Naudo	0.0373765	0.0045826	8.15621294	YES

6.0 CONCLUSION AND RECOMMENDATION

The main goal of collecting micro-gravity data in a geothermal prospect is to monitor vertical changes related to subsurface activities like magma movement. Microgravity is an influential tool but it is an underutilized technique for monitoring geothermal prospects prior to and during exploitation. It is a relatively cheap and rapid method in terms of manpower and time efficiency. Current survey results of gravity difference values between benchmarks will be treated as a baseline for the next survey in six months to monitor positive or negative changes from which excess or deficit mass is inferred. Microgravity is becoming increasingly recognised as a valuable tool for mapping out the subsurface mass redistributions that are associated with volcanic activity. This paper has presented preliminaries of microgravity data collected in Paka geothermal prospect in order to map out the possible subsurface void features. From the multiple observation results of the DGPS survey data processing, statistical and congruency testing, there is insignificant displacement in the baselines tested for the considered time period with displacement magnitude lying within the accuracy limits of the GPS survey. The current network of ground control benchmarks needs to be expanded to include base stations far away from Paka geothermal prospect. This will assist in eliminating other secondary causes of ground deformation apart from changes in gravity. GPS and, microgravity data may provide enough information on monitoring of volcanic systems but this can be enhanced if combined with other techniques running concurrently such as microseismics, InSAR and precise leveling.

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