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DECLINED MASS TRENDS OF UNBALANCED PRODUCTION TO RECHARGE ACTIVITY IN KAMOJANG GEOTHERMAL FIELD, INDONESIA: A CONTINUOUS MONITORING WITH HYBRID GRAVIMETRY

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ABSTRACT

Repeated gravity measurements have been applied at the Kamojang geothermal field in Indonesia. Previously, we used only relative gravimeters to measure precise gravity change. We detected gravity changes caused by the production and injection. However, we cannot assess the gravity change at the reference station, because we only used the relative gravimeter. Hence we introduced the A10 absolute gravimeter (Micro-g LaCoste, Inc.) in 2009 for not only the assessment of the gravity changes at the reference station, but also the detection of the gravity change caused by the underground fluid flow changes.

Mass variations of these microgravity data since 1984 in Kamojang geothermal field described a relatively steady natural recharge around 2.7 MT/year during increased production capacity from 30 MWe to 140 MWe in 1987 and 200 MWe in 2007. Fluid recharge to reservoir that come from injection activity is limited around 2 MT/year while increased production rate. This unbalanced production to recharge activity leads a declined mass trend in Kamojang Geothermal Field. Monitoring data between 1999 and 2008 by relative gravimeter displayed declined mass trend in southern area and the most negative of gravity changes have been around 20 µGal in some area. A continuous monitoring using absolute gravimeter in 2009, 2010 and 2011 revealed a higher negative gravity changes in some area more than 40 µGal and more declined mass trend in southern area. The declined mass trends also supported by declined pressure and steam flow rate of production wells.

Keywords: *Unbalanced mass, declined mass trends, Gravity monitoring, Kamojang geothermal field*

INTRODUCTION

Repeated gravity measurement is an indispensable method in geothermal monitoring. The gravity changes data in repeated measurement enable the characterization of subsurface processes: i.e., the mass of the intrusion or hydrothermal flow (Battaglia et al., 2003; Rymer et al., 1998). Mass variation in exploited geothermal field is controlled by production, injection and natural recharge rate. High production rate with less injections and natural recharge to geothermal reservoir create a declined mass trend in this mass variation. According to this condition, the sustainable production in the geothermal field will not be accomplished in the unbalanced mass.

Decline mass trend in Kamojang geothermal field (KGF) has been occurring since last decade. KGF in the Garut region, about 40 km from the city of Bandung, Indonesia (Figure 1), has been installing the 200 MWe capacities since 2007. From 1983 to 2005, more than 160 million tons of steam has been exploited from the KGF and more than 30 million tons of condensed water and river water were injected to the reservoir system. The make-up wells are continuously added to maintain the increased production rate. The progressive drilling action in KGF has enlarged rapidly the amount production from 8 to 13 MT/ year while injection and recharge rate to reservoir has limited rate about 2 and 2.7 MT/ year. The unbalanced high production rate to low

recharge activity has been creating a large mass loss during production years.

Some previous research data indicated the declined mass trend in KGF. Concerning to the evaluation of the steam production in the KGF, the decline of steam flow rate notably occurred at some production wells. Doddy et al. (2000) explained the decline rate of the production wells using the type curve matching in 1999 is about 7.43 %/year. Another research of numerical simulation for production forecasting in KGF also predicted the potential decrease associated to a declined mass trend and sustainability level for production capacity less than 200 MWe (Sofyan et al., 2009).

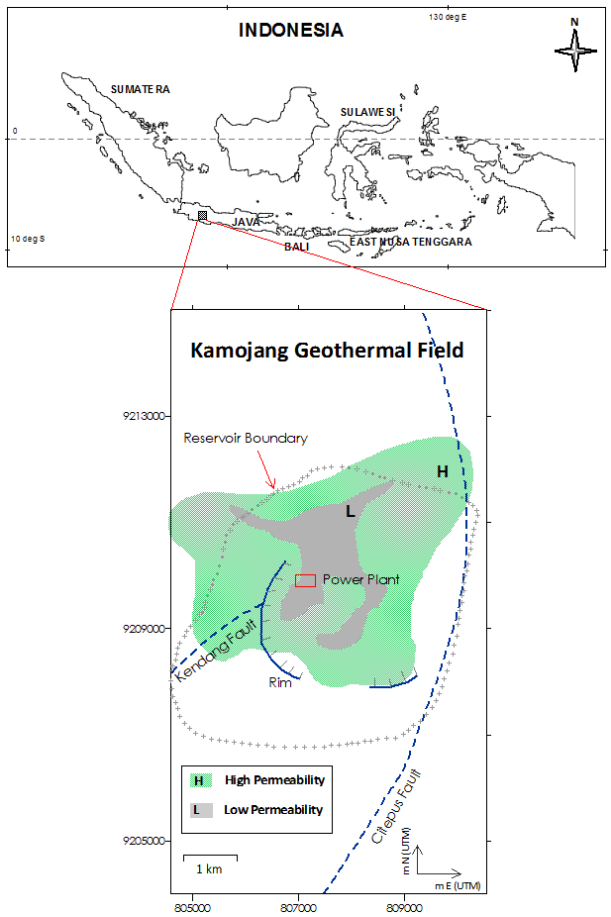

Figure 1: Location of Kamojang Geothermal Field, Indonesia

Former geothermal monitoring research of repeated gravity measurement using relative gravimeter in KGF indicated high mass loss in some periods of mass balance interpretation (Sofyan et al., 2010). Between 1999 and 2005 gravity measurements, net mass loss in Kamojang reservoir is about -3.34 MT/ year. While increased production in 2007, Net mass loss of the 1999-2008 gravity measurement is about -3.78 MT/ year. We continued the monitoring research in KGF between 2009 and 2011 using hybrid gravimetry, which is A-10 Absolute gravimeter. We introduced the A10 (serial number: 017) absolute gravimeter (Micro-g LaCoste, Inc) to measure gravity absolute in KGF once per year since 2009. The A10 absolute gravimeter is a portable absolute gravimeter that could assesses gravity changes at reference station and field near wells. It operates on a 12V DC power supply, thus we can measure the absolute gravity using the vehicle battery at the field. We carry on this monitoring research to make a comparison study with the previous result. Moreover we evaluate gravity change and mass variation in KGF after increased capacity in the late of 2007.

DATA COLLECTION

We conducted absolute gravity measurements once each year since 2009 at 10 to 12 benchmarks. These absolute gravity benchmarks were selected with available locations. We need locations that have flat surface, enough area for absolute gravity equipment, small noise, good contact with the ground and can be accessed by car. Mostly located inside of the reservoir boundary and there is one absolute gravity benchmark located outside of reservoir area that is PG 48A benchmark. The principle of this instrument is simple. A test mass is dropped vertically in a vacuum chamber, and then allowed to fall an average distance of 7 cm. The A10 uses a laser, interferometer, long period inertial isolation device and an atomic clock to measure the position of the test mass very accurately (Nishijima et al., 2010).

The raw gravity data are processed with the software ‘g’ version 7. This software is designed to work with the Micro-g LaCoste absolute gravimeter to acquire and process the gravity data. And this software needs the input of some parameters, including the location of the site (Latitude, Longitude and Altitude), polar motion, and so on. Actually we did not need a gravity reference benchmark for gravity measurement with absolute gravimeter. We directly have absolute gravity value for each gravity benchmark.

We chose the 12 stations (PG20B, PG33A, KMJ11, KMJ73, KMJ30, KMJ28, PG01A, KMJ76, KMJ67, PG48A, PG18A and KWHKMJ) to conduct the repeat gravity measurement using A10 Absolute Gravimeter (Figure 2). In 2010, we added another benchmark as a base benchmark inside the reservoir area. We conducted absolute gravity measurement three times in July 2009, 2010 and 2011. We considered the same month of measurement to avoid the correction factor of seasonal changes.

We conducted measurement to gain good results that are indicated with small scattered data and uncertainty. We conducted measurement more than once at one benchmark in large scattered and uncertainty of gravity data. The average of uncertainty from absolute gravity measurements in each year is around 10 to 11 µgal. Uncertainty of each measurement is directly shown in display unit of absolute gravimeter. This is good data close to 10 µgal as the accuracy factor of the A10 absolute gravimeter. Absolute gravity data are used as gravity reference and will be compared to the next repeated relative and absolute gravity measurement.

The obtained gravity data is combined into a set which usually consist of 100-150 drops. Our typical setup parameters for one data consist of 100 drops/ set and 10 sets/ 1 data. It took about 50 minutes to one hour for measurement in each benchmark.

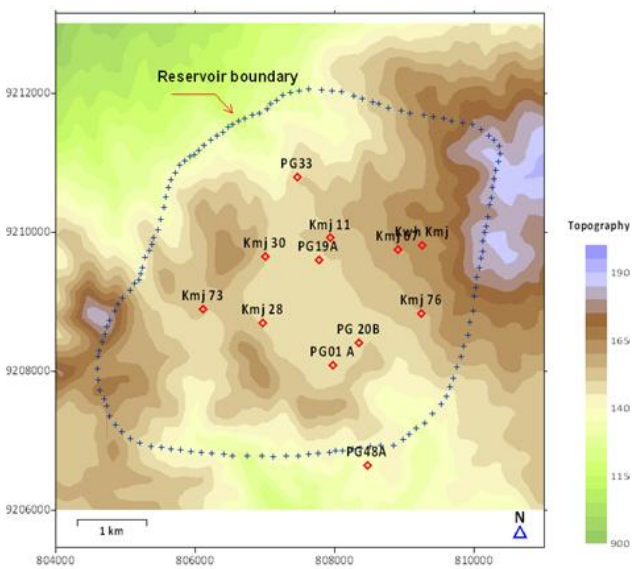

Figure 2: Absolute gravity benchmarks in KGF

DATA PROCESSING

Corrections

The A10 Absolute gravimeter has software that can correct directly the effects of the earth tide, ocean load, barometric pressure and polar motion in acquiring the gravity data. The different height of equipment while using tripod in uneven surface of benchmark is also measured in order to calculate of height correction factor in the software. Telford et al. (1976), explained the gravity field changes by the height changes (dg/dz) of about 0.3085 mgal/m.

The seasonal changes in the shallow groundwater level can have a significant effect to the microgravity data (e.g. Allis and Hunt, 1986). According to similar weather in same period measurement between 2009 and 2011, there is no significant correction factor of seasonal change in this repeated gravity measurement. Time of measument were scheduled during dry season in the same month of July at KGF. From 30 years measurement, Aldrian et al. (2003) explained the rainfall rate of the region A of Indonesia (including the Java Island) in July to October is in low part of the rainfalls rate in Indonesia.We assumed the correction of groundwater level change will be very small.

The elevation data between 1999 and 2005 revealed unsignificant ground deformation. The average negative vertical displacement from 16 gravity benchmarks is about -0.6 cm/year or corresponding to free air effect less than -2 µGal. This effect is very small in comparison with the observed gravity change. Consequently, the effect of vertical ground movement is negligible on the observed gravity in short term (several years). But we can't assume long-term (more than 10 years) vertical ground movements to be negligible.

Calibration data (2009 and 2010)

We need to calibrate absolute gravimeter in order to acquire good data. Absolute gravity data was calibrated in 2009 and 2010 to the continuing absolute gravity data that was conducted in Kyushu University, Fukuoka, Japan. The continuing absolute gravity measurement for this calibration data in 2009 and 2010 also was considered to groundwater level changes in some wells around Kyushu University. According to data in Figure 3, the gravity changes using A10 absolute gravimeter in 2010 in Kyushu University has no correlation with groundwater level changes.

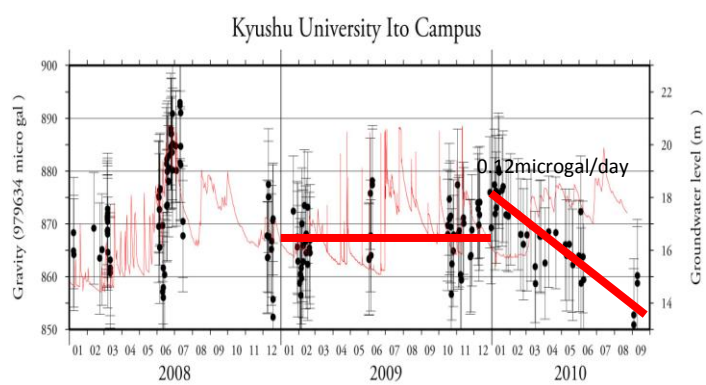

Figure 3: Continue absolute gravity measurement. Red line is groundwater level in Kyushu University, Japan.

According to calibration data, the continuing absolute gravity data in 2009 clarified a stable gravity data set, while significance decrease was found in 2010 data set. The equipment factor is one reason of the gravity change in 2010. The correction factor from calibration data in 2010 is about 0.12 µGal/ day (Figure 3).

Calibration data (2011)

There was an unusual result of 2011 gravity measurement in KGF. A high gravity difference increased more than 60 µGal in each gravity benchmark compared to last year measurement. This is an odd result in a short time different, while there is no significant increased amount of injection during 2010 to 2011.

To acquire a precise result of microgravity data, the calibration process in 2011 was conducted with a comparison to FG-5 absolute gravimeter. In the first comparison, the high difference of absolute gravity data appeared between two absolute gravimeters. We considered the equipment factor during long travel or other actions has change in significant value. The calibration process was conducted for two main equipment parts, which is laser and clock calibration. The calibration was conducted about two month after the measurement.

Laser calibration

The effect of applying calibration of the frequency standard as well as the laser interferometer data on the quality of gravity data was investigated. The He-Ne laser of A10 absolute gravimeter was calibrated on September 26, 2011, against iodine stabilized He-Ne laser (the type used by FG-5). Average frequency of blue and red laser measurements that have similar wavelength was compared to nominal frequency of A10 absolute gravimeter. The gravity difference of laser calibration is about -20 µGal.

Clock calibration

The rubidium clocks of the absolute gravimeters were calibrated on the same day of laser calibration. According to oscilloscope analyses data, difference time of one wavelength between A10 and FG5 is 4.6125 s. The gravity difference of clock calibration is about -23.7 µGal.

Total calibration

The results of a number of calibrations of both, the rubidium oscillator and the polarization stabilized laser interferometer of the A10-017 were considered in the analysis. The calculation of gravity difference using combined laser and clock calibration of the A10-017 absolute gravimeter in 2011 is about -66 µGal.

DISCUSSION

Gravity changes

Temporal residual gravity changes recorded over benchmarks were evaluated in terms of mass variation in subsurface. The contouring of gravity changes used long wavelength over 500 m. This method was carried out after smoothing the data to remove some variations (Sugihara and Ishido, 1998). The negative gravity changes dominated the comparison of absolute gravity data between 2009 and 2010. Another comparison of absolute gravity data between 2010 and 2011 showed similar domination of negative contour or associated with mass decrease. The smoothed contouring of long wavelength data has various gravity changes range that can be seen in Figure 4.

Gravity measurement using absolute gravimetry in 2009, 2010 and 2011 indicated small scattered data and uncertainty factor around 10 µgal that close to accuracy of the A10 absolute gravimeter. According to small uncertainty factor, we assumed the absolute gravity data is a good data. The distribution of the gravity changes in these periods are look continuing the similar negative trend of the previous gravity change of relative gravity data (Sofyan et al., 2010). Reservoir area with many production wells mostly have high negative gravity changes.

The gravity changes between 2010 and 2011 data has bigger decreased mass than previous period between 2009 and 2010. Between 2009 and 2010, the contouring gravity changes (long wavelength) are from -60 to 0 µGal/year while from -80 to 20 µGal/year gravity change appeared in the next period. The production rate amount from these two periods similar for 200 MWe installed capacity. Some make up wells were continue added and some stand by wells were activated according to this high production demand. According to limited source, the injection rate amount in these two periods also has not significant change. The continuing bigger mass loss in these periods is consistent with research of numerical simulation for production forecasting in KGF (Sofyan et al., 2009).

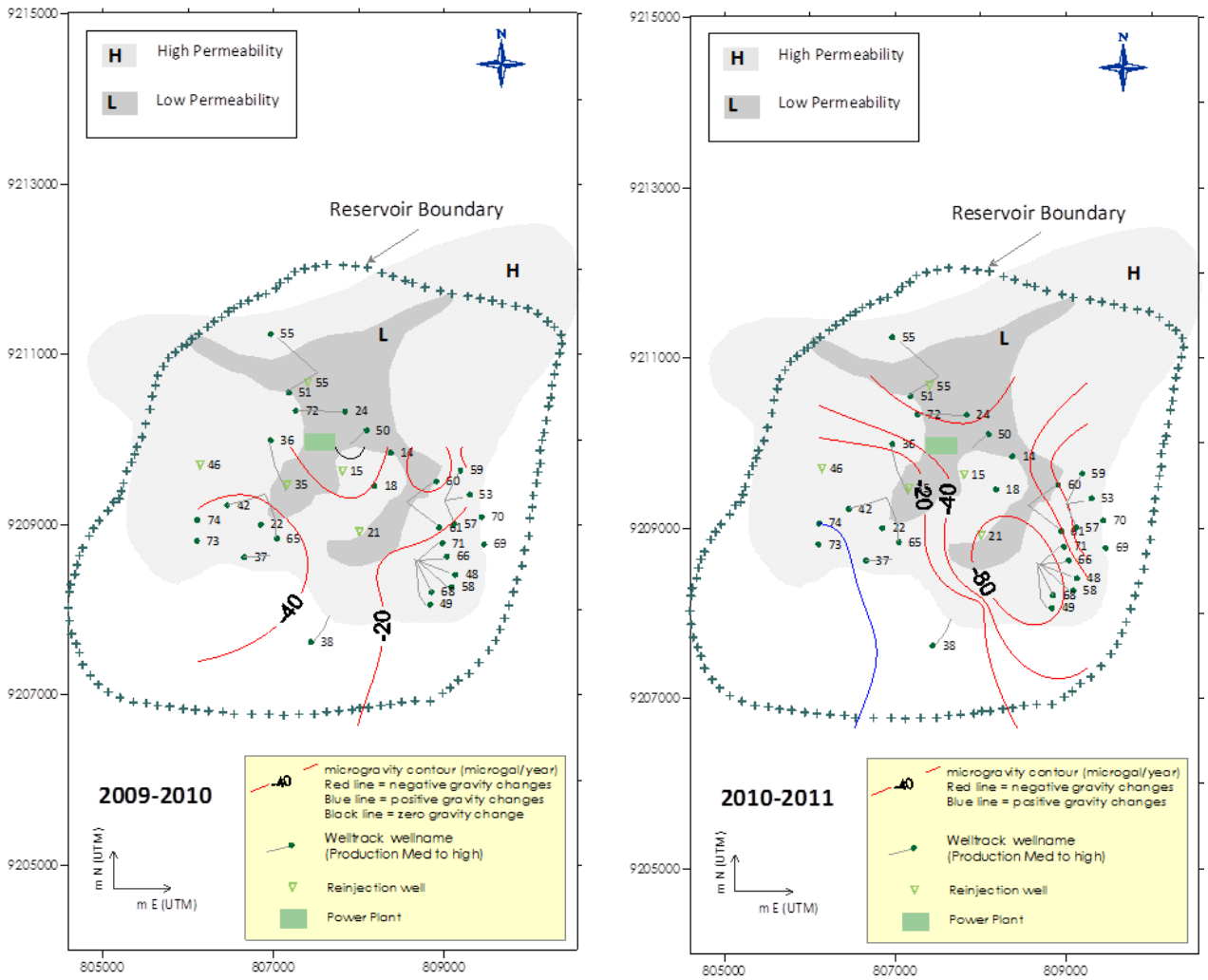

Figure 4: Distribution of the 2009-2010 and 2010-2011 gravity changes at KGF

The interesting gravity change in the south western area of reservoir appeared from three absolute gravity benchmarks that is KMJ 30, KMJ 73 and KMJ 28. These benchmarks located around active production wells with same name. Decreased value between 2009 and 2010 was followed by a slightly increased gravity change in next period between 2010 and 2011. This area is closed to two injection wells that are KMJ 46 and KMJ 35. The slightly decreased mass also occurred in eastern part of reservoir in two benchmarks that is KMJ 76 and KWH KMJ (closed to Kamojang crater). The detailed gravity change at each benchmark could be seen in Figure 5.

Mass balance

The mass balance is used to analyze and to count the mass that enters or leaves the system. The mass balance in the geothermal reservoir is regulated by the amount of production, injection and natural recharge. Gauss's theory (Hammer, 1945; Hunt, 2000) explains the mass variations are obtained by gravity changes. This method has advantage in the way of averaging gravity changes in each grid area. It means that these results will also averaging and reducing some uncertainty factors of these gravity data. In the simple error propagation analysis, uncertainty in some observed variables can be combined become final result. The final result determines a smaller uncertainty than total error. In this mass variation analyses at KGF by applying Gauss's potential theorem to gravity change data, we could not avoid "error in tailing off" and "error in gravity datum" (Hammer, 1945; Sugihara and Ishido, 1998). According to small number of benchmark, we make assumption to manage these problems. We expected that gravity changes data in more number and larger area will make a close loop of Gaussian method.

Mass variation data throughout production activity in geothermal field can be referred to monitor geothermal reservoir. The calibrated absolute gravity data between 2009 and 2010 estimated a decreased mass in KGF about -7.1 MT/year. The same Gaussian method estimated mass change of about -7.95 MT/year between 2010 and 2011. These mass loss jumped about twice than previous gravity monitoring data before increased production to 200 MWe (Sofyan et al., 2010).

CONCLUSIONS

Gravity changes from repeated measurement openly illustrate the mass variation in the subsurface. Distribution of the corrected gravity changes at the KGF helps to give an image of the mass movements that occurred as a result of exploitation. Repeated gravity measurement at KGF using A10 Absolute gravimeter was started in 2009 and then is continued once per year.

The long wavelength above 500 m of contour data of corrected gravity changes in these two periods has a various range with similar trends. The negative value is interpreted in terms of net mass loss of production and the positive value is interpreted in terms of net mass gain of water injection and natural recharge. Large negative anomaly typically occurred at the gravity benchmarks that located near to medium or high production wells. This large negative gravity changes were primarily caused by the net mass loss of steam from the geothermal reservoir due to exploitation.

The long wavelength contour of corrected gravity change in one year production period (2009-2010) is between -60 and 0 μGal/year. Mass loss estimation in this period is about -7.1 MT/year. During 2010 and 2011, the long wavelength contour of corrected gravity change is about -80 to 20 μGal/year. The estimated mass changes rate from the 2010-2011 gravity changes data is decreased mass of about -7.95 Mt/ year.
The Increased negative gravity change and continuing large mass loss in these periods is consistent with previous gravity monitoring research at KGF. During the increase production, the net mass loss will continue increase and affect an unsustainable production.

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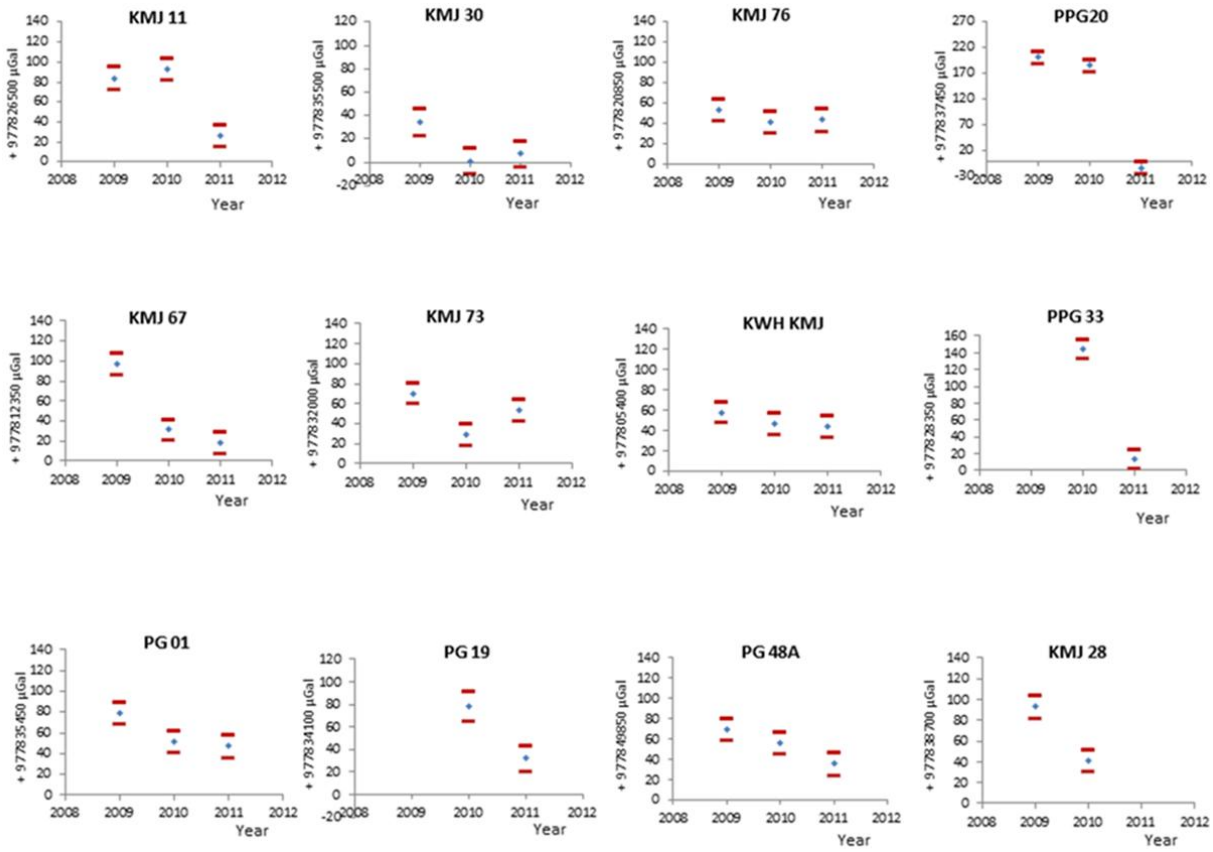

Figure 5: Absolute gravity data in 12 benchmarks at KGF