PROCEEDINGS, Thirty-Eighth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 24-26, 2014
SGP-TR-202

# Monitoring Geothermal Activity at Aso Volcano, Japan, After Small Eruption in May 2011

Yayan SOFYAN[1,3], Jun NISHIJIMA[1], Yasuhiro FUJIMITSU[1], Shin YOSHIKAWA[2], Tsuneomi KAGIYAMA[2], Takahiro OHKURA[2]

[1]Department of Earth Resources Engineering, Faculty of Engineering, Kyushu University

[2]Aso Volcanological Laboratory, Graduate School of Science, Kyoto University

[3]Department of Physics, University of Indonesia

sofyan_hasan@yahoo.com

**Keywords:** Aso volcano, Gravity changes, Mass variation

## ABSTRACT

The small eruption in May 2011 has occurred following intense volcanic activity in Aso volcano since the end of 2010. An eruptive pattern should defined a calm period after the eruption. The volcanic activity subsides to calm period levels and crater bottom are filled again with hot water and the water level increases in the Nakadake crater. This Crater Lake dynamic phenomenon has relation to hydrothermal dynamics in the subsurface of Aso volcano. We monitor the geothermal activity using repeated gravity measurement in the western part of Aso volcano, which has 4 hot springs, during this period.

The repeated gravity measurement for monitoring hydrothermal dynamics beneath Aso volcano was initiated using A10-017 portable absolute gravimeter in 2010 and ScintrexCG-5 (549) relative gravimeter in April 2011. Relative gravity measurements were performed at 28 benchmarks in every three to five months. It covered the area more than 60 km$^2$ in the west side of Aso caldera. A new gravity network was also installed at seven benchmarks using an absolute gravimeter on May 2010, which re-occupied in October 2010, and June 2011.

As a result, the gravity changes detect hydrothermal flow in the subsurface which has a correlation to water level fluctuation in the crater. The 3D inversion models of 4-D gravity data deduce the density contrast distribution beneath Aso volcano. The mass changes are quantitatively estimated using two methods, which is Gaussian from gravity data and density contrast from the simulation result. The largest increased mass about 21 MTon by density contrast or 30 MTon by Gaussian method occurred between April and August 2011. This is the calm period, a 6 month after the eruption in May 2011. The largest decreased mass about -36 MTon by density contrast or -35 MTon by Gaussian method occurred between April 2011 and May 2013, about 2 years after the eruption. This result will contribute to understanding the process of eruption.

## 1. INTRODUCTION

Aso volcano, which is one of the most active volcanoes in Japan, is situated at the center of the Kyushu Island, Japan. The Aso caldera is one of the largest caldera in the world that was formed in a huge pyroclastic eruption in 89 or 90 ka (Ono and Watanabe, 1983; Matsumoto et al., 1991). Nakadake, one of the youngest pyroclastic central cones in Aso, over the past 70 years is an active area that is characterized by strombolian, phreatic eruption of ash, mud, and scoriae ejecta occurring every few years (Sudo Y. and L. S. L. Kong, 2001). In the recent years, some volcanic activity along with mud eruption, volcanic tremors, small amount of erupted ash and a rise of thermal activity have been observed in June 2003, January 2004 and April 2005. After May 2005, the volcanic activity has subsided and has been followed by a calm period until 2010. At the end of 2010, some volcanic activity increased intensely and water level in the Nakadake crater had been decreasing until early of 2011. In April 2011, the crater floor is exposed and a very minor phreatic eruption was observed in the Nakadake crater while micro seismicity is relatively low. It was followed by a series of small phreatic eruptions at Aso volcano that was begun in May 6, 2011 (Issued by Japan Meteorological Agency).

The explanation of the hydrothermal flow system in the caldera is important to the assessment of geothermal activity and resources in Aso volcano. The monitoring of hydrothermal dynamics as one of the geothermal activity is focused on the Nakadake crater lake to the western slope geothermal zone of Aso volcano. The thermal features in the western part of the Nakadake crater include three hot springs that has intense surface alteration, Yunotani, Yoshioka, and Jigoku-Tarutama (Figure 1). The previous magnetotelluric research on Aso volcano (Kanda et al., 2008) detected a significant low resistivity region about 200m to 400m below the crater lake and extend horizontally to the west path. The hydrothermal fluid is transported along this low resistivity area and has a correlation to the crater lake and the deep reservoir. Yamamoto et al. (1999) explained that the hydrothermal fluid moved from depth to the low resistivity region through a crack-like conduit. The subsurface structure of Aso volcano from gravity Bouguer anomaly (Okubo and Shibuya, 1993) and seismic velocity predicted the center of the magma chamber in the crust, which is roughly spherical in shape, shallower than 10 km of depth below the central cones of the volcano. The low velocity region of tomographic result in well-recorded seismic data that are associated with active magma system was found at 6 km of depth (Sudo, 1991; Sudo et al., 2006; Miyabuchi et al., 2007).

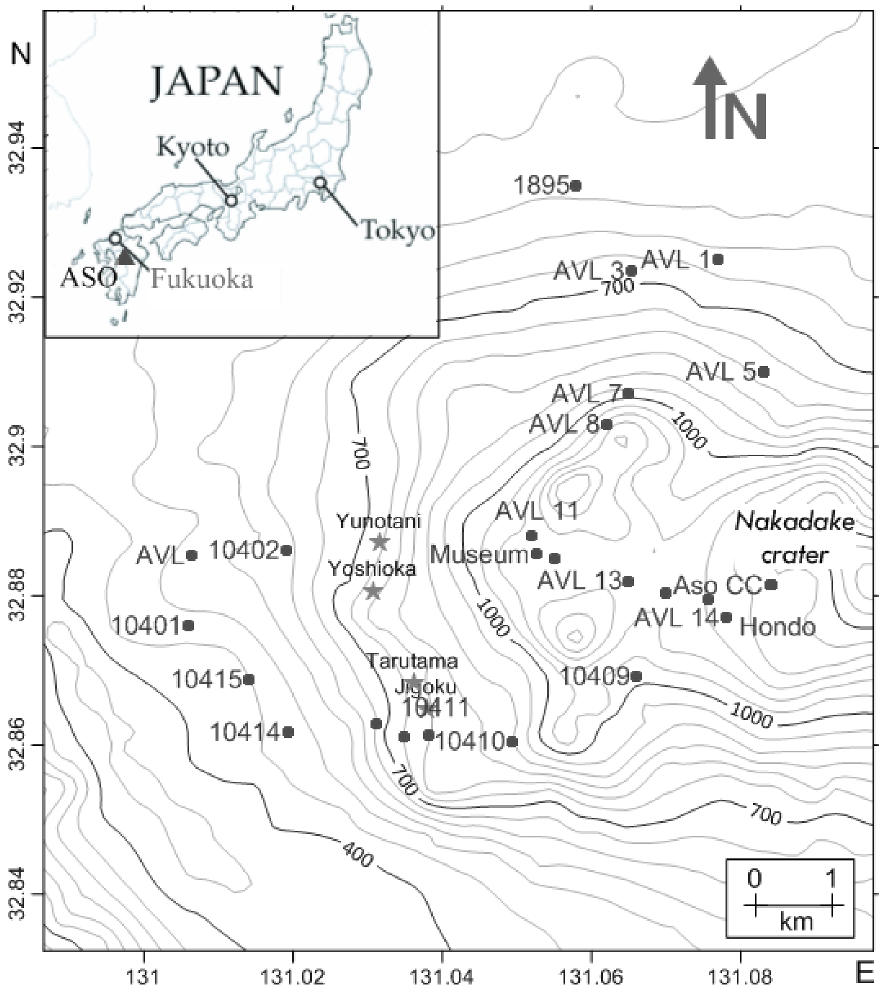

**Figure 1: The research area, western part of Aso volcano. A star symbol is location of hot spring, black circle is a microgravity benchmark in topographic contour (in meters).**

Geothermal activity in the subsurface has a correlation with water level variation in Nakadake crater. Previous research on Aso volcano defined an eruptive pattern in the crater. The water level in crater falls rapidly preceding an active period. During the increasing volcanic activity, the crater bottom is heated by deep-level thermal energy, temperature increases, crater gradually dries up, and a red glow is seen on the crater wall or bottom. Subsequently, vents open and emit ash, sometimes accompanied by phreatic eruptions and can progress to a strombolian eruption stage. After the eruption, the volcanic activity subsides to calm period levels and crater bottom are filled again with hot water and the water level increases in the Nakadake crater (Kanda et al., 2008; Ono et al., 1995; Sudo et al., 2006). The hot water level of the Aso crater during active and calm period can be compared in Figure 2.

Monitoring geothermal activity at Aso volcano in this present study, which is considered as hydrothermal fluid dynamics in the subsurface, use the repeat gravity measurement method. We conducted gravity measurements at Aso volcano in the active period before the latest eruption on May 2011 and then is followed by a series gravity measurements in the calm period after the eruption. The gravity change data are evaluated to monitor the hydrothermal fluid dynamics in the subsurface. The density changes distribution in 3D model beneath Aso volcano is estimated using 3D inversion modeling software in order to examine the geothermal activity before and after the eruption.

## 2. REPEAT GRAVITY MEASUREMENT

Repeated gravity measurement (RGM) is generally used to distinguish data in the range of 1 – 500 μGal (Hunt, 2000) but sometimes larger variations have been observed (Jousset et al., 2003). The RGM method estimates the density distribution of subsurface and its variation with time. Gravity changes enable the characterization of subsurface processes: i.e., the mass of the intrusion or hydrothermal flow. A key assumption behind gravity monitoring is the changes in earth's gravity reflect mass-transport processes at depth (Battaglia et al., 2003; Rymer et al., 1998; Battaglia et al., 2008; Dzurisin, 2003). Leveling surveys independently obtain topographic and elevation change data.

The gravity measurements collected data between 2010 and 2013 using absolute and relative gravimeter. The combination of absolute and relative gravity measurement at Aso volcano notably monitor gravity changes at the reference and other stations. The short time monitoring of repeat gravity measurement enables detection mass changes distribution in hydrothermal reservoirs of the subsurface. According to this short monitoring period, which is every three to five months, the gravity variations are possibly dominated by shallow hydrothermal reservoirs instead of midcrustal and deep reservoirs.

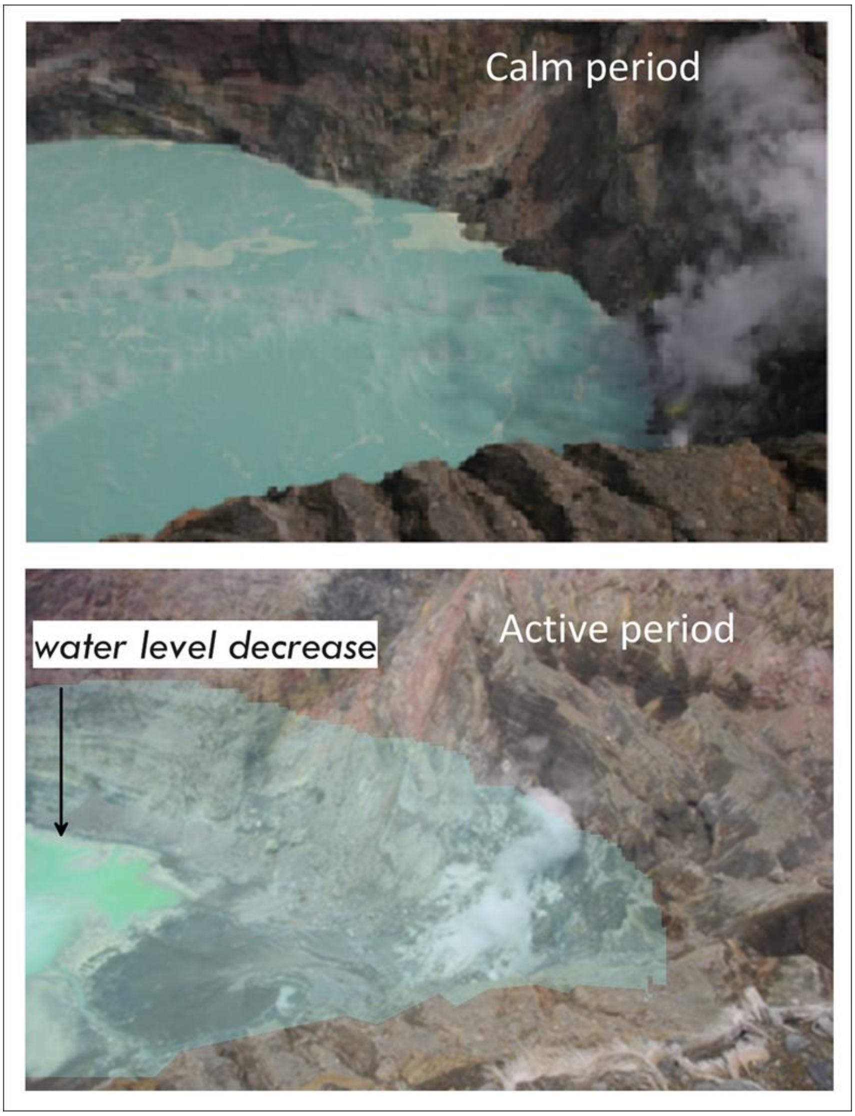

**Figure 2: Water level in crater lake during calm and active period in one eruptive pattern on Aso volcano.**

The relative gravity measurements were conducted in April 2011, August 2011, November 2011, April 2012, August 2012, December 2012 and May 2013 at 20 to 28 benchmarks. These measurements covered the area more than 60 $km^2$ in the west side of Aso caldera. We collected relative gravity data using a Scintrex CG5-549 gravimeter, a microprocessor-based automated gravimeter that has a measurement range of over 8000 mGal and reading resolution of 1 µGal (CG-5 Scintrex Autograv System, 2006). At the same time, relative gravity measurements using LaCoste-Romberg type G-1016 was conducted at the same benchmarks for comparison in accuracy of gravity data. These relative gravity data referred to the absolute gravity variation data at AVL reference benchmark. The reference gravity benchmark is located in western area far from Nakadake crater. The close looping technique of the gravity measurements was conducted to minimize the drift errors and to identify shock induced tares. A careful field technique and repeat readings were also performed to minimize these uncertainties.

We introduced the A10-017 absolute gravimeter to measure gravity change at Aso volcano on May 13, 2010 at seven benchmarks, then we repeated on October 27, 2010 and June 2, 2011. The portable A10 absolute gravimeter assesses gravity changes at reference station and a field near the crater. It operates on a 12V DC power supply or vehicle battery (Micro-g LaCoste, Inc.). The principle of this instrument is simple, which a test mass is dropped vertically into 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). Accuracy and precision of absolute gravity data using this equipment are about 10 µGal. We reduce the uncertainty of regional gravity variation using the average variation of absolute gravity data set.

## 2.1 Correction factor

Hunt (2000) explained the correction factors of the gravity measurement were classified into the correction of variations with position, variations with time, and changes in position of mass in the earth. In the relative gravity data by Scintrex CG5 gravimeter, the drift, height, and tide corrections are the standard correction factors that are firstly corrected in the data. Earth tide corrections and automatic rejection data of high deviation or error of measurements are directly provided by this automated gravimeter. We manually calculated height and drift corrections in gravity data set while atmospheric pressure and temperature effects during each survey are insignificant.

Elevation change data were determined by comparing leveling survey data between 2008 and 2012 (Ohkura et al., 2013) (Figure 3). Vertical displacement maximum of one benchmark in this field is about 0.35 cm/year or corresponding to free air effect of about 1 µGal/ year (Telford et al., 1976). According to the history of these two leveling data set, the elevation change in Aso volcano is centered near Nakadake crater. The change is very small and the assumption for short difference period of measurements between 2010 and 2013 also have an insignificant elevation change.

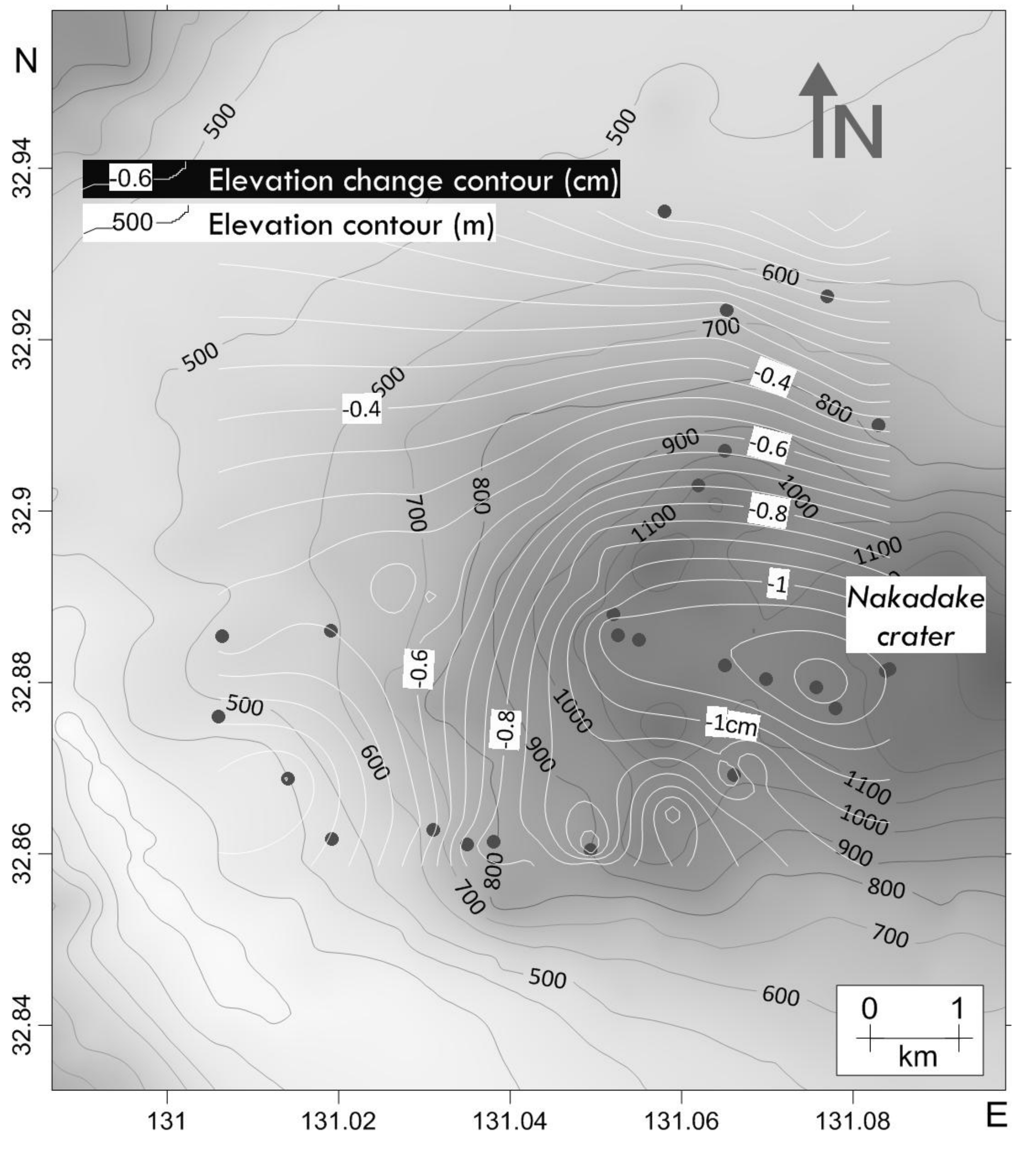

**Figure 3: Elevation changes between 2008 and 2012 in western part of Aso volcano.**

The A10 Absolute gravimeter has software that can directly correct the effects of the earth tides, ocean load, barometric pressure, and polar motion in acquiring the gravity data. Nevertheless, we need to calibrate this absolute gravity data in order to acquire good data. Absolute gravity data in 2009 and 2010 were calibrated to the data set of absolute gravity and groundwater level that was measured at Kyushu University, Japan. In 2011, the calibration process was conducted with a comparison data of FG-5 absolute gravimeter. FG-5 gravimeter is a more accurate absolute gravimeter instead of A-10, but it is not portable equipment. In the first comparison between two absolute gravimeters, the difference of absolute gravity data on the same benchmark appeared large. The calibration process was performed in two main equipment parts, which is laser and clock calibration.

### 2.2 Gravity changes

Gravity variation of relative data between April 2011 and May 2013 in some short period repeated measurements (April 2011, August 2011, November 2011, April 2012, August 2012, December 2012, and may 2013) help to give a picture of the hydrothermal dynamics in the subsurface. According to similarity of variation, relative gravity change data in Aso volcano are divided become five groups. Group 1-3 has similar trend and a large variation while group 4 and 5 has different trend compared to previous groups and small variation (Figure 4). The most active area of absolute gravity data is located around Nakadake crater.

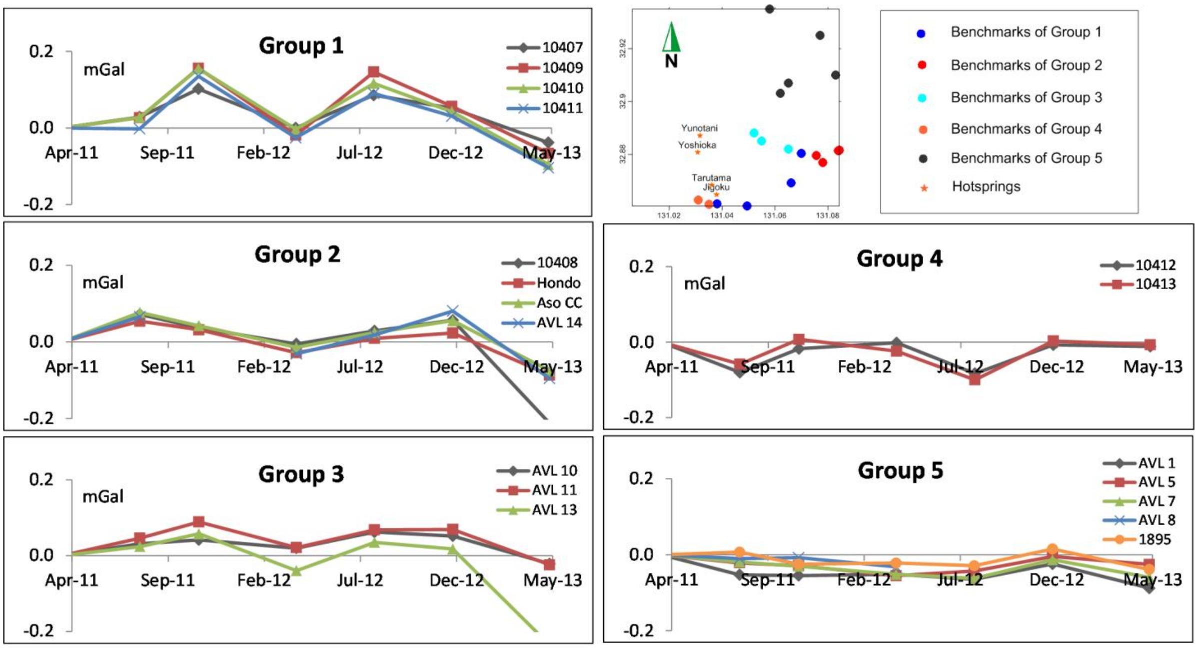

**Figure 4: Gravity changes between April 2011 and May 2013 in western part of Aso volcano.**

The distribution of relative gravity changes is carried out after smoothing the data to remove some variations (Sugihara and Ishido, 1998). The variation between April and August 2011 significantly rise near to Nakadake crater. About 60 µGal of increased gravity is located around the crater. The next period gravity monitoring from April to November 2011 shows the broad positive anomaly near the crater shifted to the western and southwestern area of Nakadake crater (Group 1 and 3). The distribution of gravity changes has a large positive gravity variation in the second period more than 80 µGal. The opposite gravity variation trend of previous period appears in April 2012. Gravity variation had been decreasing during this period, compared to November 2012 in most of research area. Gravity measurement in August 2012 showed increased variation in the research area of group 1, 2 and 3, while group 4 and 5 have decreased variation. Gravity variation in December 2012 has considerably risen near to the Nakadake crater (Group 2). The last gravity measurement in May 2013 indicated decreased variation in most of the research area.  The gravity changes distribution map in the two years between April 2011 and May 2013 in Aso volcano is shown in Figure 5.

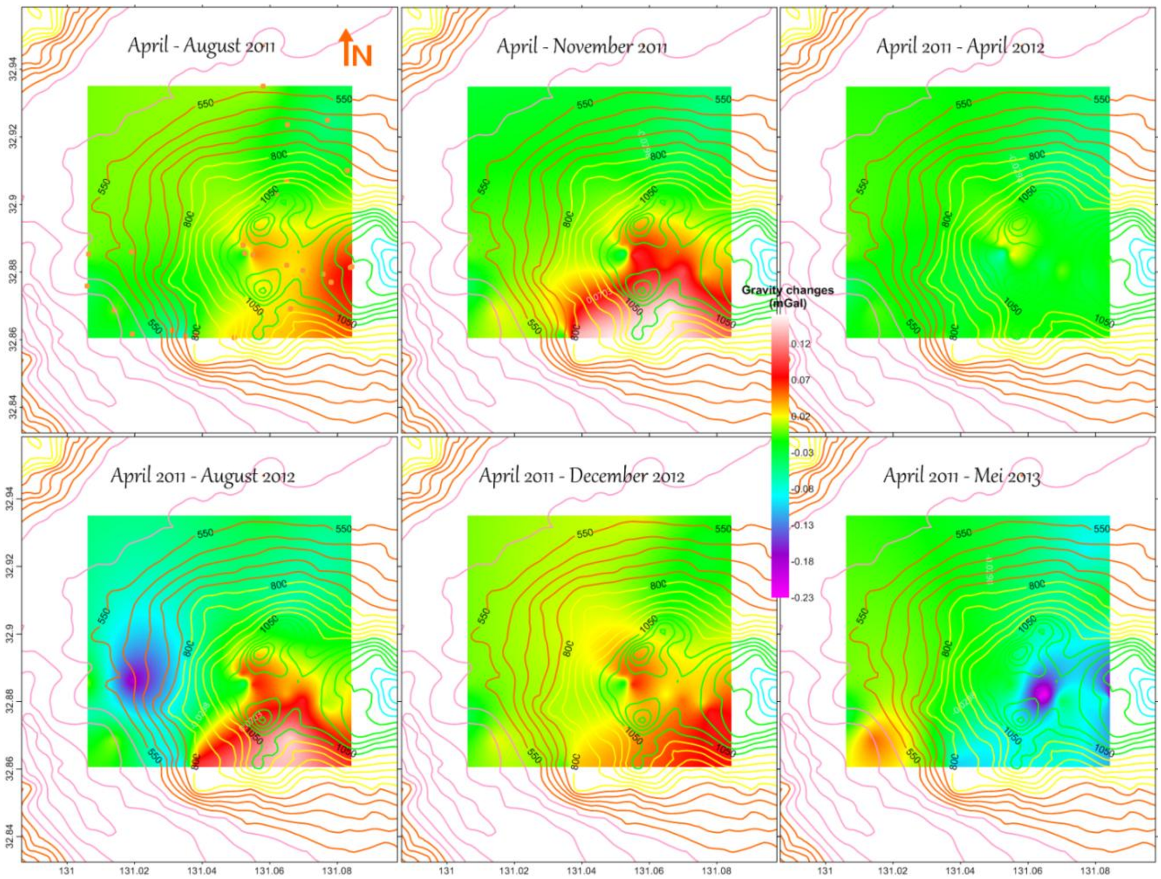

**Figure 5: Gravity changes map between April 2011 and May 2013 in western part of Aso volcano**

The time lapse gravity monitoring using an absolute gravimeter estimates gravity changes at AVL reference benchmark and in the survey field. We use absolute data to correct regional gravity variation of relative data as reference benchmark. The continued gravity monitoring using A10 absolute gravimeter reveals increased anomaly about 3.2 µGal/ year at AVL reference benchmark. This reference benchmark was measured by A10 absolute gravimeter since 2009.

## 3. MASS CHANGES

We interpret the gravity change data to construct the 3D model of density change distribution through 3D inverse modeling software. This GRAV3D inversion method was developed at the UBC Geophysical Inversion Facility (2005) and referred to the algorithm of Li and Oldenburg (1997, 1998). Usually this software is used to model gravity exploration data and determine a 3D structure of the subsurface. Nevertheless the software is also efficient and can be specifically used for time lapse gravity monitoring (Davis et al., 2008; Krahenbuhl and Li, 2009). Quantitative interpretation based on this 3D inverse modeling software produces density contrast model and describes the zones of the fluid distribution. The negative of density contrast, describes a decreased mass or mass lost while the positive of density contrast defines an increased mass. Due to short time monitoring and also previous research from MT data, we expect gravity variation come from hydrothermal dynamics in shallow depth. The area of 3D model of Aso volcano is 85.3 km$^2$ with depth up to 1 km from surface with total number 9768 finite elements. According to the short-term of measurement, the input of rock structure is not changed during measurements.

The water flow model of Nakadake crater explained supplied fluid to Nakadake crater come from groundwater, high temperature fluid supply from depth, and precipitation (Terada et al., 2012). Referring to his schematic model of mass flow around Nakadake crater, fluid supply to the lake that is come from depth or shallow hydrothermal reservoir has more influence than precipitation factor. Hydrothermal reservoir that connects to Nakadake crater is effectively detected by present 3D inversion model. The variation of crater lake condition during measurement is used as a direct validity evaluation. We assumed mass variation of shallow groundwater is small during gravity measurement. 3D inversion model displays large concentrated density contrast that is located beneath Aso crater and the southwestern part of the crater. Figure 6 presented the only positive density contrast or increased mass with minimum contrast about 0.0015 gr/cc. Geothermal activity in calm period 1 after a small eruption indicated increased mass below crater and then hydrothermal fluid moved to the southwestern part in the period 2. In the period 3, hydrothermal fluid progressed to outside of the research area or deep area. The density contrast model showed the hydrothermal fluid moved back to the crater in the period 4 and 5. Some fluid disappeared in the research area in the period 6. A color scale unit of density variation in this figure is gr/cc.

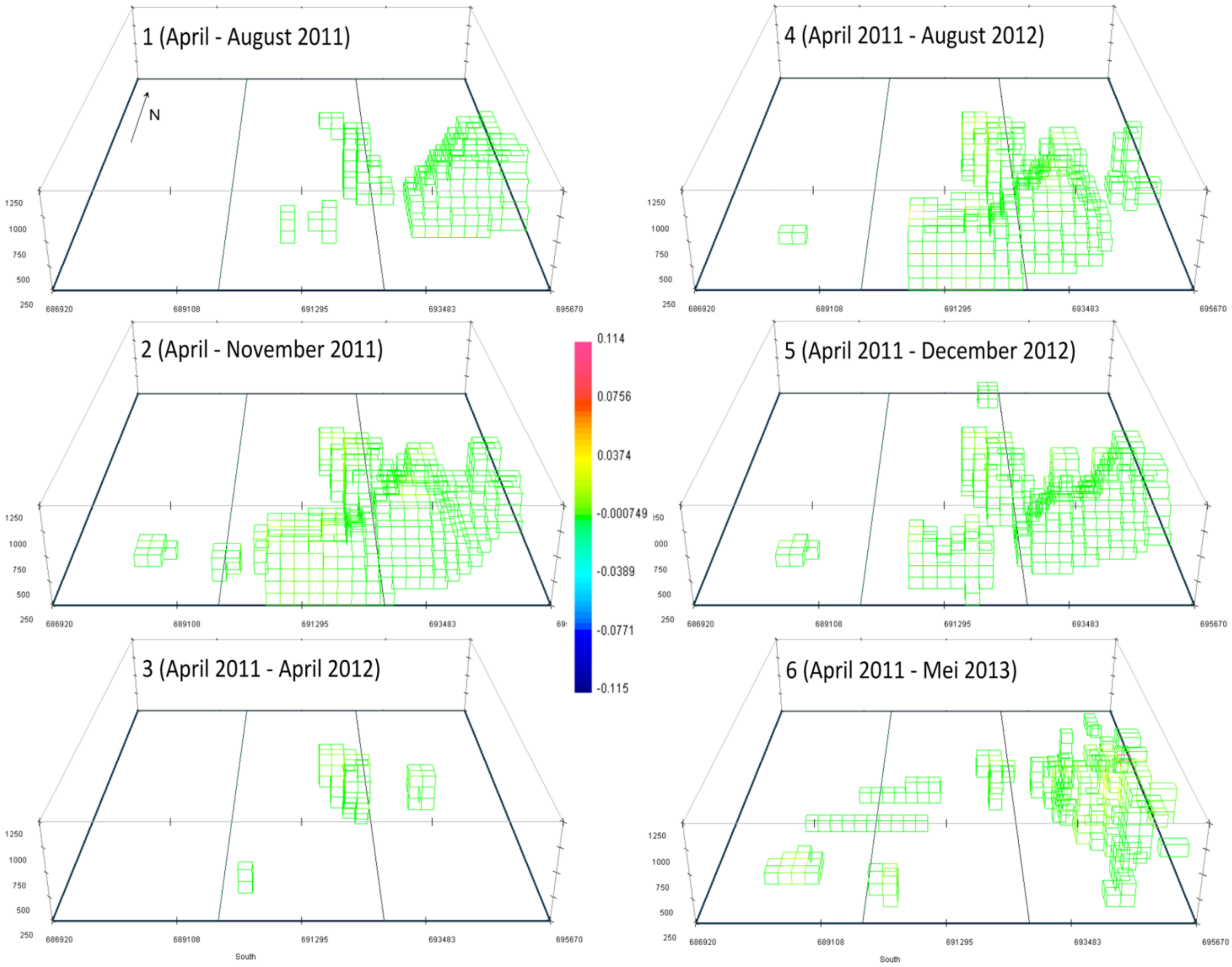

Figure 6: Hydrothermal dynamics as geothermal activity beneath Aso volcano

The mass variation is quantitatively estimated using two methods, which is Gaussian from gravity data and density contrast from the simulation result. Gauss's theory (Hammer, 1945) explained the mass changes are obtained by gravity changes:

$$\Delta m = \frac{1}{2\pi G}\sum\left(\Delta g.\Delta A\right) \tag{1}$$

where $\Delta m$ = the mass changes (kg), $\Delta g$ = the gravity changes (mGal), $\Delta A$ = Area concerned (km$^2$), $G$ = the gravitational constant 6.672x10$^{-11}$ Nm$^2$kg$^{-2}$. Mass changes ($\Delta m$) are calculated also through the density contrast ($\Delta\rho$) in a volume ($V$) model:

$$\Delta m = \Delta\rho .V \tag{2}$$

The largest increased mass about 21 MTon by density contrast or 30 MTon by Gaussian method occurred between April and August 2011. This is the calm period, a 6 month after the eruption in May 2011. The largest decreased mass about -36 MTon by density contrast or -35 MTon by Gaussian method occurred between April 2011 and May 2013, about 2 years after the eruption. The geothermal activity in mass variation between April 2011 and May 2013 can be seen in Figure 7. Mass changes of density contrast 1 come from an interest area of dominant variation near the crater and southwestern area near hot springs (group 1, 2 and 3 in Figure 4), while density contrast 2 come from the whole research area.

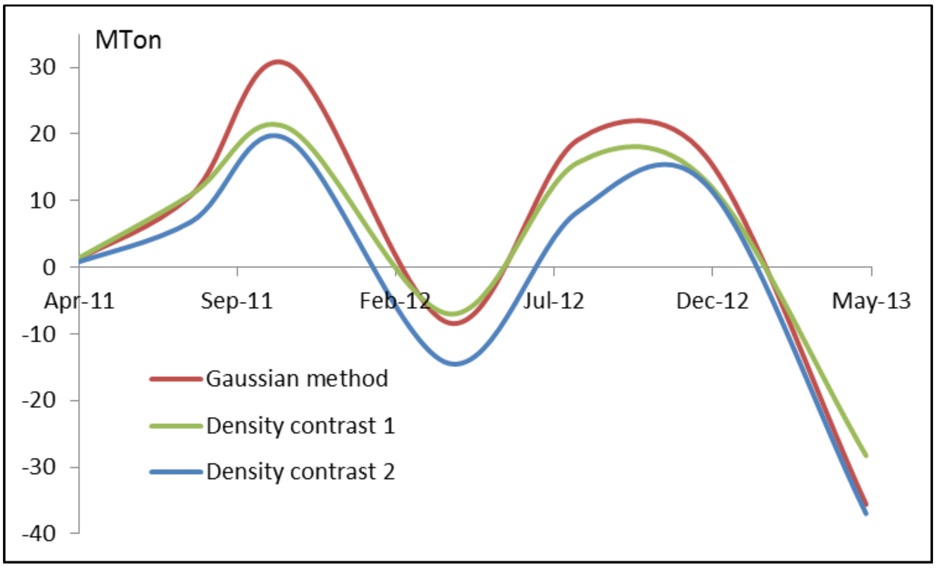

**Figure 7: Mass variation using Gaussian and the density contrast method in the west area of Aso volcano**

## 4. CONCLUSIONS

Monitoring geothermal activity using repeated gravity measurement clarify the hydrothermal mass variation in the subsurface of Aso volcano. Relative and absolute gravity measurements between 2010 and 2013 depict these variations. According to gravity change distribution map, the dynamic variation mass of the Aso volcano is more concentrated near the Nakadake crater area and southwestern of the crater. The variation of relative data in Aso volcano is divided become five groups. Group 1, 2 and 3 (active group) has similar trend and a large variation while group 4 and 5 has different trend and a small variation. After small eruption on May 2011, positive gravity changes accumulated in the active group. After one year, a temporary decreased gravity variation trend appeared in geothermal activity of Aso volcano.

The inverse modeling of repeated gravity data that estimate the density contrast and mass variation between measurements at Aso volcano has good validation from Nakadake dynamic crater during these periods. Hydrothermal reservoirs beneath Aso volcano are detected by these inversion models. Geothermal activity in the calm period indicated increased mass below crater and then hydrothermal fluid moved to the southwestern part of the crater. After one year, hydrothermal fluid progressed to outside of the research or deep area. In the next period, the density contrast model showed the hydrothermal fluid moved back to the crater.

The largest increased mass about 21 MTon by density contrast or 30 MTon by Gaussian method occurred between April and August 2011. The largest decreased mass about -36 MTon by density contrast or -35 MTon by Gaussian method occurred between April 2011 and May 2013, about 2 years after the eruption.

## ACKNOWLEDGMENT

The first author acknowledges the financial support of the Japan Society for the Promotion of Science (JSPS) for research activities in Japan. I would like to thank Dr. Yoichi Fukuda of Kyoto University and Dr. Makoto Taniguchi of Research Institute for

Humanity and Nature (RIHN) for lending us A10-017 Absolute gravimeter (Micro-g LaCoste) for gravity measurement at Aso volcano. The inverse modeling is simulated by GRAV3D Software that was developed at and licensed from UBC.

## REFERENCES

Battaglia, M., J. Gottsmann, D. Carbone, and J. Fernandez, 2008, 4D volcano gravimetry: Geophysics, vol. **73** no.6, p. WA3–WA18.

Battaglia, M., P. Segall, C. Roberts, 2003, The mechanics of unrest at Long Valley caldera, California: 2. Constraining the nature of the source using geodetic and micro-gravity data: Journal of Volcanology and Geothermal Research, **127**, p. 219-245.

Davis, K., Li, Y., and Batzle, M., 2008, Time-lapse gravity monitoring: A systematic 4D approach with application to aquifer storage and recovery: Geophysics, vol. **73**, no.6, p. WA61-WA69.

Dzurisin, D., 2003, A comprehensive approach to monitoring volcano deformation as a window on the eruptive cycle: Reviews of Geophysics, **41**, 1009, doi: 10.1029/2003RG000134.

Hammer, S. (1945), “Estimating Ore Masses in Gravity Prospecting”, *Geophysics,* **10**, 50-62.

Hunt, T. M., 2000. Five lectures on environmental effect of geothermal utilization: Geothermal Training Programme , United Nations University, 104 p.

Jousset P., H. Mori, and Okada H., 2003, Elastic models for the magma intrusion associated with the 2000 eruption at Usu Volcano, Japan: Journal of Volcanology and Geothermal Research, **125**, p. 81-106.

Kanda, W., Y. Tanaka, M. Utsugi, S. Takakura, T. Hashimoto, and H. Inoue, 2008, A preparation zone for volcanic explosions beneath Nakadake crater, Aso volcano, as inferred from magnetotelluric surveys: Journal of Volcanology and Geothermal Research, **178**, p. 32-45.

Krahenbuhl, R. A. and Li, Y, 2009, Hybrid optimization for lithologic inversion and time-lapse monitoring using binary formulation: Geophysics, vol. **74**, no.6, p. I55-I65.

Li, Y. and Oldenburg, D. W., 1997, Fast inversion of large scale magnetic data using wavelets: 67th Ann. International meeting, Soc. Exploration Geophysics, Expanded Abstracts, 490–493.

Li, Y. and Oldenburg, D. W., 1998, 3D inversion of gravity data: Geophysics, **63**, 109–119

Matsumoto, A., Uto, K., Ono, K., and Watanabe, K., 1991, K–Ar age determinations for Aso volcanic rocks-concordance with volcano stratigraphy and application to pyroclastic flows: Programme and Abstract: Volcanological Society of Japan, vol. **2**, p. 73 (in Japanese).

Micro-g LaCoste Inc., 2006, A10 Portable Gravimeter User’s Manual, 7p.

Miyabuchi, Y., Hoshizumi, H., Kaneko, K., Sudo, Y., and Kagiyama, T., 2007, Aso Volcano: Gigantic pyroclastic flow eruptions and post-caldera activity: Cities on Volcanoes 5 conference, p. C3:1-19

Nishijima, J., H. Saibi, Y. Sofyan, S. Shimose, Y. Fujimitsu, S. Ehara, Y. Fukuda, T. Hasegawa, and M. Taniguchi, 2010, Reservoir monitoring using hybrid micro gravity measurement in the Takigami geothermal field, central Kyushu, Japan: World Geothermal Congress 2010, 6 p.

Ohkura, S., S. Yoshikawa, H. Inoue, M. Utsugi, T. Kagiyama and et al., 2009, leveling in Aso (September-October 2008): Aso research report 2009 (report in Japanese), 8p.

Okubo, Y., and A. Shibuya, 1993, Thermal and crustal structure of the Aso volcano and surrounding regions constrained by gravity and magnetic data, japan: Journal of Volcanology and Geothermal Research, **55**, p. 337-350.

Ono, K. and Watanabe, K., 1983, Aso caldera: The Earth Monthly, **44**, 73-82.

Ono, K., K. Watanabe, H. Hoshizumi, and S. Ikebe, 1995, Ash eruption of the Nakadake crater, Aso volcano, southwestern Japan: Journal of Volcanology and Geothermal Research, **66**, p. 137–148.

Rymer, H., J. Cassidy, C. A. Locke, and F. Sigmundsson, 1998, Post-eruptive gravity changes from 1990 to 1996 at Krafla volcano, Iceland: Journal of Volcanology and Geothermal Research, **87**, p. 141-149.

Scintrex, 2006, CG-5 Scintrex Autograv System, operation manual, 304p.

Sudo, Y., 1991, An Attenuating Structure beneath the Aso Caldera Determined from the Propagation of Seismic Waves: Bulletin of Volcanology, **53**, p. 99-111.

Sudo, Y., and Kong, L.S.L., 2001, Three-dimensional seismic velocity structure beneath Aso Volcano, Kyushu, Japan: Bulletin of Volcanology, **63**, p. 326–344.

Sudo, Y., Tsutsui, T., Nakaboh, M., Yoshikawa, M., Yoshikawa, S., and Inoue, H., 2006, Ground deformation and magma reservoir at Aso Volcano: location of deflation source derived from long-term geodetic surveys: Bulletin of the Volcanological Society of Japan, **51**, p. 291–305 (in Japanese with English abstract).

Sugihara, M. and Ishido, T., 1998, Gravity monitoring at the Sumikawa Geothermal Field, Japan: Geothermal Resources Council Transactions, Vol **22**, p. 191 – 195.

Telford, W.M., Geldart, L.P., Sheriff, R.C., Keys, D.A., 1976, Applied Geophysics: Cambridge University Press., 770 pp, Cambridge New York.

Terada, A., T. Hashimoto, and T. Kagiyama, 2012, A water flow model of the active crater lake at Aso volcano, Japan: fluctuations of magmatic gas and groundwater fluxes from underlying hydrothermal system: Bulletin of Volcanology, DOI 10.1007/s00445-011-0550-4, 15p.

Yamamoto, M., Kawakatsu, H., Kaneshima, S., Mori, T., Tsutsui, T., Sudo, Y., and Morita, Y., 1999, Detection of a crack-like conduit beneath the active crater at Aso volcano, Japan: Geophysics Research Letter, **26**, p. 3677-3680.

UBC-Geophysical Inversion Facility, Department of Earth and ocean sciences, 2005, GRAV3D version 3.0, A program library for forward modelling and inversion of gravity data over 3D structures, UBC, 30p.