PROCEEDINGS, Thirtieth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 31-February 2, 2005
SGP-TR-176

DETERMINATION OF SHALLOW GROUNDWATER LEVEL CHANGE USING REPEAT GRAVITY MEASUREMENTS AT THE CENTRAL PART OF UNZEN VOLCANO (NAGASAKI PREFECTURE, JAPAN) FROM 1999 TO 2004

Hakim Saibi[1], Jun Nishijima[2], Sachio Ehara[2], Yasuhiro Fujimitsu[2] and Koichiro Fukuoka[2]

[1]Dept. of Earth Resources Eng., Graduate School of Eng., [2]Dept. of Earth Resources Eng., Faculty of Eng.
Kyushu University, 6-10-1 Hakozaki, Higashi-ku, Fukuoka, 812-8581, Japan
saibi-hakim@mine.kyushu-u.ac.jp

ABSTRACT

Unzen volcano is located in Shimabara Peninsula (Nagasaki prefecture), Kyushu Island, southwest of Japan, and one of the most active volcanoes in Japan. The most recent eruption occurred in 1990 to 1995. The possibility of existing or degenerating of a new hydrothermal system beneath Unzen volcano associated with the last eruption, was investigated by using repeat gravity monitoring since August 1999. The variations in observed gravity depend significantly on changes in shallow groundwater level changes. A good correlation of gravity with precipitation is observed with a phase lag about 3 months in some regions in the study area. The water level changes are studied by Unzen Scientific Drilling Project porosity data. The results show that the downflow of permeating rain water is dominant.

Keywords - Gravity, Groundwater, Unzen volcano, Hydrothermal system, Japan.

INTRODUCTION

Unzen volcano, located in Shimabara Peninsula of western Kyushu (Fig. 1), is a complex of many lava domes, thick lava flows and pyroclastics of andesite to dacite in composition (Watanabe et al., 1995). Phreatic eruptions occurred at Jigokuato crater, near the summit of Fugen-Dake on November 17, 1990, the eruption followed 198 years of dormancy. The purpose of this study is to determine changes in the level of ground water and investigate the possibility of a new hydrothermal system beneath the Unzen volcano associated with the 1990-1995 eruption events. In this study, we have carried out a repeat gravity measurement at the central part of Unzen volcano. Gravity network is composed of 15 stations (Fig. 2) performed with a Scintrex CG-3M gravimeter for assessing effects of local disturbances, which are caused essentially by variations of groundwater level (Ehara, S. et al., 1995). The method of measurement is the two-way measurement method, which was used to evaluate the instrumental drifts and precision. The measurements were repeated at almost the same date, once a year from 1999 to 2004 (August 11th, August 11th, August 10th, August 9th, August 9th, and August 11th), respectively. The survey area lies west of the newly formed lava dome. This area was selected because of the trajectory of the volcanic conduit running from the west to the east below this area deduced from geophysical studies. Observation errors were calculated at 10 to 20 micro-gals. The main reasons of the gravimeter's errors are the environmental factors (wind, vibration, rain, etc.) during station occupations, elevation uncertainties, and operator errors.

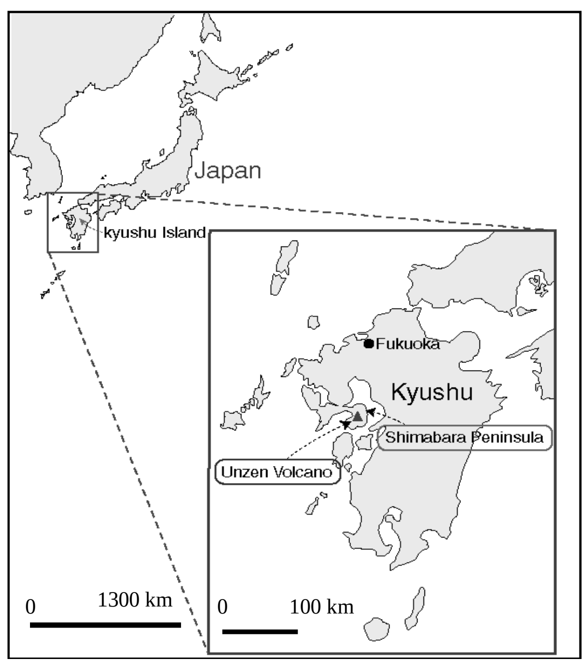

Figure 1: Location of Unzen volcano.

The data were reviewed carefully to make sure that only gravity changes due to the groundwater level changes are considered.

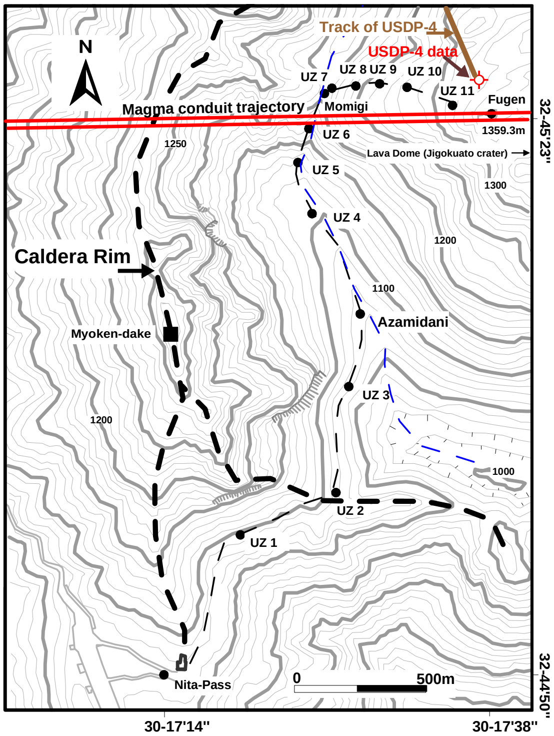

Figure 2: Location of stations (Nita to Fugen) for the repeat gravity measurement. The contour background represents the topography. Height is represented in meters.

The Unzen volcano area is not associated with artificial component like production and reinjection of groundwater. The natural effects are believed to control the gravity changes in Unzen volcano area. Seasonal changes in the shallow groundwater level can have a significant effect on the gravity. Depending on near-surface porosities and the magnitude of the changes in water level, the measured gravity may vary by tens or even hundreds of micro-gal (Allis and Hunt, 1986). Temporal variations of groundwater level causes direct gravitational effects (Torge, W., 1989). For this purpose correlations between hydrological data and gravimeter's readings have been computed in order to determine the relationship between hydrological processes and gravity changes. The hydrological data are presented by rainfall at Unzendake weather station, Japan Meteorological Agency (about 4 km SW of the lava dome). After recording gravity data, automated corrections were simultaneously done by the gravimeter for tide, instrument drift, temperature and data rejection. Then we have applied corrections for elevation (height correction) and drift (drift correction). The resulting gravity value was deduced from the Nita station gravity value. In this paper, all gravity values represent the gravity difference referred to Nita station gravity in 2000.

METHODS AND RESULTS

Correlation between Gravity Changes and Precipitation

The gravity changes data were acquired from August 1999 to August 2004. The comparison between gravity and precipitation taken in the same period (1999-2004) reveals a certain correlation (Fig. 3). After examination, gravity changes at Unzen monitoring area from 1999 to 2004 shows three different patterns, those are the pattern (A) which includes UZ1, UZ2, UZ3, UZ4, Azamidani, UZ5, UZ6 and Momiji (Fig. 4), the pattern (B) which includes UZ7 and UZ8 (Fig. 5) and the pattern (C) which includes UZ9, UZ10, UZ12 and Fugen (Fig. 6). The three different patterns represent three regions: A, B and C. The gravity data have a good correlation with precipitation (>0.7 in (A) region, >0.77 in (B) region and >0.9 in (C) region), with a phase lag of about 3 months in (A) region, 4 months in (B) region and about 3 to 4 months in (C) region. The precise gravity data are shown in Table 1.

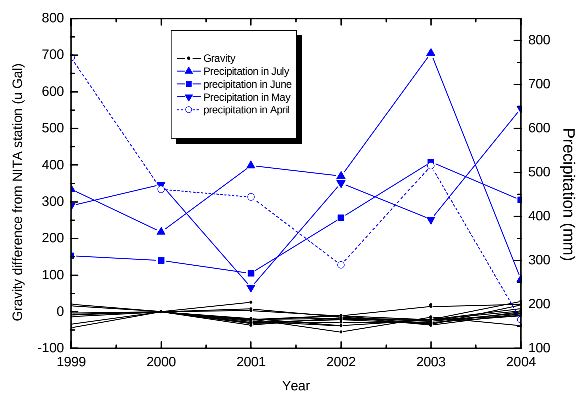

Figure 3: Comparison between gravity and precipitation at Unzendake Weather Station.

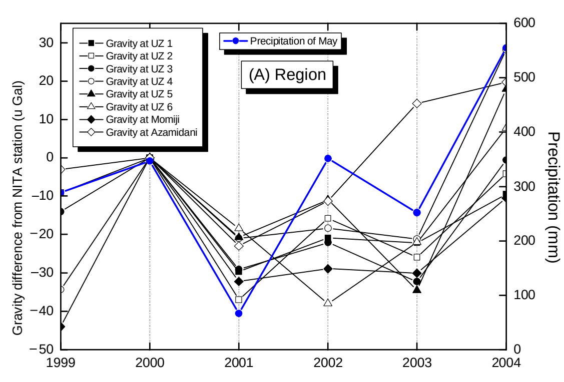

Figure 4: Correlation between gravity and precipitation in (A) region.

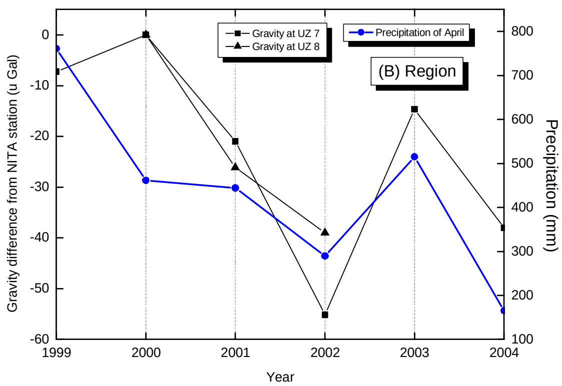

Figure 5: Correlation between gravity and precipitation in (B) region.

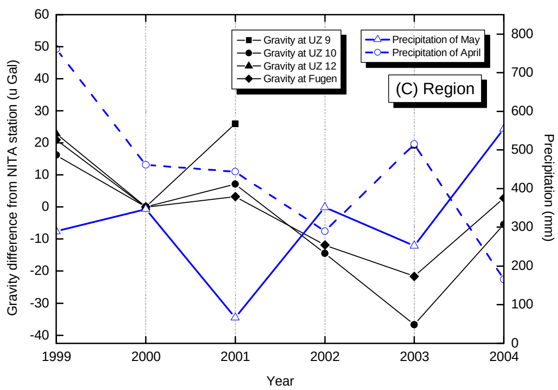

Figure 6: Correlation between gravity and precipitation in (C) region.

Calculation of Groundwater Level Change from Gravity Change

The gravity changes associated with a change in groundwater level is given by Allis and Hunt (1986):

$$\Delta g = 2\,\pi\, G\, \phi\, \rho_w\, \Delta h \qquad (1)$$

where Δg is the gravity change (1μGal=10^{-8} m/s^2), G is the universal gravity constant (6.67x10^{-11}m^{3}kg^{-1}s^{-2}), ϕ is the porosity at the depth of water table, ρ_w is the density of groundwater (≈1 kg.m^{-3}), Δh is the change in water level (m).

Using equation (1), the groundwater level change is calculated as follows:

$$\Delta h = \frac{\Delta g}{2\,\pi\, G\, \phi\, \rho_w} \qquad (2)$$

Porosity is the only unknown factor in the equation (2). To solve this problem, we will use porosity measured by USDP-4 drilling log (JMC). The Unzen Volcano Scientific Drilling Project (USDP) has been conducted to target the magma conduit shortly after the 1990-1995 eruption. After two drillings of 752 m and 1463 m deep at the flank site, the conduit surveying well (USDP-4) was drilled to the depth of 1995.75 m in the mountainside to clarify the ascending and degassing mechanisms of magma. Many physical logging have been conducted to elucidate the structure and material properties in and around the conduit. One of the physical logging items is neutron porosity (Fig. 10). From the USDP-4 logging results the porosity value at the surrounding monitoring area is about 20 to 30 %. Using equation (2), the results of groundwater level changes are plotted with topographic elevation to deduce even relation with the flow pattern in shallow part of Unzen. The Figure 7 shows the changes of ground water level with 20 % of porosity plotted with topographic elevation and the Figure 8 shows the changes of groundwater level with 30 % of porosity. The extremities of changing of groundwater level in the two cases ranges from -6.58m in UZ7 to +3.36m in UZ4 (20 % of porosity). We have large changes around the summit which is the recharge area of Unzen and in valley area (UZ3, Azamidani and UZ4) because the groundwater flows from the highlands to the lowlands. In general the results agree with the characteristics of groundwater flow system, the groundwater flow is downwards in the summit of Unzen; this region of the flow system is the recharge area. In Unzen the shallow zone around the magma vent should be highly fractured and hence, have especially large permeability, estimated as 60 Darcy (Hashimoto, 1997), also the summit region is characterized by many dykes related to the old volcanic conduit. The water table forms a subdued replica of the topography and its depth beneath the ground surface is greatest in the upper part of Unzen volcano and least in the lower part of Unzen volcano.

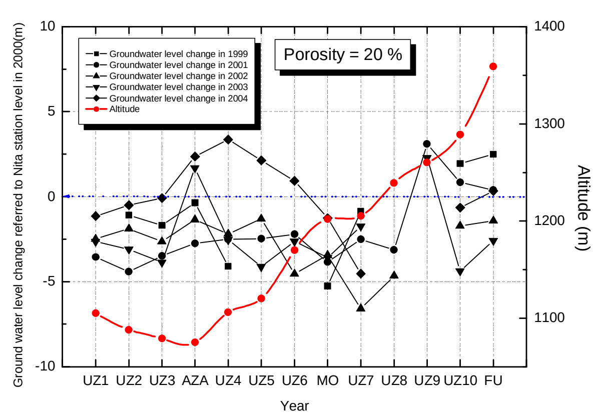

Figure 7: Change of groundwater level with 20 % of porosity and topographic elevation along the path crossing stations UZ1-Fugen in Fig. 2.

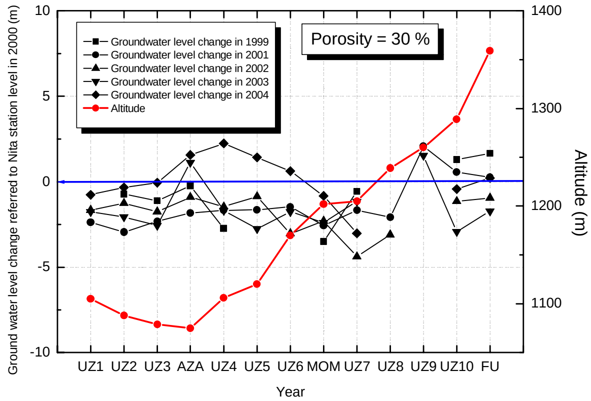

Figure 8: Change of groundwater level with 30 % of porosity and topographic elevation along the path crossing stations UZ1-Fugen in Fig. 2.

The observed gravity changes in Unzen depend significantly on changes in shallow ground water level change (Ehara, S. et al., 1995).

Gravity Change between 1999 and 2000

The gravity change from August 1999 to August 2000 is shown in Fig. 9. During this period, gravity changes from -44 to +23 μGal occurred at most of gravity stations. The largest positive gravity changes are detected in the zone occupied by station UZ12 (near the lava dome). This indicates a certain excess in mass balance. This could be explained by natural recharge by infiltration of water to the shallower aquifer. The gravity decrease coincides with the most fractured zone, around Momiji station.

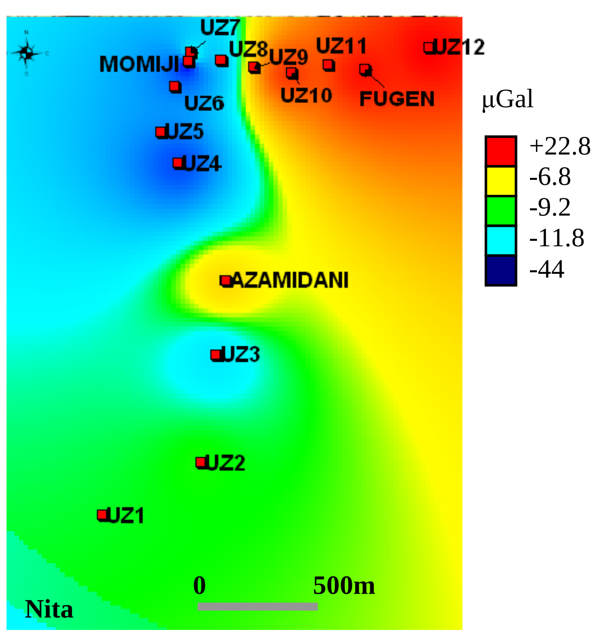

Figure 9: Contour map of the gravity changes at the central part of Unzen volcano from August 1999 to August 2000. Reference station is Nita.

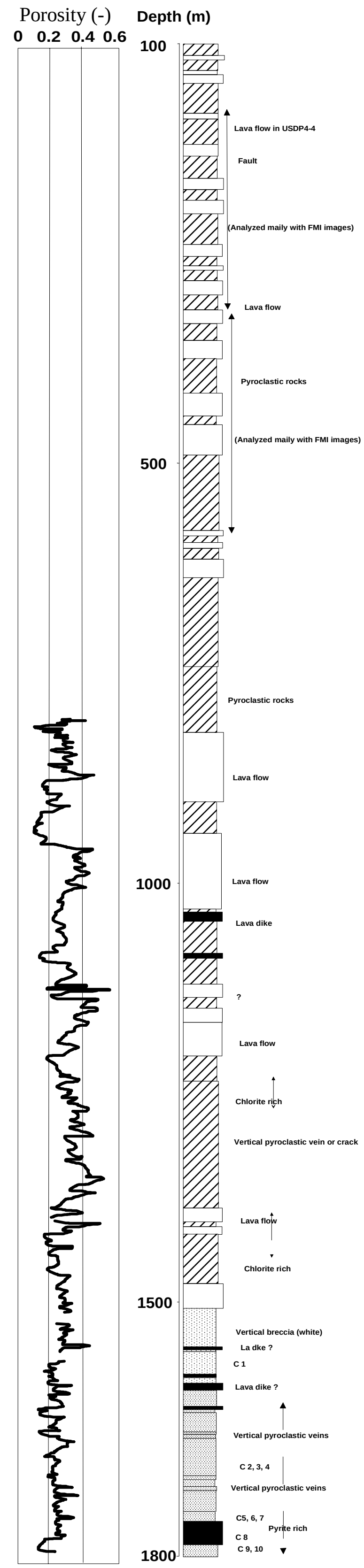

Figure 10: USDP - 4 drilling log with porosity results (JMC, 2004).

Gravity Change between 2000 and 2004

Gravity change for the period 2000 – 2004 is given in Fig. 11. There are differences (increases) of up +28 μGal in UZ4, the other of about +18 μGal in Azamidani, zone of low topography, therefore the groundwater flows to this region, as consequence increasing in gravity. On the other hand, gravity decreases around UZ7 about -38 μGal, near Momiji station. The increasing of gravity in low topography areas is explained by the good negative correlation between gravity changes and altitude (Fig. 12). The summit of Unzen volcano represents the recharge area where water moves downward through the high permeable rocks (pyroclastic flow deposits) and faults from a high topography area into the zone of saturation. In other words, the low topographic region (around Azamidani) replenishes groundwater, where groundwater moves towards this area.

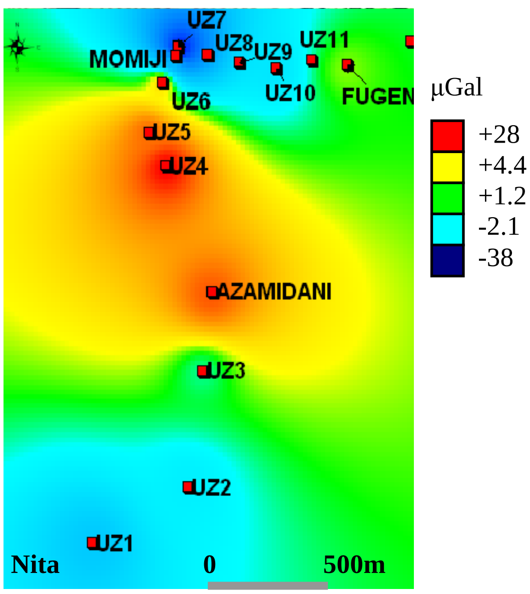

Figure 11: Contour map of the gravity changes at the central part of Unzen volcano from August 2000 to August 2004. Reference station is Nita.

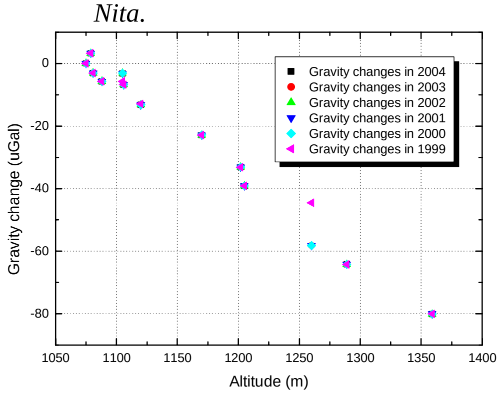

Figure 12: Comparison between gravity change and altitude.

Comparison between Gravity Changes and Ground Temperature Changes

In this section, we would like to check the relation between gravity changes and the 1-meter depth temperature changes. That for the case if up flowing of hot fluid is the cause of increasing in gravity.

In the same period of gravity monitoring (1999-2004), 17 temperatures recording (UT1 until UT17) at 1m depth were measured; each station is measured two times (go and back) referring to UT1 station (Fujimitsu, Y. et al., 2002). The raw temperature data were analyzed for original sensor error and daily change correction.

The measured temperature points are almost located on the same road of gravity monitoring. For convenience, we have chosen 6 points of temperature measurements, which are exactly on the same location of gravity stations, (UT2, UT4, UT5, UT8, UT9 and UT11 respectively Azamidani, UZ4, Momiji, UZ9, UZ11 and Fugen). The correlations are shown in Fig. 13. The results show a good correlation between gravity and temperature, except two different anomalies, one in Momiji and the other one in Azamidani. In Momiji, we observe decreasing of gravity with increasing of ground temperature; it is possible that this anomaly is caused by volcanic gas.

Note that high concentration anomalies of Hg and radon and thoron gases were also observed in this region (Unoki et al., 2003). In Azamidani, we observe increasing of ground temperature but with positive gravity. As cited in previous section, the gravity increases as fact of movement of ground water towards this area. The increasing of ground temperature particularly in the period (1999-2003) in Azamidani may suggest existing of magma pass beneath this area. Around Azamidani, the geochemical observations also revealed the existence of high soil air Hg (70 ng/m^3) and CO_2 (0.6%) (Unoki et al., 2003).

The observed high temperature changes are located essentially around UZ9 (+2^{o}C) and UZ4 (+2^{o}C). UZ9 and Momiji are above the plane image of the trajectory of the volcanic conduit estimated by geophysical methods (STA, 1999). Therefore the ground may be heated by a magma pass beneath those stations. For the case of UZ4, as it's near Azamidani (distant of 100m), the cause may be the same.

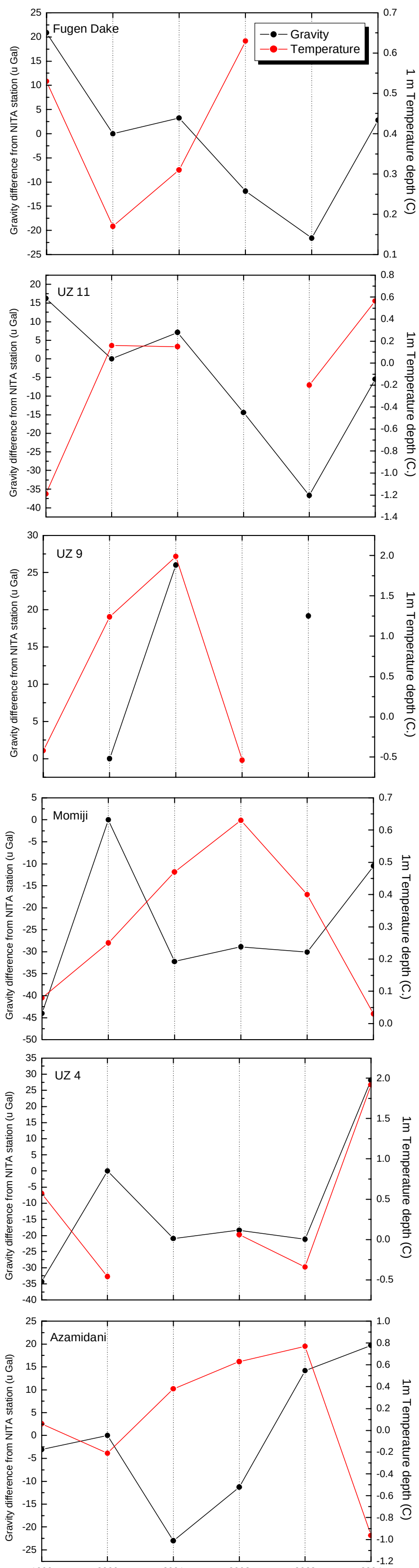

Figure 13: Correlations between gravity change (black) and 1-meter depth temperature depth change (red).

DISCUSSION AND CONCLUSION

We have carried out gravity measurements in the west area of the newly formed lava dome, Heiseishinzan at Unzen volcano, from 1999 to 2004. The results of the correlation between gravity changes and precipitation in Unzen area thought to be logical. To reach the shallower water table in the summit (region B and C), the infiltration takes time, while the low region (A). The water table forms a subdued replica of the topography and its depth beneath the ground surface. The changes of gravity are attributed to the changes of the shallower groundwater level. A shallower water layer was inferred by many geophysical works (JURG, 1992; Hashimoto, 1997, Kagiyama, 1999, Fukuoka, 2003). As example: The Magneto-Telluric surveys conducted by Joint University Research Group have revealed that an aquifer exists widely below Shimabara peninsula at the depth between -1 km and 0.5 km above the sea level (JURG, 1992). The SP survey conducted by Hashimoto (1997) reveals existence of a shallower water-bearing layer in the summit area of Unzen volcano. It is noteworthy that the shallow ground temperature and gravity anomalies around Momiji and Azamidani areas match the geochemical observations. A magma pass beneath those regions is thought to be the cause of degassing. The flow pattern in shallower part of Unzen volcano is dominant down flow (Fig.14). Further studies are required to examine the proposed hydrothermal system beneath Unzen Volcano.

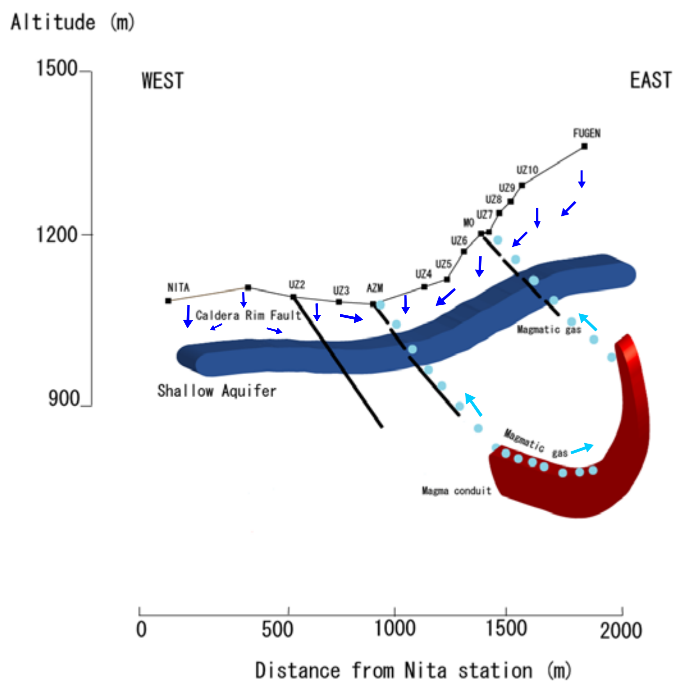

Figure 14: Conceptual hydrothermal model beneath Unzen Volcano deduced from geophysical and geochemical observations.

	1999/08/11		2000/08/11		2001/08/10		2002/08/09		2003/08/09		2004/08/11	
STATION	**GRAVITY**	**ERROR**	**GRAVITY**	**ERROR**	**GRAVITY**	**ERROR**	**GRAVITY**	**ERROR**	**GRAVITY**	**ERROR**	**GRAVITY**	**ERROR**
AZAMIDANI	3.043	0.011	3.047	0.014	3.031	0.050	3.035	0.013	3.060	0.045	3.066	0.009
NITA	0.000	0.030	0.000	0.008	0.000	0.047	0.000	0.016	0.000	0.048	0.000	0.013
UZ1	-2.676	0.011	-0.066	0.005	-0.089	0.053	0.208	0.008	-0.090	0.012	-0.077	0.003
UZ2	-2.669	0.002	-2.659	0.009	-2.698	0.035	-2.676	0.026	-2.686	0.028	-2.664	0.021
UZ3	6.316	0.004	6.331	0.007	6.310	0.049	6.308	0.022	6.298	0.011	6.330	0.025
UZ4	-3.744	0.015	-3.709	0.024	-3.721	0.059	-3.728	0.008	-3.731	0.010	-3.682	0.032
UZ5	-9.866	0.010	-10.167	0.010	-10.185	0.045	-10.179	0.021	-10.203	0.021	-10.150	0.033
UZ6	-19.820	0.021	-19.801	0.013	-19.818	0.054	-19.841	0.022	-19.825	0.010	-19.795	0.002
MOMIJI	-29.086	0.037	-30.047	0.027	-30.110	0.007	-30.077	0.017	-30.078	0.005	-30.058	0.044
UZ7	-30.092	0.004	-36.094	0.008	-36.120	0.033	-36.141	0.002	-36.101	0.017	-36.124	0.019
UZ8	-36.093	0.001	-46.970	0.019	-47.009	0.056	-47.010	0.008	ND	ND	ND	ND
UZ9	-41.476	0.002	-55.156	0.007	-55.132	0.061	ND	ND	-54.664	0.020	ND	ND
UZ10	-47.006	0.006	-61.152	0.008	-61.166	0.079	-61.168	0.032	-60.868	0.033	-61.159	0.020
UZ11	-61.137	0.011	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
FUGEN	-76.992	0.010	-77.012	0.012	-76.999	0.009	-77.025	0.013	-76.697	0.002	-77.010	0.011

Gravity: Gravity value referred to Nita station in μGal.
ND: Not Determined.

Table 1: Gravity Monitoring Date in Unzen Volcano From 1999 to 2004.

ACKNOWLEDGEMENTS

The first author gratefully acknowledges the financial support of the Ministry of Education, Culture, Sports, Science and Technology, Government of Japan in the form of scholarship.

REFERENCES

Allis, R.G. and Hunt, T.M. 1986: Analysis of exploitation induced gravity changes at Wairakei geothermal field. *Geophysics*, 51, 1647-1660.

Ehara, S. et al., 1995: Gravity monitoring of geothermal reservoirs-A case study of the production and reinjection test at the Takigami geothermal field, central Kyushu, *Japan. Proc. World Geothermal Congress* 1995, pp. 1955-1958.

Fujimitsu, Y. et al., 2002: Study on hydrothermal system development, Unzen volcano, Japan. A topic in phase 1 of the Unzen scientific drilling project. *Proceedings 24th NZ Geothermal Workshop 2002*, 283-287.

Fukuoka, K. et al., 2003: resistivity prospecting at Unzen volcano. Oral presentation.

Hashimoto T., 1997: Self-Potential changes and subsurface hydrothermal activity accompanying the 1990-1995 eruption of Unzen volcano. *J. Geomag. Geoelectr*. 49, 977-993.

Japan Metals and Chemicals (JMC) Co., Ltd, 2004: USDP-4 drilling results.

Joint University Research Group (Geophysical Party), 1992: Geophysical observations of the 1990 – 1992 eruption at Unzen volcano (part1), *Bull. Volcanol. Soc.* Japan, 37, 209-215 (in Japanese).

Kagiyama, T. et al, 1999: Magma ascent beneath Unzen Volcano, SW Japan, deduced from the electrical resistivity structure. *Journal of Volcanology and Geothermal Research*, 89, 35-42.

STA, 1999: Unzen volcano – International Cooperative Research with Scientific Drilling for Magmatic Activity. *Brochure of Science and Technology Agency*, Japan.

Torge Wolfgang, 1989: Gravimetry. Edition: Walter de Gruyter. Berlin – New York.

Unoki, R. et al., 2003: Soil air gas and gamma-ray surveys at Unzen volcano, Japan. *Proceedings 25th NZ Geothermal Workshop* 2003. pp. 137-141.

Watanabe, K. et al., 1995: Geological map of Unzen volcano 1: 25.000, *Geological Survey of Japan*.