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Current status and problems of gravity observations for monitoring the Ontake Volcano

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Abstract

We have been conducting absolute gravity measurements at the eastern foot of the Ontake Volcano since 2004. After the phreatic eruption in 2014, we started conducting relative gravity observations. Referring to recent volcanic activities, we ran gravity-change simulations to evaluate the optimal location for gravity observation. The following points have become clear: (1) the absolute gravity variation is closely related to rainfall, (2) relative continuous gravity observations may have a sensitivity of several μGal, and (3) a gravity observation base should be established closer to the mountain top.

Introduction

Gravity measurements for the monitoring of volcanic activities are important to detect density change and/or mass movement (Furuya et al. 2003; Okubo et al. 2013). If the accompanying earthquakes and crustal movements are dominant, seismological and other geodetic observations are effective to model the source of volcanic activity. However, for induced density changes without fracture deep underground, which may correspond to the initial stage of volcanic activity, we should make the most use of gravity observations.

Earthquake swarm activities are active in the eastern foot of Ontake volcano and various studies have indicated that this activity is caused by hydrothermal activity (Tanaka and Ito 2002; Kasaya et al. 2002; Kimata et al. 2004). We have repeatedly (annually or less frequently) conducted absolute gravity measurements at the Mitake Central Community Center Branch (MCCCB) near the pressure source detected by Kimata et al. (2004). (Fig.1) The observed absolute gravity fluctuation of a few tens of μGal (1μGal = 10^{-8} m s^{-2}) is too large compared with observed crustal movement. The MCCCB has problems related to the stability of electric power supply, room temperature, and resistance to wind. Therefore, we had to move the gravity observation base to the Ontake Golf & Resort (OGR) hotel, which has a good track record of gPhone gravimeter observations. (The facility's name was previously the Ontake Kougen Hotel (OKH), as described in Tanaka et al. (2013)).

Generally, the gravity disturbance caused by inland water or rainfall reaches several tens of μGal

(Kazama and Okubo 2009; Kazama et al. 2014). The spring discharge around the MCCCB is relatively large (Asai et al. 2006) and is susceptible to rainfall. We sought to precipitation data to suppress the rainfall-origin gravity disturbance by empirical approach.

After the phreatic explosion in September 2014, we started conducting relative field gravity observations by using Scintrex land gravimeters (CG3-M and CG5) addition to collecting absolute gravity measurement, specifically hybrid observation (Furuya et al. 2003). However, relative field-gravity data did not produce meaningful results: some gravimeters were unstable due to mechanical abnormalities and weather conditions. The CG3-M relative gravimeter (#9711406) owned by TRIES was judged to be a poor fit for field observations (particularly due to air-temperature changes). However, it has been used to conduct continuous observations at the OGR since July 2015, and it produces data with a high temporal resolution and also provides rainfall gravity-response data. The relative field-gravity observations will be continued by using CG5 gravimeters owned by other institutions, to achieve precise observations in the future.

Based on the above-mentioned history, the present gravity observation base, OGR, is not a perfect place to detect volcanic activity beneath the mountaintop. We should evaluate what magnitudes of events can and cannot be detected at the MCCCB and OGR. As one approach, it may be useful to simulate gravity change at the ground surface by reference to past volcanic events.

This report presents the following points: (1) Absolute gravity values were affected by rainfall. Gravity changes caused by the dyke intrusion event in 2007 were roughly estimated. (2) The relative continuous gravity observations had a sensitivity of several μGal. (3) The ideal location of a gravity observation base was identified on the basis of gravity-change simulations.

Methods and Results

Absolute gravity measurements

We have conducted absolute gravity measurements by using an FG5 Absolute Gravimeter manufactured by Micro-g LaCoste Inc. at the MCCCB almost every summer since 2004. As mentioned above, the absolute gravity measurements at the MCCCB have concluded. The reference point for gravity measurements in the MCCCB is a mark on the concrete floor in the storage room. We adopted −3.006 μGal/cm as the vertical gravity gradient based on the actual measured value in 2004. The absolute gravity values in Table 1 were obtained by 10-sec interval drop × (50 or 100) sets with (30 or 60) min set intervals. With the exception of a few projects, we found that high gravity values had a tendency to correlate with high rainfall around the site. As a result of trial and error, the cumulative precipitation of the Ontakesan AMeDAS (Automated Meteorological Data Acquisition System) station (9 km away from the MCCCB) by JMA (Japan Meteorological Agency) from 24 hours before the gravity measurement to the end of the measurement strongly correlated with gravity variations (Table 1 and Figure 2). The dyke-intrusion event in 2007 occurred between the 2006 project and the 2007 project. Therefore, we assumed that this event caused a gravity increase of several μGal, which was the difference between the 2005 project and the 2014/2015 projects, in which no rainfall effect occurred. (However, the 2014 data were less credible due to the unstable anti-vibration spring, SuperSpring.) The vertical crustal movement across the periods was negligible regarding gravity (less than 1 cm, according to Murase et al. (2015)).

Table 1. Summary of absolute gravity values and cumulative precipitation at the Ontakesan AMeDAS. The meaning of "cumulative" is described in the main text.

Date(Year/Month/Day) Year = Project name	Cumulative precipitation [mm]	Gravity [μGal]	Remarks	Set Scatter [μGal]	Num. of Sets	Total Drops	Observation period(JST)
2004/7/27	6.0	979577380.53		0.96	58	5504	7/26 21h ~ 7/29 9h
2005/7/21	0.0	979577370.60		1.60	88	8578	7/19 16h ~ 7/23 8h
2006/7/26	150.0	979577391.08		1.52	91	8770	7/24 15h ~ 7/28 10h
2007/7/23	46.0	979577388.35		1.33	187	18507	7/19 18h ~ 7/27 10h
2008/7/30	5.0	979577375.74		1.64	184	17228	7/28 16h ~ 8/1 12h
2009/7/20	316.0	979577393.65		1.90	186	18239	7/16 17h ~ 7/24 10h
2010/7/24	16.5	979577396.48	Laser unstable	3.48	270	12503	7/21 16h ~ 7/28 13h

2011/7/30	74.0	979577377.32	Precipitation data unreliable and effect of Mega quake?	1.66	143	12338	7/28 17h ~ 8/3 15h
2014/11/20	0.0	979577375.09	SuperSpring unstable	3.69	72	3498	11/19 18h ~ 11/21 6h
2015/5/11	0.0	979577374.43	Strong wind	2.03	33	1461	5/11 16h ~ 5/12 9h

Continuous relative gravity measurement

At the OGR, since July 2015, we have conducted relative continuous gravity observations using CG3-M. This site has a proven track record of gPhone gravimeter (Tanaka et al. 2013). We have also conducted atmospheric pressure observations using a Paroscientific Model 765. Five-minute intervals were adopted for both gravity (the average of 1 sec × 120 samples) and pressure. We were able to monitor and fetch these data from one PC connected by USB cables to both the gravimeter and the barometer through cell-phone reception. The time stamp of gravity data was added by OS (Windows 7), time calibrated with NTP (Network Time Protocol). But, the time stamp of the barometers was manually corrected once a month through the internet.

Thus, the obtained data were resampled on the minutes with spline interpolation (realized by “sample1d” in GMT (Wessel et al. 2013)) and then decimated to the hours after correcting the step and gap with Tsoft (Van Camp and Vauterin 2005) (Fig. 3) Therefore, the influence of clock error within several minutes is negligible. However, the CG3-M gravimeter generally has a large drift rate accompanied with non-linearity (e. g. Nawa et al. 2008) Fig. 3(1) The tilt and internal temperature variations may also have contributed to the non-linear component (Fig. 3 (3-5)). Here, for simplicity, the drift was assumed to decrease with the polynomial filtering of the quadratic function for a 20-day window (shifting a half window) in Tsoft (Fig. 3 (7, 8)). Then, after applying Baytap08 (Tamura and Agnew 2008) with a maximum lag of zero for the auxiliary data (i.e., atmospheric pressure), we obtained reasonable results, as shown in Fig. 4. The response coefficient of atmospheric pressure and the principal component of diurnal/semi-diurnal tides were determined to be approximately −0.38 μGal/hPa and 1.16−1.22, respectively.

The OtakiOmata AMeDAS (Fig.1) is special precipitation observation point founded in response to the phreatic explosion, and stops operating at the end of October 2015. We did not use the Ontakesan AMeDAS because of missing data for this analysis period. Gravity increases of several μGal in Trend component seemed to have occurred during heavy rainfall over 10-mm hourly precipitation (Fig. 4). (Note the opposite vertical axis of Fig. 2b in Tanaka et al. 2013.) However, the rainfall response might have been overestimated when the atmospheric pressure reached a minimum around early October because the simple response method (lagp=0 of Baytap08) is insufficient to evaluate to an accuracy of 1 μGal or less. Taking all of this into account, we believe that this relative continuous gravity observation has a sensitivity of several μGal. If we use a gPhone gravimeter, the sensitivity should achieve approximately 1 μGal (Tanaka et al. 2013).

Gravity change simulation from simple mass change models

As mentioned above, our gravity observation base was moved from the MCCCB to the OGR. However, at these sites, we were left with doubts about the capability of detecting gravity changes relating to volcanic activity. Here, we simulated gravity changes on the ground around the mountain body based on the recent mass-change models of the dyke intrusion in 2007 and the phreatic explosion in 2014. We used Tesseroids (Uieda 2011) to compute the gravity change caused by the rectangular body of different densities with its surroundings. We referred to the shape of the dyke models of the 2007 event introduced by Ishikawa's deep/shallow models cited by Nakamichi et al. (2008). As for the phreatic explosion in 2014, we referred to JMA (2015), although it is a tentatively identified model. The contribution of crustal deformation from both vertical displacement (i.e., free-air or the Bouguer gradient) and dislocation theory (Okubo et al. 1991) were assumed to be sufficiently small. After trial and error, the deep dyke density contrast resulted in approximately +100 kg/m3 (larger than its surroundings), thus explaining the gravity increase of several-μGal in the absolute gravity measurements (Fig. 5). However, our two gravity observation bases were unable to detect gravity changes caused by shallow dykes, even if the density contrast reached +500 kg/m^3 (Fig. 6 is in case of +100 kg/m^3). Finally, the volume change of the pressure source was assumed to abruptly break out a cubic cave of 160×160×160 m^3 due to the volume change of +4×10^5 m^3 (JMA 2015). With the assumption of a −500 kg/m^3 density contrast for its surroundings and the same location as the 2007 event (this also might be cited by Nakamichi et al. 2008), only the area near the mountain top is suitable for gravity observation (Fig. 7).

Discussion and Conclusions

Because rainfall dominates the absolute gravity values, at this time, we can use only a few projects of perfect dry periods. Therefore, it is assumed that the 2007 volcano caused gravity increases of several μGal even though it is somewhat assertive. The relative continuous gravity observation may monitor gravity variations with an accuracy of several μGal, although the sensor drift may introduce unreliability. Therefore, it might be realistic to maintain both a relative continuous gravity observation that has high time resolution and absolute gravity measurements implemented during the dry period for detecting volcanic-origin gravity changes, given the limited observation devices and manpower available. Our present gravity observation base, OGR, might be effective to monitor gravity changes comparable to or larger than that of the 2007 event. However, it will be difficult to detect gravity changes caused by small events such as the shallow dyke of the 2007 event and the volume increase in the 2014 event. We should seek to establish an observation base much closer to the summit of the Ontake Volcano in the future while continuing the present observations in the well-appointed OGR.

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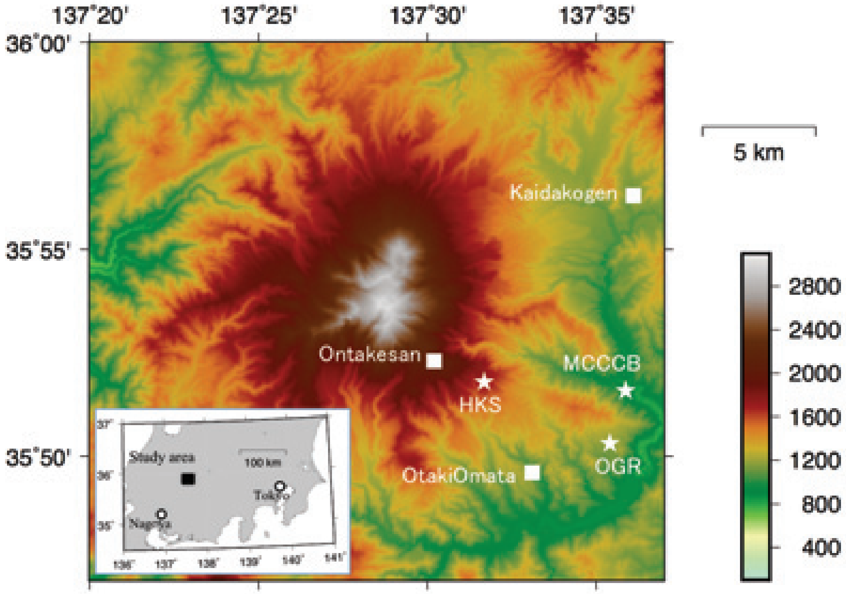

Figure 1. Location of Ontake volcano area and topography around the volcano. Open stars indicate two gravity observation bases, MCCCB (Mitake Community Center Central Branch), OGR (Ontake Golf & Resort hotel) and HKS (HaKkaiSan). HKS is the 3rd gravity base since December, 2015, so the main text did not mention about the site. Open squares indicate the Automated Meteorological Data Acquisition System (AMeDAS) stations of Japan Meteorological Agency.

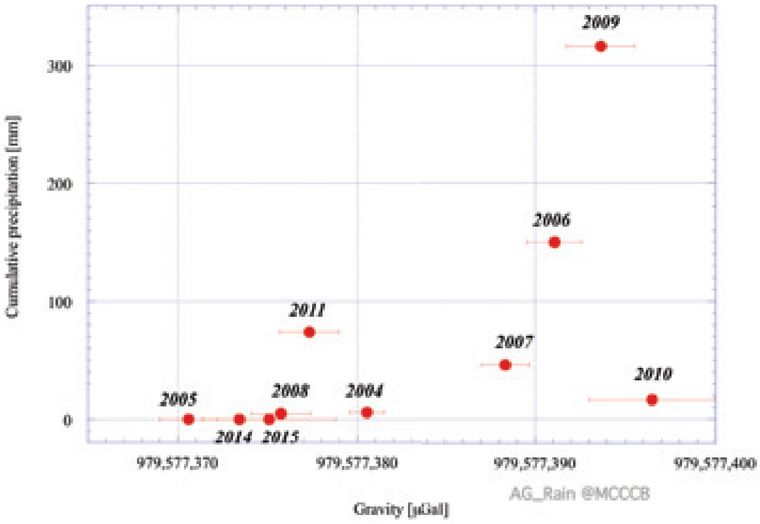

Figure 2. Relationship between absolute gravity values and cumulative precipitation of Ontakesan AMeDAS station. The cumulative precipitation means total precipitation between from 24 hours before the gravity measurement to the end of the measurement. Horizontal error bar shows Set Scatter which reflects the quality of a measurement project. See also Table 1.

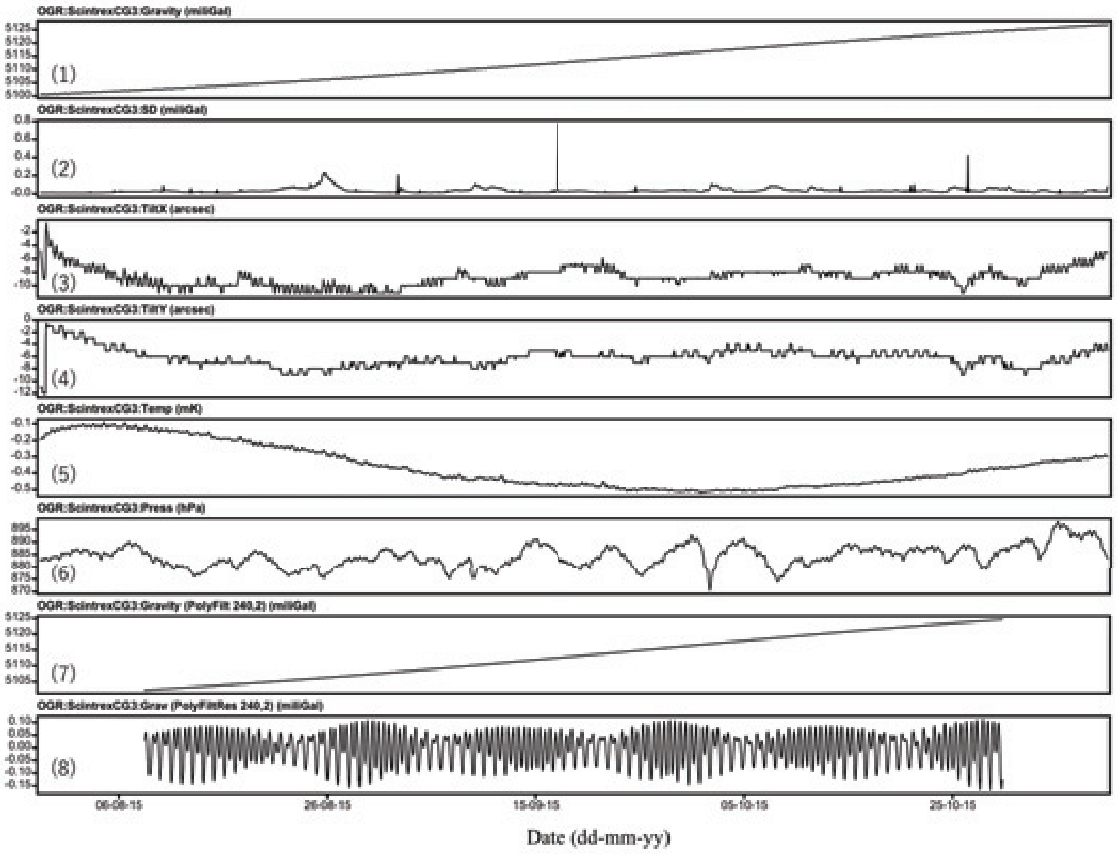

Figure 3. Observed 1-hour interval continuous gravity and pressure data at OGR. Original 5-minutes sampling data are corrected (gap and step) and then decimated: Scintrex CG3-M outputs (1-5), Paroscientific Model 765 barometer output (6). (7) is the regression curve of polynomial filtering (quadratic in half a window of 10 days) for (1). (8) is the regression residual of the filtering ((1) minus (7)).

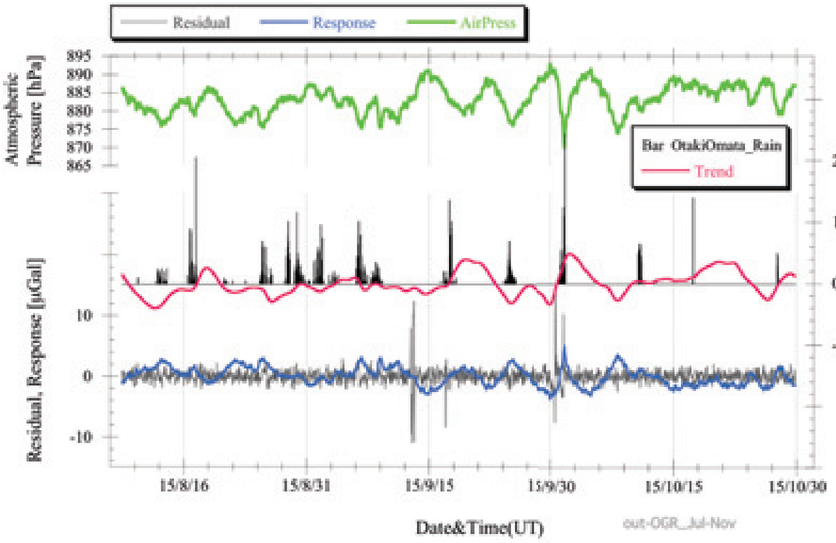

Figure 4. Output of the Bayesian tidal analysis program (Tamura and Agnew 2008). The input is regression residual

(Figure 3(8)) and the auxiliary data as atmospheric pressure (Figure 3(6)). Black vertical bar shows hourly precipitation at OtakiOmata AMeDAS station.

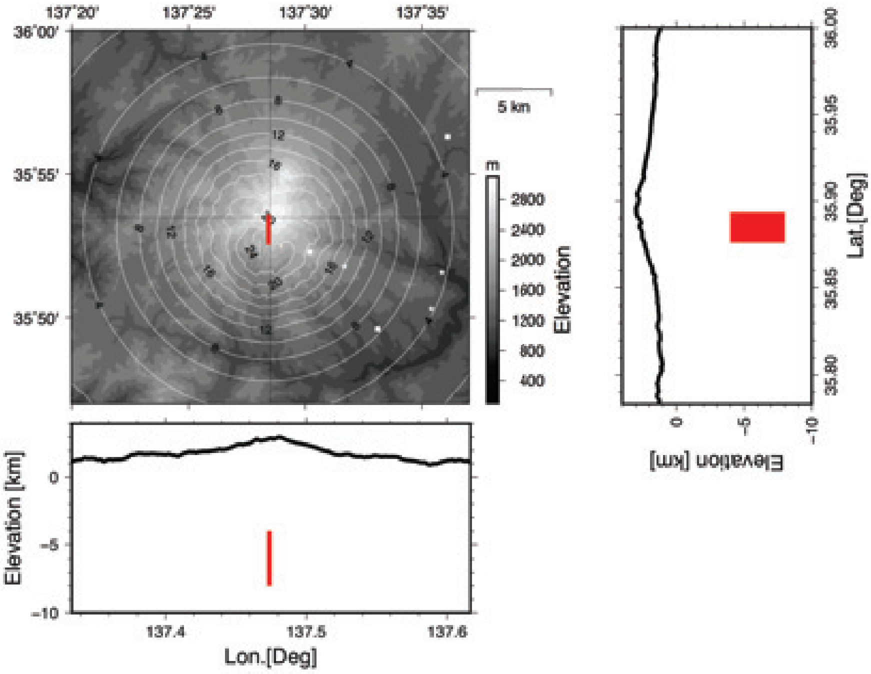

Figure 5. Simulated gravity change at the ground surface due to a deep large dyke model. The shape / location is based on Ishikawa's deep dyke model of the 2007 dyke intrusion event cited in Nakamichi et al. (2009). The density contrast +100 kg/m^3 is derived to explain several-μGal absolute gravity change at the MCCCB by trial and error. Open stars and squares are same in Figure 1. The contour interval is 2 μGal.

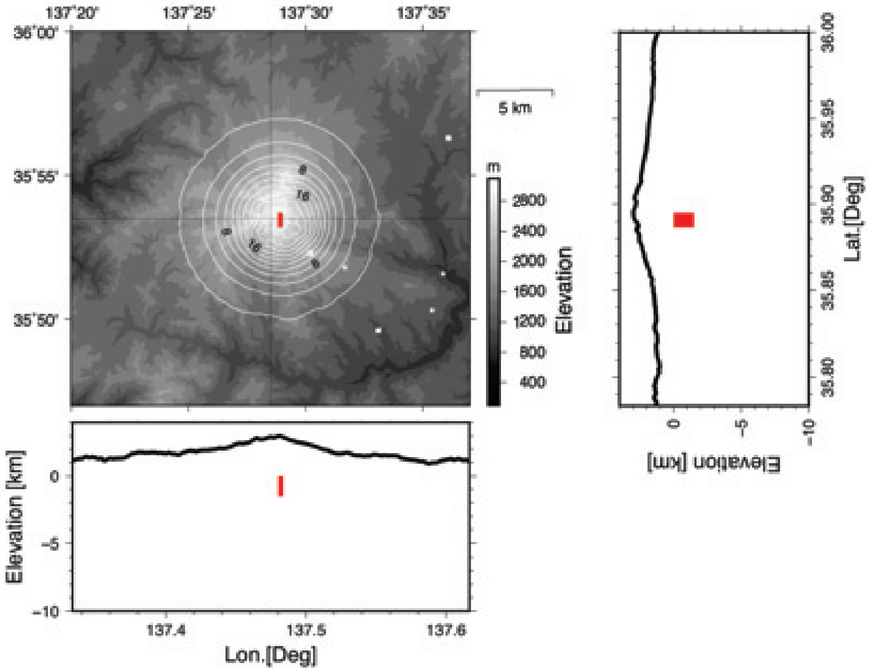

Figure 6. Simulated gravity change at the ground surface due to a shallow small dyke model. The shape / location is based on Ishikawa's shallow dyke model of the 2007 dyke intrusion event cited in Nakamichi et al. (2009). The density contrast adopts +100 kg/m^3 to match the deep one in Figure 5. Open stars and squares are same in Figure 1. The contour interval is 2 μGal.

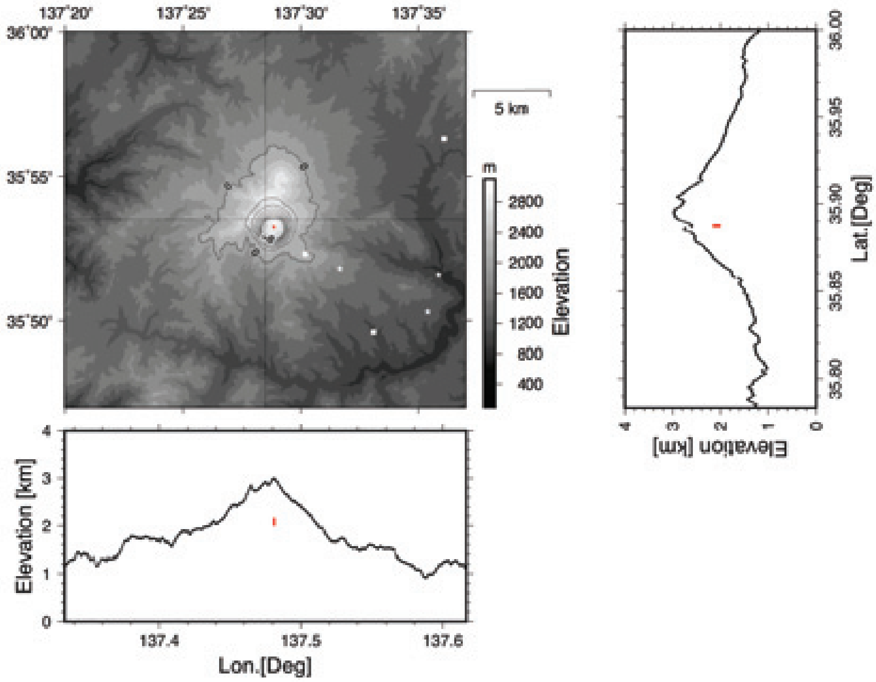

Figure 7. Gravity change at the ground surface due to a very shallow and low density body. The depth and volume is based on inflation source model of the 2014 phreatic explosion event (JMA 2015). The density contrast is presumed to be −500 kg/m^3. Open stars and squares are same in Figure 1. The contour interval is 1 μGal. Note that the contours lower than −8 μGal are not shown for avoiding to overlap contour lines. The minimal value near the mountaintop is −19 μGal.