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Estimation of the Bulk Density of the Omuro Scoria Cone (Eastern Izu, Japan) from Gravity Survey

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Abstract

A gravity survey is performed at 25 stations on and around the Omuro scoria cone (Izu Peninsula, Japan) using a LaCoste & Romberg gravimeter and precise GNSS positioning. The bulk density of the cone is determined to be $1.39 \pm 0.07\,\mathrm{g\,cm^{-3}}$ from an analysis that takes the terrain effect on gravity and regional gravity trend into account. This value agrees well with preliminary results of muography (cosmic-ray muon radiography) observations performed at the same target, 1.41–$1.52\,\mathrm{g\,cm^{-3}}$. The present paper focuses on the gravity survey and data analysis.

Keywords: gravity, bulk density, Omuro scoria cone, Izu, muography

1. Introduction

Mt. Omuro (34° 54′ 11″N, 139° 05′ 40″E, 580 m asl.) is the largest scoria cone in the Eastern-Izu monogenetic volcano group (Aramaki and Hamuro, 1977), Izu Peninsula, Japan. The cone is 300 m in height from its base and the diameter of the base is 1 km. It has a small crater (300 m in diameter, 50 m depth) at the summit. The birth of this cone is considered to be approximately 4 Ka (Saito et al., 2003). This eruption extruded a large lava flow (~10^8 m^3 in total) from the southern and northeastern feet of the cone and formed the extensive Izu-Kogen plateau southeast of the cone (Koyano et al., 1996). Although lava flows are identified from geological evidence, the pathway of the lava inside the scoria cone is not constrained: why does the lava flow emerge from the foot of the cone, not from the crater on the summit? Is there any remnant of the solidified lava in the cone? These questions can be addressed by studying the internal density distribution of the cone because a huge density contrast between scoria and lava blocks would be expected (e.g. Yamamoto, 2003). Miyamoto et al. (2018) initiated a research project to determine the 3D density profile inside the Omuro scoria cone with multi-directional muography observations. Muography (cosmic-ray muon radiography) is an imaging technique that determines the density of targets using cosmic-ray muons as natural radiation sources (see e.g. a pioneering work by Tanaka et al., 2007 and a comprehensive review by Bonechi et al., 2020). They installed eight cosmic-ray detectors that surround the Omuro scoria cone at equal distances apart and aim to take a "CT-scan" of the volcano (Nagahara and Miyamoto, 2018).

The present paper focuses on the gravity survey we performed on and around the Omuro scoria cone. The purposes of the gravity survey are to estimate the bulk density of the cone solely from gravity data and to compare the value with that obtained from muography data. Besides, we aim to prepare a dataset for jointly analyzing gravity and muography data (joint inversion). Because both gravity and muography methods are sensitive to the density profile of the target volume, a joint analysis of both is expected to improve the resolution of three-dimensional imaging. This idea has already been proposed and demonstrated in several volcanic regions (e.g. Nishiyama et al., 2014, 2017; Rosas-Carbajal et al., 2017; Cosburn et al., 2019).

2. Gravity Survey and Dataset

The gravity survey was performed during the period 10–12 March 2020. A LaCoste & Romberg gravimeter (serial no. G875) was employed for the survey (Figure 1). On each day of the survey period, measurements were commenced and concluded at the local base station. The daily closure error was within 30 μgal ($1\,\mathrm{gal} = 10^{-2}\,\mathrm{m s^{-2}}$). The drift of the gravimeter (approximately 20 μgal per day), the variation of instrumental heights, and the effect of solid Earth tide were corrected. The absolute gravity value of the local base (979719.083 mgal) was determined by relative measurement from the FG5 absolute gravimeter (serial no. 109) in the

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basement laboratory of ERI (979788.302 mgal). The scale factor of the gravimeter had been examined on the calibration line at Izu-Oshima Island (979719–979830 mgal) in 2018. Table 1 and Figure 2 show gravity data taken at 25 stations. The measurement points were precisely located using GNSS relative positioning. Satellite data were collected with 1 Hz sampling for more than 15 minutes at each gravity station. Post-processing of the collected data was performed by RTKLIB 2.4.2 p11 (Takasu and Yamada, 2009). The base station set was GEONET 93062 station, about 4 km southeast of the Omuro scoria cone. GSIGEO2011 (Miyahara et al., 2014) was employed for the geoid model. The accuracy of vertical positioning was confirmed to be ~10 cm from a comparison with the triangulation station at the summit.

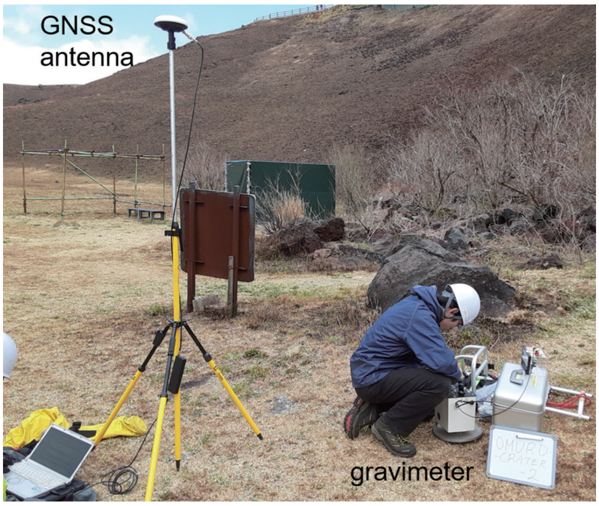

Fig. 1. Gravity survey being performed inside the crater of the Omuro scoria cone (site: OMR-CRATER-2). Basaltic-andesite lava blocks lie behind the operator.

The accuracy of elevation maps is crucial for calculating the terrain effect on gravity. We employed the 5 m mesh digital elevation model published by the Geospatial Information Authority of Japan (DEM5 A). The coordinates of the 25 gravity stations are compared with DEM5 A (Figure 3). The accuracy of the elevation model is estimated to be approximately 1.1 m (standard deviation).

3. Method

Methods for estimating the topographic density have been proposed by many researchers (e.g. Netletton, 1939; Rikitake et al., 1965; Parasnis, 1979). In the present paper, we consider the regional trend of the gravity field

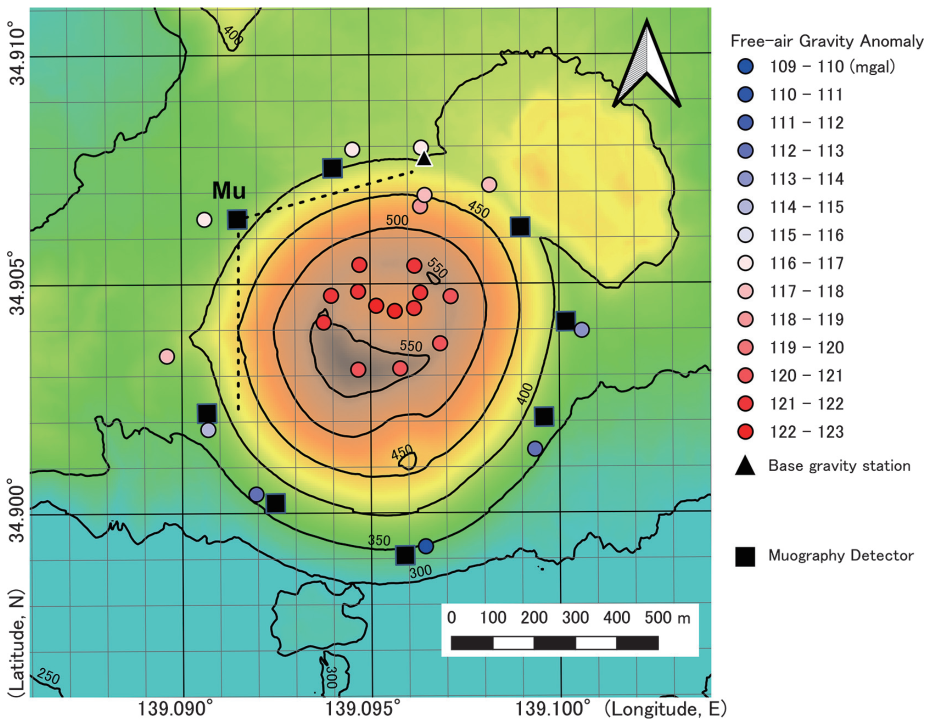

Fig. 2. Locations of gravity stations (circles) on and around the Omuro scoria cone with their colors indicating values of free-air gravity anomaly. Black squares indicate positions of muography detectors. Background color contour map and lines represent the topography of the cone (unit: meter).

Table 1. Gravity data collected at 25 stations on and around the Omuro scoria cone.

Site Name	Latitude ϕ_i (degree)	Longitude λ_i (degree)	Altitude h_i (m)	Gravity Value $g_{obs,i}$ (mgal)	Normal Gravity $\gamma(\phi_i)$ (mgal)	Free-air Anomaly (mgal)	Terrain Effect T_i (mgal g^{-1} cm^3)
OMR-N	34.9079340	139.0945475	391.80	979721.293	979725.932	116.272	15.694
OMR-NW	34.9064207	139.0906181	361.46	979730.433	979725.803	116.177	14.521
OMR-W	34.9034390	139.0896054	376.27	979726.539	979725.548	117.107	15.018
OMR-SW	34.9004149	139.0919570	363.47	979725.770	979725.291	112.645	13.818
OMR-SSW	34.9018308	139.0906918	365.11	979727.182	979725.413	114.443	14.143
OMR-NE	34.9071502	139.0981702	407.92	979717.065	979725.865	117.085	16.207
OMR-NNE	34.9079687	139.0963680	393.50	979720.895	979725.935	116.393	15.711
OMR-SUMMIT-NE	34.9053923	139.0961747	546.81	979678.106	979725.716	121.135	19.702
OMR-SUMMIT-E	34.9047219	139.0971304	544.44	979678.041	979725.657	120.398	19.607
OMR-SUMMIT-SE	34.9036950	139.0968449	544.12	979678.242	979725.572	120.585	19.604
OMR-SUMMIT-S	34.9031513	139.0957855	562.15	979672.421	979725.525	120.376	19.741
OMR-SUMMIT-SW	34.9031289	139.0946727	580.01	979667.369	979725.523	120.838	19.863
OMR-SUMMIT-W	34.9041624	139.0937634	556.00	979675.980	979725.611	121.951	19.734
OMR-SUMMIT-NW	34.9047456	139.0939628	545.90	979678.585	979725.661	121.388	19.689
OMR-SUMMIT-N	34.9054168	139.0947181	535.54	979681.659	979725.717	121.210	19.557
OMR-S	34.8992656	139.0964388	346.46	979728.251	979725.194	109.975	13.148
OMR-SE	34.9013813	139.0993456	364.73	979724.859	979725.374	112.039	13.952
OMR-E	34.9039711	139.1006007	368.37	979725.684	979725.595	113.768	14.565
OMR-CRATER-1	34.9048048	139.0963254	523.74	979685.430	979725.666	121.392	19.377
OMR-CRATER-2	34.9044670	139.0961607	504.44	979691.379	979725.636	121.413	19.034
OMR-CRATER-3	34.9044059	139.0956496	507.26	979691.335	979725.632	122.243	19.211
OMR-CRATER-4	34.9045225	139.0951577	511.98	979689.989	979725.642	122.342	19.302
OMR-CRATER-5	34.9048349	139.0946794	525.83	979685.103	979725.668	121.705	19.625
OMR-SLOPE-1	34.9066890	139.0963359	464.24	979700.982	979725.824	118.422	17.681
OMR-SLOPE-2	34.9069341	139.0964554	446.39	979705.857	979725.845	117.769	17.191
(Local base station)	34.90775	139.09645	–	979719.083	–	–	–

when fitting the gravity data, following Papp (2009), and Toushimalani and Rahmati (2014). The method is outlined in the following paragraphs.

A gravity value $g_{obs,i}$ measured at latitude ϕ_i, longitude λ_i, and altitude h_i should be decomposed into the following four contributions:

$$g_{obs,i}(\phi_i, \lambda_i, h_i) = \gamma(\phi_i) - \beta h_i + T_i \rho + (AX_i + BY_i + C). \tag{1}$$

The first term γ is the normal gravity at the observation point (latitude correction). The second term is the elevation correction, where $\beta = 0.3086\,\mathrm{mgal\,m^{-1}}$ is the vertical gradient of the normal gravity field. The third

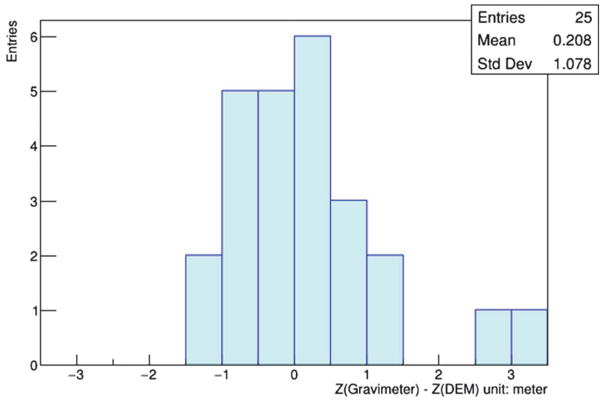

Fig. 3. Comparison between altitude of gravity station determined from the GNSS survey and altitude taken from the digital elevation model (DEM5 A by Geospatial Information Authority of Japan).

term is the gravitational attraction by the mass of topography. T_i is the gravitational attraction for unit density (see next paragraph for calculation method) and ρ is the density of the topography to be determined from least-squares fitting. The last term in parentheses represents the linear trend of the gravity field. X_i (easting) and Y_i (northing) are the horizontal position of the gravity station relative to the summit (34° 54′ 11″N, 139° 05′ 40″ E). A, B, and C are to be determined together with the bulk density ρ from gravity data.

For the calculation of the gravitational attraction by the topography (T_i), we employed the 5 m mesh digital elevation model published by the Geospatial Information Authority of Japan (DEM5 A), in which the topography is represented by rectangular prisms with 0.2″× 0.2″ sides. The vertical component of the gravitational attraction of each prism is calculated (Plouff, 1976) and the sum of these components gives T_i. The summation is performed for a rectangular computational area with 3 km×3 km. The outside of the area is approximated by prisms extending to infinity with their heights set identical to the edge of the computational area.

4. Results

The best parameters determined from least-square fitting are:

$$\begin{aligned} A &= -2.67 \pm 0.65 \ (\mathrm{mgal\,km^{-1}}) \\ B &= +2.31 \pm 0.66 \ (\mathrm{mgal\,km^{-1}}) \\ C &= 94.03 \pm 1.12 \ (\mathrm{mgal}) \\ \rho &= 1.39 \pm 0.07 \ (\mathrm{g\,cm^{-3}}). \end{aligned} \tag{2}$$

The determined values of A and B indicate that the regional trend of the gravity field is in the northwest direction with a gradient of 3.5 mgal km^{-1}. This trend is consistent with the regional characteristics of the Bouguer anomaly map (see the Bouguer anomaly map for terrain density 1.8 g cm^{-3} in GALILEO database https://gbank.gsj.jp/gravdb/; Miyakawa et al., 2015). The residual gravity anomaly (data minus fitted model) is shown in Figure 4. The RMS of the residual is 0.74 mgal. The terrain density around the Omuro scoria cone is determined to be 1.39±0.07 g cm^{-3}.

5. Discussion

Figure 5 shows the two-dimensional density map obtained from a muography survey performed at the northwest foot of the cone ("Mu" label in Figure 2). The colored rectangles in the map indicate the average density of the mountain along the lines of sight of the detector. Combining all the bins of the eight detectors, the bulk density of the cone is determined to be 1.41 to 1.52 g cm^{-3} (Miyamoto et al., in prep). It is confirmed that gravity (1.39±0.07 g cm^{-3}) and muographic results (1.41–1.52 g cm^{-3}) agree well with each other within their estimated errors. The determined density value is significantly lower than a typical crust density (2.67 g cm^{-3}). It is rather consistent with the literature values of bulk density of scoria (0.84–1.01 g cm^{-3} from Taha and Mohamed, 2013; 0.56–1.20 g cm^{-3} from Bush, 2001). Yokoyama (1957) claims that parasitic cones are composed of coarse material with low bulk density from their gravity survey on the two scoria cones on Izu-Oshima Island (0.79 g cm^{-3} for Mt. Atago; 0.35 g cm^{-3} for Mt. Takenohira).

The residual gravity map (Figure 4) presents a ~2 mgal positive gravity anomaly in the middle of the crater. This may be due to high-density lava blocks solidified inside the cone. One can observe basaltic-andesite lava blocks near the eastern rim of the crater (see Figure 1). The three-dimensional shape of such high-density lava inside the cone can be resolved by multi-directional muography (Miyamoto et al., 2018). The dense gravity dataset (~100 m intervals near the summit) in the present work can be used to locate the size and the magnitude of density anomalies by joint inversion. In the previous case of the joint inversion performed at a lava dome (Mt. Showa-Shinzan, Usu; Nishiyama et al., 2017), the gravity data were collected in a similar spacing and the resultant spatial resolutions of the imaging were 100 m (vertical) and 200 m (horizontal).

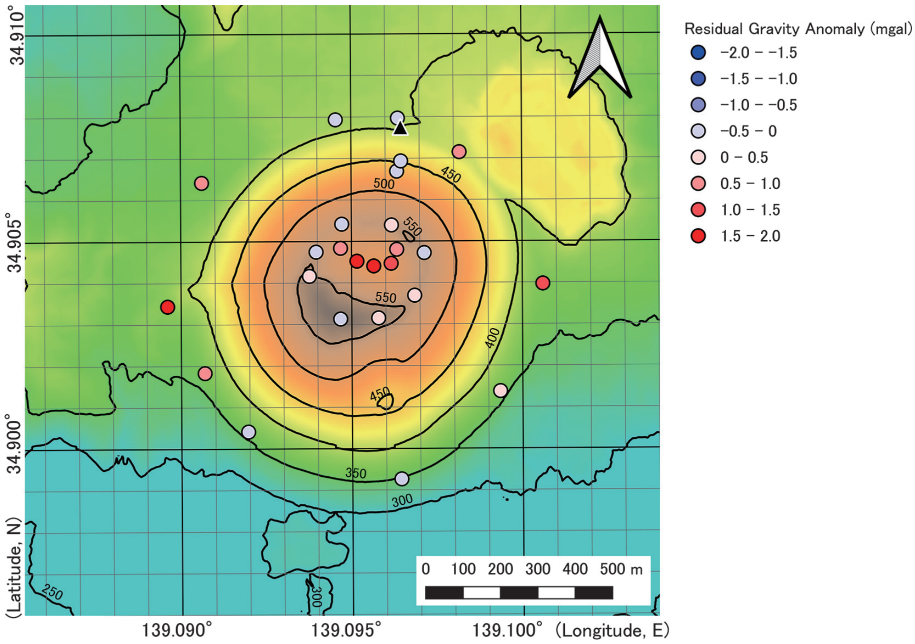

Fig. 4. Residual gravity map after removing the topographic effect (terrain density: 1.39 g cm^{-3}) and the regional trend. The background color contour map and lines represent the topography of the cone (unit: meter).

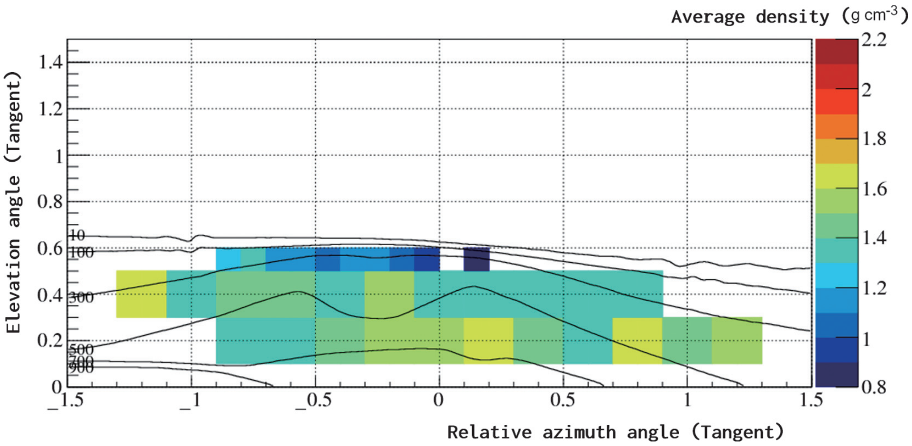

Fig. 5. Two-dimensional density map from muography observations at the northwest foot of the Omuro scoria cone ("Mu" in Figure 2). Color in each rectangular bin represents average density along lines of sight of the detector. Black solid contour lines represent the thickness of the mountain along lines of sight of the detector (unit: meter).

6. Conclusion

A gravity survey was performed on and around the Omuro scoria cone, East-Izu, Japan. The bulk density of the scoria cone, estimated from the gravity data (1.39± 0.07 g cm^{-3}), agrees well with the preliminary results of muography observations performed at the same target. The present work validates the results both of gravity and muography observations.

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重力測定による伊豆・大室山スコリア丘の平均密度の推定

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要　旨

伊豆・大室山スコリア丘を対象に，25 測点での重力観測を実行した．地形による引力の効果や，重力場の広域的な傾向を加味した解析を施した結果，スコリア丘のバルク密度は，$1.39 \pm 0.07\,\mathrm{g\,cm^{-3}}$ と決定された．この結果は，同地域で独立に測定されているミュオグラフィ観測の暫定結果（$1.41\text{–}1.52\,\mathrm{g\,cm^{-3}}$）と推定誤差の範囲内で一致した．本論文では，重力データの取得，解析について詳述する．

キーワード： 重力，密度，大室山スコリア丘，伊豆，ミュオグラフィ