Title page:

Title: Tilt and strain change during the explosion at Minami-dake, Sakurajima, on November 13, 2017

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Abstract

We herein proposed an alternative model for deformation caused by each eruption at Sakurajima, which have been previously interpreted as being due to a Mogi-type source beneath Minami-dake. On November 13, 2017, a large explosion with a plume height of 4,200 m occurred at Minami-dake. During the three minutes following the onset of the explosion (November 13, 2017, 22:07–22:10 (Japan standard time (UTC+9); the same hereinafter), phase 1, a large strain change was detected at the Arimura observation tunnel (AVOT) located approximately 2.1 km southeast from the Minami-dake crater. After the peak of the explosion (November 13, 2017, 22:10–24:00), phase 2, a large deflation was detected at every monitoring stations due to the continuous Strombolian eruption. Subsidence toward Minami-dake was detected at five out of six stations whereas subsidence toward the north of Sakurajima was detected at the newly installed Komen observation tunnel (KMT), located approximately 4.0 km northeast from the Minami-dake crater. The large strain change at AVOT during phase 1 can be explained by a very shallow deflation source beneath Minami-dake at 0.1 km below sea level (bsl). For phase 2, a deeper source beneath Minami-dake at a depth of 3.3 km bsl deflated in addition to the shallow source beneath Minami-dake, which turned inflationary after the deflation obtained during phase 1. However, this model cannot explain the tilt change of KMT. Adding a spherical deflation source beneath Kita-dake at a depth of 3.2 km bsl can be explain the tilt and strain change at KMT and the other stations. The Kita-dake source was also found in a previous study of long-term ground deformation events. Not only the deeper Minami-dake source M_D but also the Kita-dake source deflated due to the Minami-dake explosion.

Keywords

Sakurajima volcano, Spherical source, Dike, Tilt, Strain

1. Introduction

The tilt and strain changes accompanying vulcanian eruptions of Sakurajima have been interpreted as being due to the deflation of a Mogi-type source beneath Minami-dake, because downward tilts associated with eruptions are oriented towards Minami-dake in the underground tunnels Harutayama (2.7 km northwest of the Minami-dake crater) and Arimura (2.1 km south-southeast of the crater). A deflation source was found beneath Minami-dake at a depth of 2–4 km below sea level (bsl), with a deflation volume of 10^3–10^5 m^3 (e.g., Ishihara, 1990; Iguchi et al., 2013). In August 2016, new tilt and strain observations were undertaken at a new observation tunnel at Komen, 4.0 km northeast of Minami-dake, and changes were detected, associated with a large explosion with a plume height of 4,200 m at Minami-dake on November 13, 2017. Ground inflation started at 8:00 (Japan standard time (UTC+9); the same hereinafter) on November 7, 2017, which became a gradual deflation on November 11, 2017. When an explosion occurred at 22:07 of November 13, 2017, the gradual deflation became rapid and continued for two hours, which is longer than the frequent eruptions at Minami-dake. The downward tilt direction at the Komen tunnel deviated by 90° clockwise from the direction of the Minami-dake crater, in a different manner than at the Arimura and Harutayama tunnels, which showed a downward tilt in the direction of the crater. This indicates that the Mogi-type source beneath Minami-dake does not affect the tilt at the Komen tunnel.

In the present study, we propose a composite source model for tilt and strain changes at ground deformation stations, taking into account the tilt change at the Komen tunnel.

We then discuss on magma plumbing system of Sakurajima for a large-scale vulcanian eruption.

2. Observations and data

At Sakurajima, tilt and strain observations have been performed by the Sakurajima Volcano Research Center (SVRC) of Kyoto University; the Osumi Office of River and National Development Bureau, Ministry of Land, Infrastructure, Transport and Tourism of Japan (MLIT); and the Japan Meteorological Agency (JMA). The tilt and strain stations for the present study are distributed as shown in Fig. 1. We used data obtained by water-tube tiltmeters and linear strainmeters at the Arimura, Harutayama and Komen underground tunnels (AVOT, HVOT and KMT, respectively) and borehole tiltmeters at Yokoyama, Amida-gawa and Komen (JMA-A, JMA-F and KOM, respectively). The tiltmeters and strainmeters at AVOT, HVOT, KMT and KOM were installed in directions radial and tangential to Minami-dake and the tiltmeters at JMA-A and F were in the north-south and east-west directions. The sensitivities were 0.056 V/μrad for the water-tube tiltmeters and 0.056 V/μstrain for the linear strainmeters. The sensitivity of the borehole tiltmeters was 0.02 V/μrad. The analog-to-digital resolution was 24 bits and the resolution of tilt and strain was 10^{-6} nrad.

3. Characteristics of tilt and strain change

The tilt and strain changes at AVOT, HVOT and KMT during the period of November 5–14, 2017, are shown in Fig. 2(a). Upward tilts of the crater side of Minami-dake and extension strains started to appear at about 6:00 of November 7 at AVOT and HVOT, whereas a tangential tilt was dominant at KMT. The tilts turned to gradual downward tilts on November 11, 2017. Then, the downward tilt suddenly became rapid at the onset of the explosion on November 13. A deflation tilt change of 283 nrad occurred over two hours at HVOT, which is larger than the tilt changes associated with explosions at Minami-dake crater in the previous reports (Ishihara, 1990; Tateo and Iguchi, 2009).

The tilt and strain changes associated with the explosion are magnified in Fig. 2(b). In phase 1 (three minutes from the onset of the explosion at 22:07), rapid extensions were detected in the radial strains as strain steps. The step at AVOT, the nearest station to the Minami-dake crater, is the largest at 120 nstrain, and the steps are smaller at the farther tunnels HVOT and KMT. In phase 2 (22:10–24:00), a large deflation with a contraction strain and downward tilts oriented towards the Minami-dake crater are observed, except at KMT. The downward tilt vectors are shown in Fig. 3a. The vector at KMT is oriented toward the north flank of Sakurajima.

4. Analysis

4.1. Deformation source model

We applied a finite spherical source (McTigue, 1987), a dislocation source (Okada, 1992) and a combination of these in a half-infinite homogenous elastic solid. We assumed a Poisson's coefficient of $\nu = 0.25$. Battaglia et al. (2013) obtained the volume change of a spherical source ΔV by an internal pressure change of ΔP, for a modulus of rigidity μ and depth and radius of the source d and a, respectively, to be

$$\Delta V = \pi a^3 \frac{\Delta P}{\mu}\left[1 + \left(\frac{a}{d}\right)^4\right]. \quad (1)$$

Topographical effects can be corrected by adding the elevation of the station to the source depth (Williams and Wadge, 1998).

To expand the original elastic source models described below to a multiple-source model, we assumed that the sources do not interact with each other and that the calculated tilt and strain are linear sums of the tilt and strains caused by the sources (Hotta et al., 2016a).

4.2. Residual evaluation

We searched for the optimal parameters for each source using a grid search method. For models with more than seven parameters, we used a genetic algorithm instead of a grid search method. In this case, we set the number of individuals to be 50; the probabilities of crossovers, jump mutations and creep mutation to be 70, 2 and 18%, respectively; and the number of iterations for the genetic algorithm to be 200,000. To avoid a local minimum, we executed the iteration process several times (Hotta et al., 2016a; 2016b). To minimize the difference between the observed and theoretical values, we used the weighted residual sum of square (WRSS):

$$\mathrm{WRSS} = \Delta^2 + \mathrm{E}^2, \tag{2}$$

where

$$\Delta^2 = \sum_{1\le i\le 6}\left[\left(\frac{\delta R^i_{obs}-\delta R^i_{cal}}{\sigma\delta R^i}\right)^2+\left(\frac{\delta T^i_{obs}-\delta T^i_{cal}}{\sigma\delta T^i}\right)^2\right], \tag{3}$$

$$\mathrm{E}^2 = \sum_{1\le j\le 3}\left[\left(\frac{\varepsilon R^j_{obs}-\varepsilon R^j_{cal}}{\sigma\varepsilon R^j}\right)^2+\left(\frac{\varepsilon T^j_{obs}-\varepsilon T^j_{cal}}{\sigma\varepsilon T^j}\right)^2+\left(\frac{\varepsilon O^j_{obs}-\varepsilon O^j_{cal}}{\sigma\varepsilon O^j}\right)^2\right], \tag{4}$$

and where the subscripts obs and cal indicate observed and calculated values; δR^i and δT^i indicate the radial and tangential tilt change at the i-th tilt station, respectively; εR^j, εT^j and εO^j indicate the radial, tangential and oblique strain changes at the j-th observation tunnel, respectively; and σ indicates the observation error. The search spaces and step sizes for the parameter estimates are given in Table 1.

5. Results

5.1. Phase 1

We applied a single spherical source model to the deformation of phase 1. We obtained a very shallow deflation source beneath Minami-dake (source M_S) at 0.1 km bsl (Fig. 3(a), Table 1). Its radius was the minimum value of the search range, 0.1 km. The large strain change detected at AVOT, small tilt change including AVOT and strain change at the other station can be explained by this source (Fig. 3(a) and (b)).

5.2. Phase 2

5.2.1. Deformation sources beneath Minami-dake

During phase 2, subsidence in a direction toward the mountain top was detected except at the KMT observation tunnel where a subsidence in the direction toward the north flank was detected. Excluding the data of for KMT, we applied dual spherical sources: a shallow source (source M_S) fixed at the location obtained for phase 1 and a deep source, M_D. M_D is a deeper (3.3 km bsl beneath Minami-dake) deflation source, whereas M_S causes inflation as shown in Fig. 3(c) and Table 1. We note, however, that these sources beneath Minami-dake cannot explain the oblique strain change at HVOT. These sources also cannot explain the tilt and strain changes at the KMT observation tunnel, where subsidence toward the north area of Sakurajima was detected (Fig. 2).

5.2.2. Improvement by the addition of sources for KMT data

We tested a composite source model by adding two types of sources; a spherical and a dislocation type model, to the dual sources model to improve the fitness of the calculation to the observed data, including KMT.

5.2.2.1. Triple spherical source model

Hotta et al (2016a) found a Mogi-type deformation source beneath Kita-dake in addition to that beneath Minami-dake for the long-term deformation event of October 2011–March 2012. We applied a triple spherical deformation source model adding a spherical source to M_S and M_D, fixed at the locations obtained above. The new source is a deflation source beneath the northeast flank of Kita-dake (Fig. 3(e); Table 1). The fitness of the calculation to the observed oblique strain change at HVOT and tilt and strain changes at KMT are improved by this addition (Fig. 3(e) and (f)).

5.2.2.2. Composite model of a tensile fault and dual spherical source

Hotta et al. (2016b) applied a tensile fault mode to the deformation of Sakurajima. Here, we add a tensile fault to M_S and M_D. In addition to the inflation of M_S and deflation of M_D, a sill with a length and width of 4.7 and 0.4 km, respectively, and striking in the north-south direction is located beneath the Aira caldera at a depth of 0.7 km bsl (Fig. 3(g), Table 1). The fitness of the calculation to the observed oblique strain change at HVOT and tilt and strain changes at KMT are improved by this addition (Fig. 3(g) and (h)).

6. Discussion and conclusions

To select an improved model, for each model we evaluated the correction of Akaike's Information Criterion (c-AIC) values (Sugiura, 1978), which is a finite correction of Akaike's Information Criterion (AIC; Akaike, 1973). The WRSS values of the three spherical sources and the dual spherical sources with tensile fault models are 13,408 and

9,140.0, respectively, and the number of free parameters is seven and ten, respectively. These yield c-AIC values of 222.19 and 233.53, respectively. Although the residual is larger than the dual spherical sources with a tensile fault model, the three spherical sources model is better, based on the obtained c-AIC values.

During the three minutes from the onset of the explosion at 22:07, phase 1, a very shallow deflation source was obtained beneath Minami-dake, similar to previous eruptions at the Minami-dake (Ishihara, 1990) and Showa craters (Iguchi et al., 2013). This means that the deflation starts from a shallow part of the magma plumbing system of Sakurajima.

After the peak of the vulcanian eruption, phase 2, the deeper source beneath Minami-dake deflated while the shallower source inflated. The deep deflation source beneath Minami-dake had been identified based on tilt and strain changes during previous eruptions at the Minami-dake and Showa craters (e.g., Ishihara, 1990; Iguchi et al., 2013). In addition to the deeper source, inflation of the shallower source was detected. The shallow inflation source beneath Minami-dake found in the present study was not found in the previous studies. During the Minami-dake eruption including this event, the shallower source is considered to deflate for the first phase of each eruption. In this event, the shallower source inflated after the peak of the explosion probably because the amount of accumulation from the deeper source exceeds that of the emission from the Minami-dake crater due to continuous Strombolian eruptions (Fig. 4).

In addition to the two Minami-dake sources, we found a deflating spherical source at a depth of 3.2 km bsl at the northeastern flank of Kita-dake. The Kita-dake source might correspond to the source K found beneath Kita-dake at a depth of 3.3 km bsl from a combination analysis of GPS, tilt and strain data during the period from October 2011 to

March 2012 (Hotta et al., 2016a). The Kita-dake source was also found based on vertical displacement during the period from November 2008 to November 2009, obtained from a precise leveling survey (Yamamoto et al., 2013). Not only the deeper Minami-dake source M_D but also the Kita-dake source deflated due to the Minami-dake explosion (Fig. 4).

A clear reflector at a depth of 6.2 km bsl beneath Kita-dake, identified as an overcritical PP reflection, was found by seismic experiments during the period from December 2009 to December 2014 (Tsutsui et al., 2016). The reflection became clear after December 2014, and the reflector was interpreted as a sill. The source K obtained in the present study is shallower than the reflector, but the horizontal location is similar. The 99% confidence interval of the depth of source K is 2.6–5.8 km bsl, as shown in Table 1, and the depths of source K and the reflector may overlap considering the uncertainty in the depth of the reflector. If source K and the reflector are the same, the difference in the optimal depth may be due to the source shape, such as a penny shaped source (Fialco et al., 2001). This should be considered in future studies.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

List of abbreviations

bsl: below sea level; SVRC: Sakurajima Volcano Research Center; MLIT: Ministry of Land, Infrastructure, Transport and Tourism of Japan; JMA: Japan Meteorological Agency; c-AIC: correction of Akaike's Information Criterion; AIC: Akaike's Information Criterion; GPS: Global Positioning System

Availability of data and materials

The datasets supporting the conclusions of this article are included within the article.

Competing interests

The authors declare that they have no competing interests.

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Author's contributions

KH contributed to the study conception and design; acquisition, analysis and interpretation of the data; and drafted the manuscript. MI contributed to the study conception and design; acquisition and analysis of data; and helped to draft the manuscript with critical revisions.

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