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Review:

Volcanic Activity of Sakurajima Monitored Using Global Navigation Satellite System

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A dense Global Navigation Satellite System (GNSS) network has been deployed at Sakurajima volcano since 1995 and extends to the surrounding area of the Aira caldera. The ground deformation obtained by GNSS observation corresponds to transient eruptive activity of Sakurajima volcano, which has produced frequent vulcanian eruptions since 1955. Inflation of the volcano was detected prior to the increase in vulcanian eruptions in 1999, and resumption of the eruptions at the Showa crater. Magma intrusion events and an increase in eruptions in late 2009, late 2011, and early 2015 suggest the existence of an open-conduit system from the Aira caldera to the vents at the summit area of the Minamidake cone, through the sub reservoir beneath the older Kitadake cone. Ground deformation induced by sudden dike intrusion is different from that of previous intrusions, as revealed by the dense GNSS network. GNSS data are useful in evaluating and forecasting volcanic activity, and are available to grasp the advection and diffusion of volcanic ash.

Keywords: GNSS, ground deformation, eruption, Sakurajima volcano

1. Introduction

Observation of volcanoes has been dramatically improved by Global Navigation Satellite System (GNSS) monitoring of ground deformation, especially because of its continuity, wide coverage, stability, and real-time detection. Sakurajima volcano, which is located on the southern rim of the Aira caldera, is one of the most active volcanoes in the world. Ground deformation of the volcano has been measured by precise leveling, which has been repeated since 1890 in south Kyushu [1]. Leveling surveys were also initiated on Sakurajima volcano in the 1960s and have revealed pressure sources inducing ground deformation beneath the Aira caldera and Sakurajima volcano [2, 3]. As precise leveling has been conducted at time intervals of one to several years, ground deformation between the surveys was not detected. For detection of the horizontal displacement of Sakurajima volcano and Aira caldera, electronic distance measurement (EDM) was applied to detect horizontal deformation. EDM was conducted along short baselines on the flanks of volcanoes; however, it was difficult to the obtain slope distance along long baselines and the slope distance between points on the opposite sides beyond the summits of the volcanoes. Continuous measurements of tilt and strain in underground tunnels or in boreholes provide highly sensitive ground deformation data, which sometimes contain long-term trends. Further, because of their high sensitivity, they are affected by noise (e.g., from underground water). The GNSS can resolve some problems in ground deformation of volcanoes above-mentioned. At Sakurajima volcano, seven GNSS stations were first installed in 1995 to monitor the activity of the volcano. Observation results using the GNSS have resulted in a more comprehensive understanding of volcanic activity and an improvement in the forecasting of volcanic eruptions. Here, changes in volcanic activity and forecasting of eruptions at Sakurajima volcano will be described based on GNSS observations over the past 23 years.

2. Dense GNSS Network of Sakurajima

Figure 1(a) shows the locations of GNSS stations on Sakurajima volcano. GNSS observation using seven stations was initiated by Kyoto University on the flanks of the volcano in 1995. Campaign measurements have been repeated since 1996 to compensate for the small number of continuous observation points. GNSS stations have been added over time to enhance monitoring of the volcano. For example, three GEONET stations were added by the Geospatial Information Authority of Japan (GSI) in 1997. At present, a GNSS network of 24 stations is operated by Kyoto and Tohoku universities, a network of four stations by the Japan Meteorological Agency, and there are three GEONET stations. In addition, GNSS stations in south Kyushu are available for monitoring ground deformation of the Aira caldera and 17 additional stations are operating within 30 km of the center of the caldera (**Fig. 1(b)**).

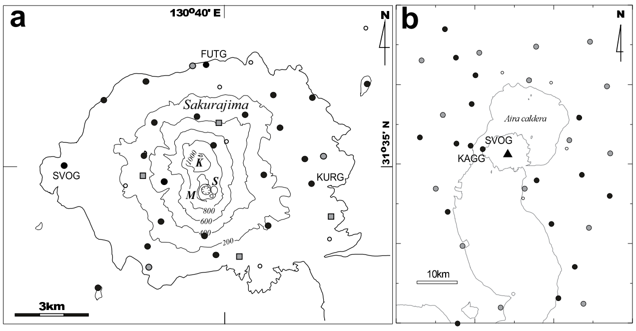

Fig. 1. Location of GNSS stations on Sakurajima volcano (a) and in south Kyushu including the Aira caldera (b). Black and gray circles represent GNSS stations of Kyoto University and GEONET, respectively. Gray squares show stations operated by the JMA. Open circles are campaign bench marks.

3. Understanding Sakurajima's Activity from Long-Term Measurement Using the GNSS

The eruption in 1914 (Taisho eruption) is the largest eruption in Japan during the 20th century, ejecting 0.5 km^3 of pumice and 1.3 km^3 of lava flow [4]. After the 1914 eruption, Sakurajima was dormant; however, eruptive activity restarted in 1935 and was followed by eruption of 0.14 km^3 [4] of lava in 1946 (Showa eruption). Vulcanian-style eruptions started at a crater on the summit of the Minamidake cone in October 1955 and a total of 7903 vulcanian eruptions have occurred through 2017. The vulcanian eruptive activity has remained at a high level with an annual number of more than 200 from 1972 to 1992. After 1993, the eruptive activity gradually declined, except for a peak in 1999, and the annual number decreased to just 10 in 2003. Ground deformation measured using precise leveling corresponded well to the eruptive activity. Larger eruptions were accompanied by greater subsidence of the ground of the Aira caldera. It is inferred that the ground subsided by 0.8 m after the 1914 eruption and 0.1 m after the 1946 eruption [5]. The high-level eruptivity during the 1980s was accompanied by a slight subsidence of 0.03 m [6]. In contrast to the high-eruptive period, the ground was uplifted during dormant or less active eruptive periods.

Although the history of GNSS observation is shorter than that of precise leveling, ground deformation detected using GNSS observation for the 23 years following 1995 also corresponds well to the transitions of the eruptive activity. **Fig. 2** shows a temporal change in horizontal distance along the baseline from west (SVOG) to east (KURG) over the summit. A long-term extensional trend has been mostly caused by inflation of the Aira caldera (Iguchi, 2013) except for a step in 2015. The ground deformation pattern can be divided into seven periods: (1) rapid extension from the beginning of the GNSS observation to 1999, (2) slow extension from 2000 to September 2004, (3) rapid extension from October 2004 to February 2005, (4) slow extension from March 2005 to September 2009, (5) a period with eventual rapid extensions from October 2009 to June 2015, (6) a large extensional step on August 15, 2015, and (7) minor extension after the large step.

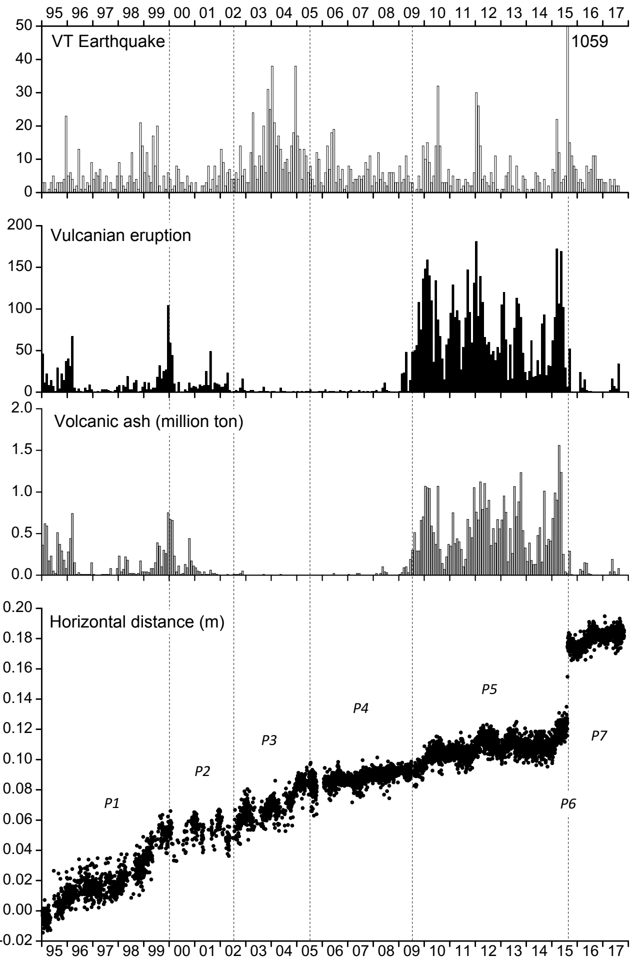

Fig. 2. Transition of volcanic activity during the period from 1995 to 2017: 1) monthly number of VT earthquakes, 2) monthly number of vulcanian eruptions, 3) monthly discharge weight of volcanic ash, and 4) relative horizontal distance change between KURG and SVOG.

It is inferred that the 1st period started in 1993, considering the transition from subsidence to uplift of the ground at both the Aira caldera and northern Sakurajima in 1993 [7]. The 1st period, particularly from November 1997 to October 1999 when the extension rate increases, is considered as the stage of magma intrusion into Sakurajima. The eruptive activity gradually increased from July 1999 and reached a peak in December 1999, when 104 vulcanian eruptions occurred (**Fig. 2**). Eruptive activity declined during the 2nd period. As ground deformation was minimal, magma did not move during this period. On June 4, 2006, the eruptive activity at the Showa crater resumed after a dormancy of 58 years and increased during late 2009. The baseline showed extension during the 3rd period, and extension from October 2004 to February 2005 was the most rapid. The seismicity of volcanotectonic (VT) earthquakes increased during this period. In addition to earthquakes that occurred beneath the summit of Minamidake, several earthquakes occurred

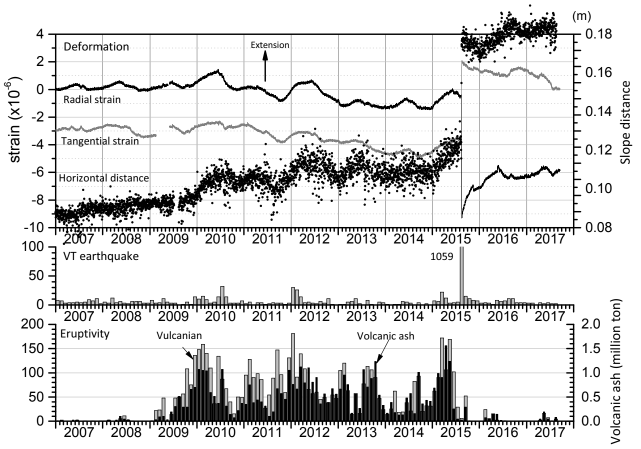

Fig. 3. Transition of volcanic activity during the period of the Showa crater's eruption (2007–2017). First column shows ground defamation. Black and gray lines indicate radial and tangential components of strain beneath Arimura, respectively. Dots are relative horizontal distance change between KURG and SVOG. The second column is monthly number of VT earthquakes, and the third is eruptivity. Black and gray bars indicate monthly number of vulcanian eruptions and discharge weight of volcanic ash, respectively.

southwest of Sakurajima and the Wakamiko caldera [8]. The 3rd period witnessed the resumption of the eruptions at the Showa crater during 2006, and it is inferred that the rapid extension during this period was induced by magma intrusion and followed by an increase in eruptive activity during 2009. During the 4th period, eruptions intermittently occurred at the Showa crater during June 2006 and June 2007 and during the period from February to July 2008; however, the eruptive activity was not very high. Ground deformation showed slow inflation.

Eruptive activity drastically increased during 2009 and remained at a high level. Eruptive activity with frequent vulcanian eruptions corresponded to the 5th period. Peaks of eruptive activity were identified during three periods: from December 2009 to March 2010, November 2011 to March 2012, and February to June 2015, when the monthly number of vulcanian eruptions exceeded 100. The peaks of the eruptions correspond to horizontal extension of ca. 2 cm (**Fig. 3**). This indicates that magma products were effused simultaneously with intrusion of magma. This may be characteristic of the open-conduit system of Sakurajima [9]. The step on August 15, 2015, (6th period) was a highlight of the ground deformation during the period from 1995 to 2017. The horizontal distance suddenly extended by 5 cm (**Fig. 3**). The step accompanied a swarm of VT earthquakes (887 events on the day); however, the step-like deformation was not followed by eruptions, in contrast to the correspondence of inflation to eruption during the 5th period. The rapid inflation was interpreted as dike intrusion of magma [10]. Extension during the 7th period was mostly caused by inflation of the Aira caldera.

4. Magma Plumbing System of Sakurajima Volcano

Spatial distribution of vertical displacements obtained using precise leveling provide a location of a pressure source. The ground surrounding the Aira caldera subsided after the 1914 eruption. The ground subsided widely in south Kyushu and the greatest subsidence of 0.894 m was detected at BM 2474 at the west rim of the caldera [1]. The center of the ground subsidence was not located beneath Sakurajima but rather near the center of the Aira caldera. Mogi [2] applied a model of the pressure source as a small sphere embedded in a homogeneous half space to the spatial distribution of the vertical displacement and obtained a deflation pressure source at a depth of 10 km near the center of the Aira caldera. Analyzing the vertical displacement during the period of lower eruptive activity during 1957 and 1958, Yoshikawa [3] found an inflation source at a depth of 10 km beneath the center of the Aira caldera, where the depression source was located for the 1914 eruption [2]. Similarly, a deflation pressure source occupied the same position during the highly eruptive period starting in 1974 [11]. A dual-pressure source model was proposed by adding a minor source beneath Sakurajima to the major source beneath the Aira caldera. Minor pressure sources were estimated to be at a depth of 3 km during the inflation stage [3], and the depth was determined to be in a range of from 2 to 6 km during the deflation stage after 1974 [11].

The observation period using the GNSS since 1995 is largely part of the inflation stage of the Aira caldera and Sakurajima. Extension of the ground surrounding the Aira caldera was clearly confirmed using GNSS measurement, revealing radially outward displacements from the center of the caldera (**Fig. 4**) [12, 13]. Analyzing the horizontal displacements from 1996 to 2007, a Mogi-type pressure source [2] was estimated to be at a depth of 11 km beneath the center of the Aira caldera and the volume increase was estimated to be 8×10^7 m^3 [12]. This implies that the magma reservoir is beneath the Aira caldera and that the volume of magma has increased since 1993.

More precise alignment of a pressure source in Sakurajima was obtained using the dense GNSS stations (**Fig. 1**). A multiple-pressure-source model was applied to the displacements of the magma intrusion events during 2009, 2011, and 2015. In addition to the inflation source beneath the Aira caldera, an inflation source was obtained at a depth of 3 km beneath the Kitadake cone and a minor deflation source at a shallower depth near the Minamidake cone (**Fig. 5**; [14]). Location of the pressure source beneath Kitadake was confirmed by intersection of the upward direction of the tilt vectors [9]. The magma intrusion events during 2009, 2011, and 2015 accompanied frequent vulcanian eruptions with effusion of a considerable volcanic ash (**Fig. 3**). Magma intruded to a depth of approximately 3 km beneath Kitadake cone and magma discharged from the Showa crater, among the vents within the summit area of Minamidake. The magma plumbing

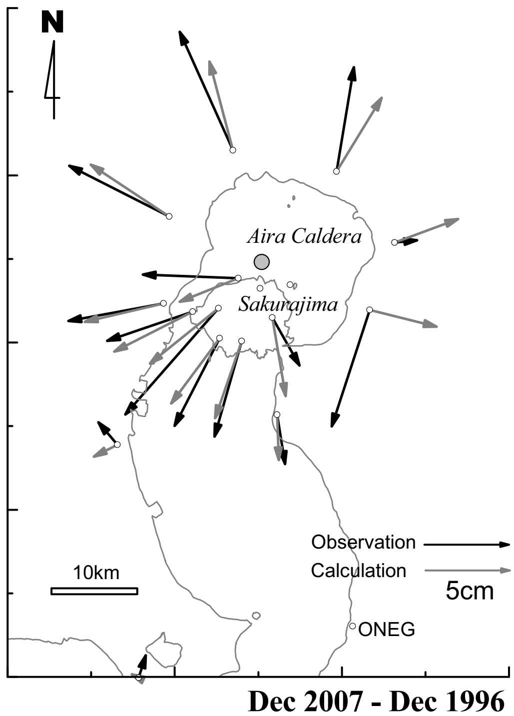

Fig. 4. Horizontal displacement vectors during the period from December 1996 to December 2007 [12]. The solid and gray arrows show the observation and calculated vectors, respectively. The gray circle indicates the location of the Mogi pressure source. Station ONEG is used for reference.

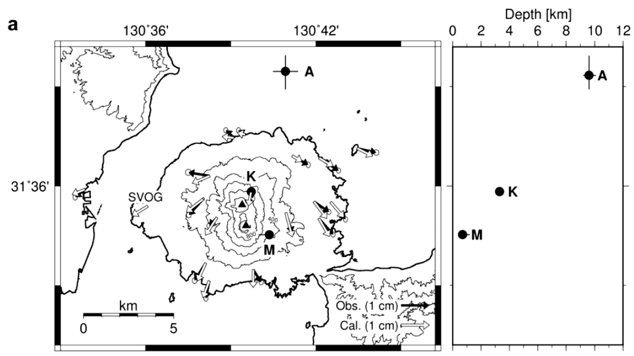

Fig. 5. Location of pressure sources obtained using GNSS data during the period from November 2011 to March 2012 by Hotta et al. (2016) [14]. Solid triangles represent Kitadake (north) and Minamidake (south). Arrows indicate observed (black) and calculated (white) horizontal displacements that are corrected for the effect caused by the calculated displacement of the SVOG station. Error ellipses are 1σ.

system starting from the Aira caldera connects to the vents of the Minamidake area through a reservoir beneath Kitadake cone.

5. Sudden Dike Intrusion in 2015

The extension of August 15, 2015, is the most rapid event during the period from 1995 to 2017. This was accompanied by 887 VT earthquakes and two large low-

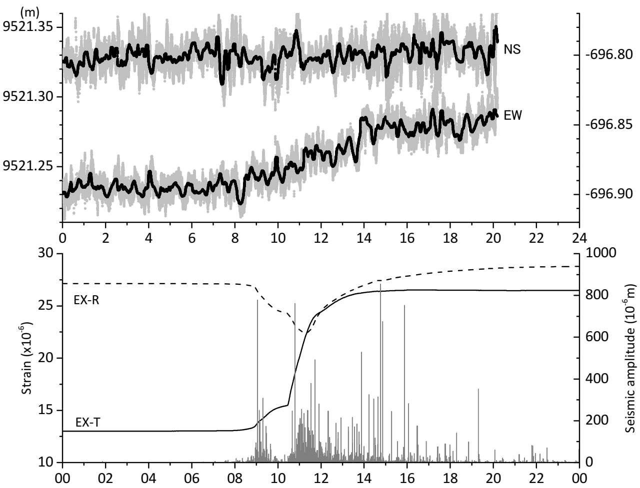

Fig. 6. Ground deformation and seismicity on August 15, 2015. Top: Eastward movement of station KURG calculated using the Epoch-by-Epoch method. Gray dots represent calculation data every 1 s and black dots are median for 10 min of data. Bottom: Strain change at the underground tunnel of Arimura and the maximum velocity amplitude of the seismogram for 1 min. Solid and dashed curves show tangential and radial components of strain changes. Bars represent seismic amplitudes.

frequency (LF) earthquakes. The extensional event was detected using the GNSS as well. The temporal change in the horizontal displacement of station KURG was calculated using Epoch-by-Epoch (1 s) analysis using Real-Time Dynamics software, as shown in **Fig. 6**, comparing the strain changes in the underground tunnels at Arimura and seismicity. The strain changes began at 7 h and were followed by two accelerations at 8:54 and 10:28 am. The strain rate decreased at approximately 12 h and the strain changes nearly stopped at approximately 15 h. The horizontal displacement obtained using GNSS shows eastward movement at KURG (**Fig. 6**). The eastward movement began at 8 h and stopped at 15 h, similar to that of the strain change. However, the temporal patterns are different from one another. The strain change shows an acceleration–deceleration pattern in temporal change. The horizontal displacement obtained using the GNSS progressed at a constant rate.

The spatial distribution of the horizontal displacement of the event is different from the magma intrusion events during the periods from December 2009 to March 2010, November 2011 to March 2012, and January to June 2015. The horizontal displacements are characterized by isotopically radial movement from the center, and can be modeled using Mogi's source [2]. The horizontal displacements on August 15, 2015, were not isotropic. The northwestern flank of Sakurajima volcano showed northwest movements and the southeastern flank moved southeastward (**Fig. 7**). The movements on the northeast and southwest flanks were much smaller than those of the northwest and southeast. The displacements were approximated by extension of tensile crack [15]. A nearly vertical dike with a N-NE–S-SW strike is at a depth of 1.0 km

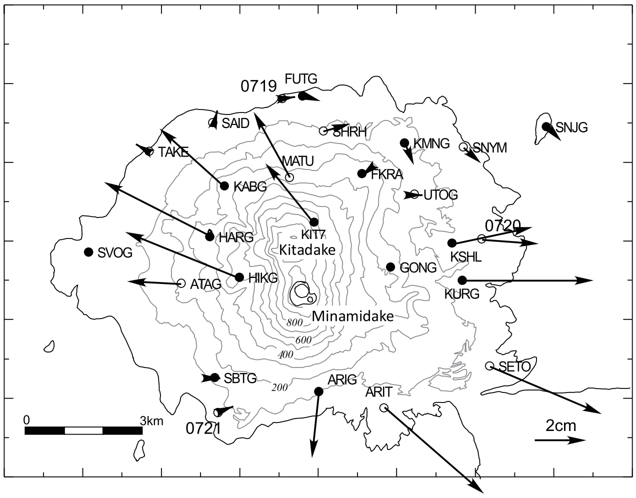

Fig. 7. Displacement vectors obtained using the GNSS during the period from August 14 to 16, 2015. Dots are continuous monitoring stations. Arrows with open circles are displacements from November 2014 at campaign stations. Rectangle shows the location of the dike obtained by Hotta et al. (2016) [10].

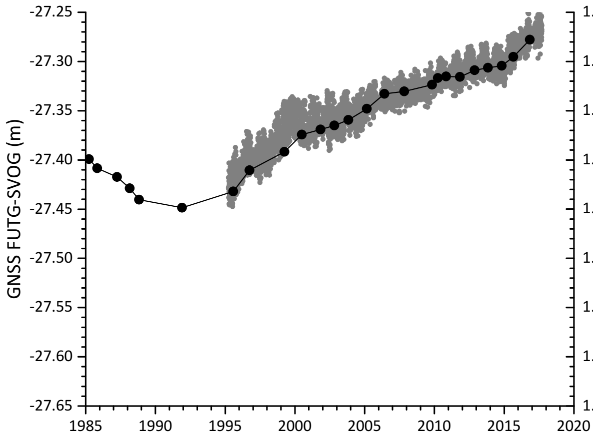

Fig. 8. Comparison of vertical displacement obtained using the GNSS to that using precise leveling. Relative vertical displacement at the GNSS station FUTG is plotted by gray dots referring to station SVOG. Black dots are uplift of benchmark S26 referring to S17.

below sea level beneath the Showa crater. The length and width of the dike is 2.3 and 0.6 km, respectively. The opening of 1.97 m yielded a volume increase of 2.7×10^6 m^3 [10]. The rapid extension events are interpreted by intrusion of dike-shaped magma beneath Sakurajima. The intrusion event was not followed by eruptions and eruptive activity rather declined.

6. Vertical Displacement

Although the precision of GNSS measurement is lower than that of precise leveling survey for vertical displacement, the advantage of GNSS is continuity. For example, rapid uplift on August 15, 2015, could not be measured using repeated precise leveling. The most recent leveling prior to the event was conducted in November 2014 [16] and a leveling survey immediately after the event detected the sum of gradual uplift from January to June 2015 and rapid uplift on August 15. As the largest vertical displacement was detected at the northern part of Sakurajima Island, the volcanic activity had been evaluated using the relative vertical displacement at the northern part (Bench mark S26) referring to the western part (S17). The vertical displacement obtained using the GNSS was compared to that of precise leveling. **Fig. 8** shows the temporary change in relative vertical displacement at station FUTG referring to SVOG. FUTG and SVOG are close to S26 and S17, respectively. The trend in vertical displacement is similar. The displacements during the period from August 1995 to November 2016 are 0.154 m using precise leveling and 0.144 m using the GNSS. The difference is only 0.010 m.

The GNSS is useful to measure at sea. At Sakurajima volcano, the uplift of Sakurajima Island referring to the Kagoshima city side has been monitored using tide gauges [17], because long-distance precise leveling from Sakurajima to Kagoshima along the Aira caldera is not realistic. GNSS observation at SVOG and at KAGG at Kagoshima port has been in operation since 1955. The vertical displacement obtained by two tide-gauge stations has been altered using the GNSS with sufficient precision.

7. Evaluation and Forecasting of Volcanic Activity in the Near Future

A volume increase in a pressure source inducing ground deformation is one of the important indicators to estimate volcanic activity. Hotta et al. [14] estimated volume increases in the three pressure sources of Mogi type (beneath the Aira caldera and the Kitadake and Minamidake cones) using displacement data obtained using the GNSS for the intrusion periods of magma from 1998 to 2012. The injection rate of magma into the source beneath the Aira caldera was estimated to be 0.8 to 1.6×10^7 m^3/year, which is comparable to the mean intrusion rate over the past 100 years (1.4×10^7 m^3/year, [19]). A volume increase in the pressure source beneath the Kitadake cone proceeded increased eruptive activity at the Showa crater. The volume began to increase during the middle of November 2011 and the discharge rate of volcanic ash increased one month later. Magma intruded from the Aira caldera was first stored beneath Kitadake and the volume increase of the pressure source was directly related to the eruptive activity of Sakurajima volcano.

Potential of eruptive activity of Sakurajima volcano has been estimated using vertical displacement measured by precise leveling [5, 18]. The ground surrounding the Aira caldera has been uplifted nearly 70 cm since termination of the 1914 eruption. Recent uplift of the Aira caldera was detected using the GNSS as horizontal displacements

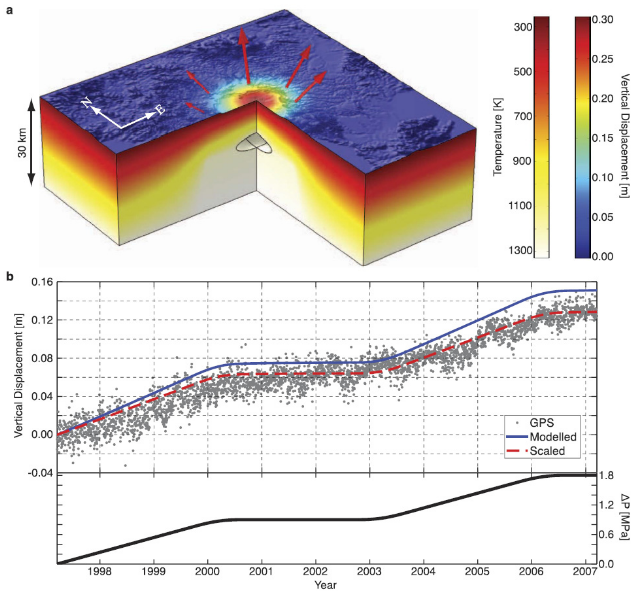

Fig. 9. Thermomechanical modeling and temporal deformation of Hickey et al. (2016) [20] (a) Cross-section of temperature-dependent viscoelastic (TDVE) model setup with best-fit source parameters. The colored surface shows the modeled vertical deformation, while the red arrows show the modeled three-dimensional displacements at five GPS sites. The depth- and source-dependent temperature distribution is also shown. (b) (Top) Vertical GPS time series recorded at the GEONET site and modeled temporal inflation patterns. The blue line shows the model prediction using a simple ramp pressure-time function. Scaling this result to 85% (red line) it is clear that the modeled temporal displacement rate matches the GPS observations. (Bottom) Pressure-time function used in the TDVE models. The ramp is curved slightly to ease the numerical computation within the FE model.

and slope distance changes beyond the caldera. Hickey et al. [20] attempted to refine the model of ground deformation rather than the small spherical pressure source in the semi-infinite homogeneous elastic body for the displacements as shown in **Fig. 3**. A two-dimensional spheroid was used as a pressure source. This made it possible to evaluate the shape and size of the pressure source. Moreover, the ground deformation was calculated by using the finite element method, considering the topography including the ocean bottom and the anisotropy of the crustal medium. The center position of the spheroid was found to be at the western edge of the Wakamiko caldera in the northeastern part of the Aira caldera at a depth of 13 km and the spheroid had a size of 14.4 km horizontally and 4.8 km vertically. Furthermore, modeling was performed considering the viscoelastic effect depending on the temperature in the crust (**Fig. 9**). Considering viscoelasticity, it is possible to express the delay and the creep of the ground and the relaxation effect of strain accumulation. Finally, a magma storage rate of 1.15×10^7 m^3/year was obtained. The inferred magma supply rate indicates an ∼130-year timeframe (time interval from the 1779 An'ei eruption to the Taisho eruption in 1914) to amass sufficient magma to feed a future 1914-sized eruption. However, the estimated storage rate is not that different from that of the previous eruption [19, 7]. Further development of modeling of ground deformation is important for eruption forecasting and risk mitigation.

8. Monitoring Volcanic Ash Using the GNSS

In addition to monitoring of ground deformation of volcanoes, the GNSS is available to detect volcanic ash clouds. Radar and Light Detection and Ranging (LIDAR) are applied to monitor dispersion of volcanic ash. Plumes of vulcanian eruptions at Sakurajima volcano were detected by an X-band multi-parameter (MP) radar [21]. LIDAR, which is utilized for detecting aerosol and meteorological clouds using a pulsing laser, is useful to detect thin volcanic ash particles [22]. Otherwise, the wave length of the GNSS is longer than the X-band radar (∼3 cm) and LIDAR (500–600 nm). The GNSS is suitable for detecting dense volcanic ash ejected during larger eruptions.

A vulcanian eruption on July 24, 2012, at the Minamidake crater is the largest eruption during the Showa crater's eruptivity from 2006. The volcanic plume reached an elevation of 8,000 m above the crater. Temporal and spatial development of the volcanic plume was monitored well using the dense GNSS network, using the post-fit phase residuals (PPRs) of ionosphere-free linear combinations for each satellite based on the precise point positioning (PPP) approach [23]. Shifting of PPR anomalies detected the westward movement of the volcanic plume (**Fig. 10**). From locations of the crossing points of anomalous PPR paths, dense volcanic ash was identified and the maximum height was determined to be approximately 4000 m. The signal-to-noise ratio (SNR) anomalies provided additional information of the characteristics of the plume, whether it be water vapor or volcanic ash.

Volcanic ash ejected during the 1779 [24] and 1914 eruptions [1] of Sakurajima reached the southern part of the Tohoku District, across the Japanese archipelago from the west to the east. Advection and diffusion of volcanic ash during such large eruptions can be monitored using a satellite. The satellite monitors the top of the volcanic cloud; however, the GNSS can monitor denser volcanic ash at lower altitudes. The GNSS array covering all of Japan (GEONET) can monitor advection and diffusion of dense volcanic ash that can have a serious impact on land.

9. Conclusion

Many observation results showing the effectiveness of the GNSS were obtained for monitoring and evaluation of activity of Sakurajima volcano. The GNSS is useful in detecting volcanic ash that can directly cause disasters.

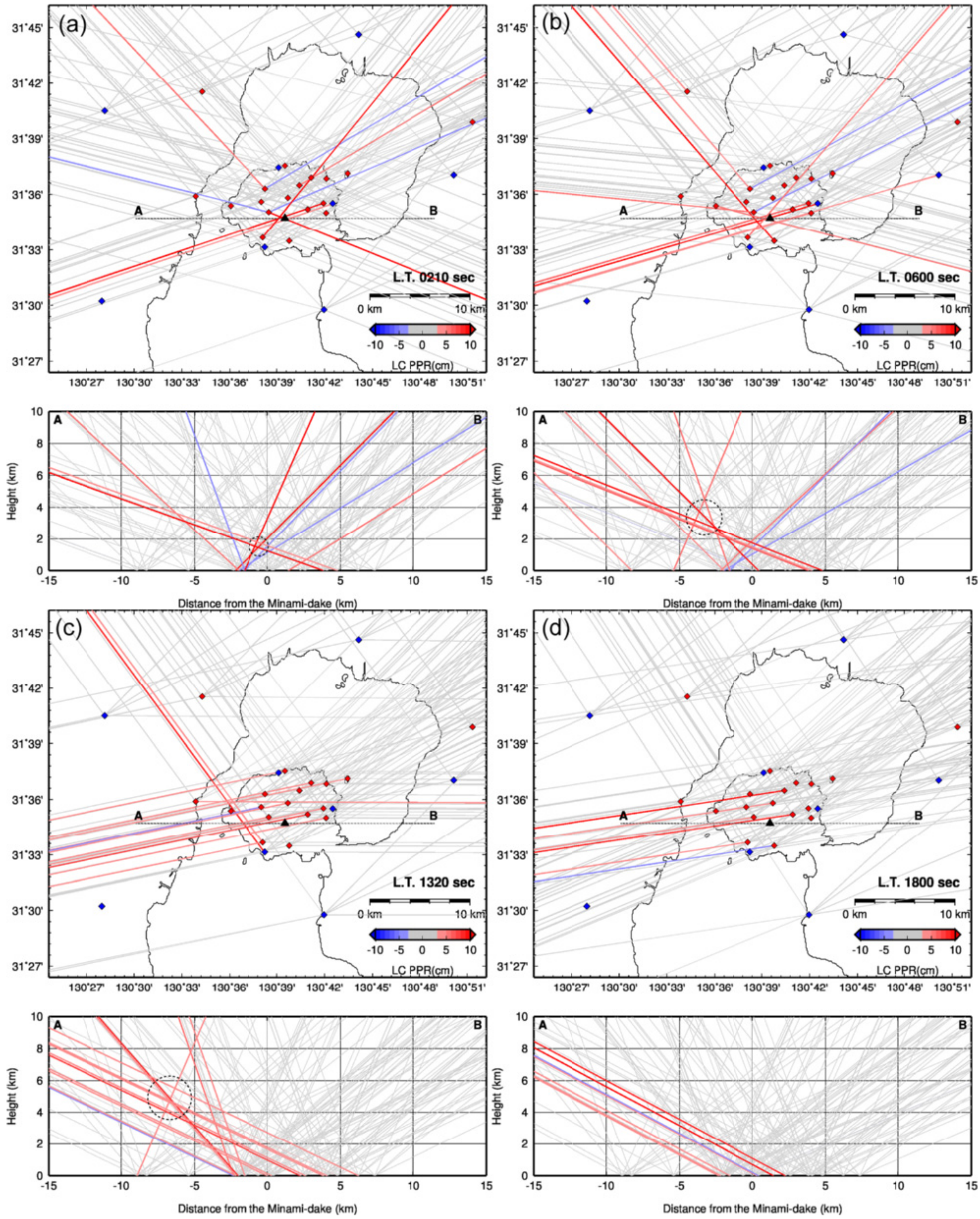

Fig. 10. Spatial and temporal distributions of post-fit phase residual (PPR) anomalies for the eruptive event at Sakurajima volcano on July 24, 2012, obtained by Ohata and Iguchi (2015) [23]. Dashed circles denote the possible maximum crossing point of anomalous PPR paths during each time step and these correspond to the volcanic ash plume blown to the west of Sakurajima.

Acknowledgements

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