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Review:

Integrated Study on Forecasting Volcanic Hazards of Sakurajima Volcano, Japan

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Several types of eruptions have occurred at Sakurajima volcano in the past 100 years. The eruption in 1914 was of a Plinian type followed by an effusion of lava. The progression of seismicity of volcanic earthquakes prior to the eruption is reexamined and seismic energy is estimated to be an order of 10^{14} J. Lava also effused from the Showa crater in 1946. Since 1955, eruptions frequently have occurred at the Minamidake or Showa craters at the summit area. Vulcanian eruptions are a well-known type of summit eruption of Sakurajima, however Strombolian type eruptions and continuous ash emissions have also occurred at the Minamidake crater. The occurrence rate of pyroclastic flows significantly increased during the eruptivity of Showa crater, with the occurrence of lava fountains. Tilt and strain observations are reliable tools to forecast the eruptions, and their combination with the seismicity of volcanic earthquakes is applicable to forecasting the occurrence of pyroclastic flows. An empirical event branch logic based on magma intrusion rate is proposed to forecast the scale and type of eruption. Forecasting the scale of an eruption and real-time estimations of the discharge rate of volcanic ash allows us to assess ash fall deposition around the volcano. Volcanic ash estimation is confirmed by an integrated monitoring system of X Band Multi-Parameter radars, lidar and the Global Navigation Satellite System to detect volcanic ash particles with different wave lengths. Evaluation of the imminence of eruptions and forecasting of their scale are used for the improvement of planning and drilling of volcanic disaster measures.

Keywords: Sakurajima volcano, Vulcanian eruption, Plinian eruption, forecasting volcanic ash, evacuation plan

1. Introduction

Sakurajima is the most active volcano in Japan and has had 17 Plinian eruptions in the past 26,000 years [1]. In the past 550 years, three Plinian eruptions (Volcanic Explosivity Indexes of 4 or 5) occurred in 1471–1476, 1779–1780 and 1914, and these Plinian eruptions were followed by the effusion of lava flows.

It is inferred that the major magma reservoir of Sakurajima volcano is located at a depth of ∼10 km beneath the submarine Aira caldera, north of Sakurajima, from aerial patterns of ground depression in South Kyushu after the last Plinian eruption in 1914 [2]. The ground around the Aira caldera subsided by ca. 80 cm [3], however the ground subsidence has recovered gradually. The elevation of the west rim of the Aira caldera was uplifted 70 cm during the period from 1915 to 2013 [4]. This indicates a large amount of magma comparable to the 1914 eruption is stored in the reservoir beneath the Aira caldera.

Due to heavy and long-term discharge of volcanic ash from the summit crater of Minamidake since 1955, various kinds of impacts have been experienced around the Sakurajima volcano. The impacts by the volcanic ash include reductions in agricultural output [5], infrastructure, particularly traffic [6], and human health [7]. The degree of impact depends on the weight of the ash-fall deposits or the density of airborne ash particles, which are directly related to the intensity of the volcanic eruption. Therefore, it is necessary firstly to understand the behavior of volcanic ash in the atmosphere and on the ground and secondly to forecast volcanic ash transport based on the discharge rate of volcanic ash from the craters.

Considering the disasters caused by past eruptions at Sakurajima volcano, especially the 1914 eruption, and the potential scale of eruption evaluated from the recent accumulation of magma beneath the Aira caldera, emergency planning for volcanic disasters must be designed from various aspects. In crisis management in case of an increase in volcanic activity, evacuation from the volcano is the most important action to be implemented. In addition to evacuation, the emergency plan formulated by Kagoshima City includes long-term evacuation and countermeasures against massive ash-fall [8].

Volcanic activity of Sakurajima has been in a state of minor, however frequent, eruptions of the Minamidake or Showa craters at the summit area since 1955 and simultaneously in a state of accumulation of magma in the major reservoir beneath the Aira caldera, indicating a large-scale eruption will happen in the near future. Observation facilities to monitor volcanic activity have been developed and eruption forecasting experience has been accumulated at

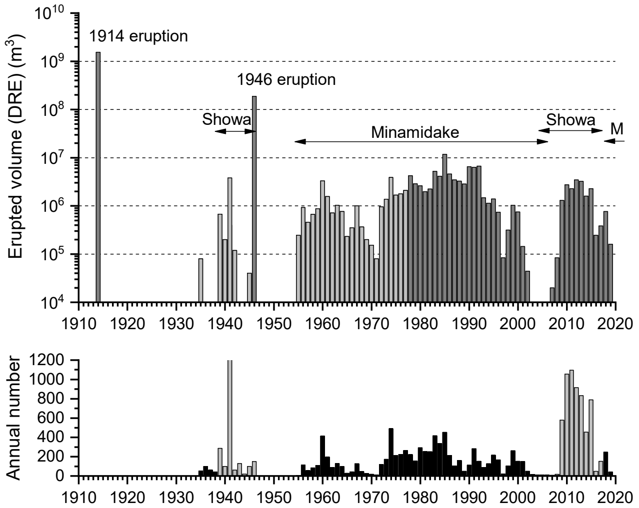

Fig. 1. Eruptive activity of Sakurajima volcano during the period from 1910 to June 2019. Top: Annual erupted volume (DRE). Bottom: Annual numbers of Vulcanian eruptions at Minamidake summit and Showa craters represented by black and grey bars, respectively. The data in 2019 are added to Fig. 1 of Iguchi et al. [9]. "M" indicates eruptive period at Minamidake.

Sakurajima volcano since launching the volcanic eruption prediction plan in 1974. Therefore, Sakurajima is the best case-study to upgrade volcanic disaster countermeasures based on the scientific knowledge obtained from the monitoring of volcanic activity. In this manuscript, volcanic activity of Sakurajima in the past 100 years is firstly summarized to show its transition and variety. Secondly, the observation phenomena prior to recent eruptions are described for forecasting the volcanic eruption. Thirdly, the impact of volcanic ash is forecasted by the detection of volcanic ash particles by remote sensing technology and the simulation of volcanic ash transport based on real-time evaluation of the discharge rates of volcanic ash. Lastly, the impact on emergency planning, particularly evacuation, is described based on forecasting the occurrence of ash-fall deposition during an eruption.

2. An Overview of Volcanic Activity at Sakurajima Since the Beginning of the 20th Century

2.1. The Plinian Eruption and Lava Flow Effusion in 1914

The annual volume of erupted magma (DRE) is shown in **Fig. 1** to outline the eruptive activity at Sakurajima since the major eruption in 1914. The Taisho eruption in 1914 was the largest eruption in Japan since the beginning of the 20th century. The eruption formed craters on the east and west flanks of Minamidake and erupted 0.5 km^3 of volcanic ash and pumice and 1.34 km^3 of lava [10]. The amount of magma ejected from the Taisho eruption is estimated to have reached the order of 10^9 m^3. The eruption started with a pumice ejection at 10:05 on January 12 at the crater on the western flank. The eruption then declined in the afternoon of January 13, but a pyroclastic flow occurred during the night, and then lava began to be effused. The lava flow continued until the following year at craters on the eastern flank [11].

2.2. Seismicity Prior to the 1914 Eruption and the Earthquake

Various kinds of abnormal phenomena were recognized prior to the eruption. Seismicity of volcanic earthquakes, including felt earthquakes were the most significant among these phenomena. A Gray-Milne type seismometer operating in the Kagoshima weather station near Kagoshima city recorded the waveforms of an earthquake that preceded the eruption by one day. Omori [12] documented the observed time and seismic intensity (0 to VI, 0 for insensitive) of the earthquakes from the records. The magnitudes were calculated from the seismic intensities with a formula [13] between them and were converted to seismic energies. The sum of the seismic energy was 1.3×10^{14} J [14]. Most of the seismic energy came from two earthquakes with a seismic intensity of V that occurred at 9:57 and 11:43 on January 11.

The seismicity declined after the eruption commenced, however a destructive earthquake (intensity VI, M = 7.0 [15]), called the "Sakurajima earthquake," occurred suddenly at 18:28 on January 12, 1914, 8 hours after the onset of the eruption [16]. Fortunately, the initial part of the ground motions was recorded, although the recording of ground motions that followed were suspended during the earthquake. An epicenter south-east of the weather station was inferred from the initial motions [16] and was determined to be located in the Kagoshima bay using P-wave arrival times and amplitudes from stations all over the world [14], and this was updated to be located near the coast of Kagoshima city by using S–P times at stations in Japan [17]. Nakamichi [14] obtained the focal mechanism of a normal fault with a strike of N30°E, a dip of 60° and a rake of $-90°$, and the hypocenter was at a depth of 10 km, 5 km off the N154°E direction from the station, which is 5 km off the southwest of Sakurajima. The moment magnitude estimated to be $M_W = 6.5$ was converted to $M_j = 6.9$, which is comparable to the M = 7.0 by [15]. Due to the large magnitude of the earthquake and it possessing a mechanism of dip-slip and strike orthogonal to the epicentral direction, Kagoshima city was badly damaged (28 causalities).

2.3. The Effusive Eruption in 1946

Sakurajima was dormant after the 1914 eruption, but on September 20, 1935, an eruption began at the summit crater of Minamidake, and the eruptive activity continued intermittently for a month [18]. The eruptive activity of Minamidake continued into 1939, but on October 26, the focus of eruptive activity moved to the 700 m elevation of Minamidake (Showa crater). This eruptive activity continued until November 12, accompanied by pyroclastic flows [19]. After that, eruptions continued at this crater, and a new lava flow from the Showa crater was confirmed in March 1946. The effusion of lava continued until May and the volume of the lava flows reached 0.18 km^3 [10]. On the other hand, the bulk volume of volcanic ash deposit was only 1.65×10^6 m^3 [20]. The magma volume erupted by the eruption in 1946 was in the order of 10^8 m^3.

2.4. Summit Eruption Since 1955

After the lava effusions in 1946, although there was a small eruption at Minamidake crater, Sakurajima was dormant. However, on October 13, 1955, a Vulcanian eruption occurred at the Minamidake crater. This was the first instance of the kind of eruptive activity which has continued at the Minamidake or Showa craters until the present. Since then, Vulcanian eruptions have occurred frequently, reaching up to 414 times in the first peak period in 1960. Explosive activity declined after 1961, and no Vulcanian eruptions occurred during the period from May 1971 to February 1972.

Sakurajima became active again in September 1972 [21]. A ballistic bomb reached the coast of Furusato, 3.3 km from the Minamidake crater during a Vulcanian eruption on October 2, 1972. Following this there were a higher occurrence of eruptions than the peak period of 1960. In 1974 and 1985, the annual numbers of Vulcanian eruptions reached 489 and 452, respectively. Magma eruptions from 1972 to 1992 were on the order of 10^6 m^3/year and exceeded 1×10^7 m^3/year in 1985. This eruptive activity, which has occurred continuously at the Minamidake crater since 1955, features frequent Vulcanian and Strombolian eruptions, and continuous ash emissions. Eruptive activity declined after 1993, with only nine eruptions in 2004 and 2005, and the magma volume of the eruptions was in the order of 10^5 m^3/year in the late 1990s and 10^4 m^3/year in the early 2000s.

On June 4, 2006, an eruption occurred at the Showa crater for the first time in 58 years. From 2006 to October 2017, eruptions occurred mostly at the Showa crater. From 2009 to 2015, $\sim$1000 Vulcanian eruptions occurred annually, and the magma volume erupted reached the order of 10^6 m^3/year. However, the size of individual Vulcanian eruptions at the Showa crater were smaller than that of Minamidake [22], with activity at the Showa crater being characterized by the frequent occurrence of small-scale eruptions. This eruptive activity declined in July 2015. There was another Vulcanian eruption at Minamidake crater from October 31, 2017.

3. Transition of Volcanic Activity in the Last 15 Years

Although the eruptive activity of Sakurajima in the 21st century is at a lower level than the peak of eruptivity during the period from 1972 to 1992, it shows a more complicated transition. In the last 15 years of volcanic activity at Sakurajima six main episodes were observed:

(1) A precursory period to the eruptivity of the Showa crater (2003–May 2006);
(2) Phreatomagmatic eruptions at the Showa crater (June 2006 and May 2007);
(3) A peak of eruptivity with frequent Vulcanian eruptions at the Showa crater (February 2008–June 2015);
(4) An unrest event with dike intrusion on August 15, 2015;
(5) Post-peak eruptivity at the Showa crater (September 2015–October 2017);
(6) A recurrence of eruptivity at the Minamidake crater (ongoing since November 2017).

The process of volcanic activity prior to the magmatic eruption in 2008 at the Showa crater showed a common sequence. The sequence started with precursory phenomena before reaching the stage of magmatic eruption. The sequence is similar to other volcanic activity, for example, the dome-forming eruption at Unzen volcano during the period from 1990 to 1995 [23].

3.1. Precursory Period

Prior to the resumption of eruptive activity at the Showa crater on June 4, 2006, three types of precursory phenomena were noted: a slight increase in A-type earthquakes, an inflation of the Sakurajima and Aira caldera areas, and an increase in geothermal activity around the crater [24]. The monthly numbers of A-type and explosion earthquakes and changes in slope distance along a baseline in Sakurajima during the period from 1991 to 2019 are shown in **Fig. 2**. The seismicity of the A-type earthquakes was low during the active period at the Minamidake crater, before 2002. Increases in seismicity were recorded during the period from November 2003 to January 2004 and in December 2004. The hypocenters of the A-type earthquakes were concentrated in the summit area and seismicity was also detected at depths of 6–9 km in the southwestern part of Sakurajima and at depths of 4–10 km below the northeastern rim of the Aira caldera [25]. The seismicity southwest of Sakurajima which occurred in November 2003 occupied the same zone of the A-type earthquakes whose hypocenters migrated from deep to shallow levels in May 1976 [26].

Ground inflation has been detected several times. Prior to the eruption of the Showa crater in 2006, the baselines extended again, starting in October 2004, as shown by the arrow in **Fig. 2(c)**. The extensional deformation corresponded to an increase in seismicity of A-type earthquakes at the summit area in December 2004.

An increase in geothermal activity was recognized half a year before the eruption. An increase in fumarolic activity around the Showa crater was observed visually in January 2006, and was confirmed by geothermal measurement using an infrared scanner in March 2006 [27].

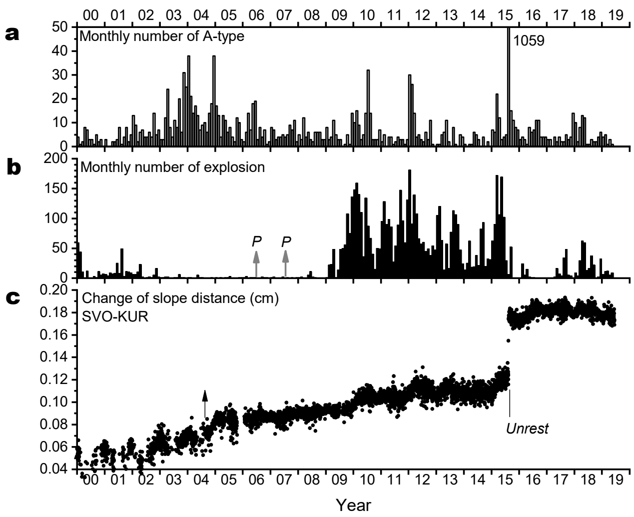

Fig. 2. (a) Monthly number of A-type and (b) explosion earthquakes and (c) change of slope distance along baseline (SVOG-KURG) during the period from 1991 to 2019. All the explosion earthquakes prior to January 2008 were accompanied by Vulcanian eruptions at the Minamidake crater. Most of the explosion earthquakes during the period from February 2008 to October 2017 were related to events at the Showa crater and there were only six events at the Minamidake crater. After November 2017, all the Vulcanian eruptions occurred at the Minamidake crater. "P" indicates phreatomagmatic eruption.

3.2. Phreatomagmatic Eruptions in 2006 and 2007

Eruptive activity at the Showa crater commenced with an emission of volcanic ash around 10:00 to 11:00 on June 4, 2006. The first eruptive activity in June 2006 continued only for two weeks, accompanying a weak emission of volcanic ash; while a second bout of activity in May 2007 continued for three weeks [28]. The eruptive activities were of the phreatomagmatic type [29]. The eruptions were very weak and were not accompanied by explosion earthquakes, ground deformation and infrasonic waves (> 10 Pa at station AVOT in **Fig. 3**).

3.3. Frequent Occurrence of Vulcanian Eruptions (February 2008–June 2015)

The style of eruptions changed to a Vulcanian type on February 3, 2008, when eruptive activity restarted after eight months of dormancy from the phreatomagmatic activity in June 2007. Eruptions at 10:17 and 15:54 on February 3 and at 11:25 on February 6 were accompanied by explosion earthquakes and clear infrasonic waves, and pyroclastic flows having a flow distance of slightly over 1 km. These events marked the beginning of episodic Vulcanian eruptions at the Showa crater that continued until October 2017.

The temporal change in eruptive activity is shown in **Fig. 4** by the amplitude of infrasonic waves, plume height, the monthly number of Vulcanian eruptions, and the monthly weight of volcanic ash ejected from the craters.

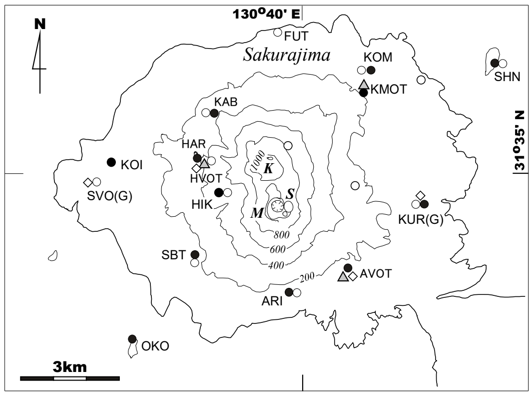

Fig. 3. Location of observation sites at Sakurajima. Dots indicate seismic stations. Open circles indicate GPS observation sites. Gray triangles indicate underground tunnels at HVOT (Harutayama), AVOT (Arimura), and KMOT (Komen), where water-tube tiltmeters and extensometers are installed. Infrasonic microphones are installed at sites indicated by diamonds. At stations KUR, HAR, and AVOT, the concentration of CO_2 is measured at hot springs. Here, M, K, and S indicate craters Minamidake, Kitadake and Showa, respectively.

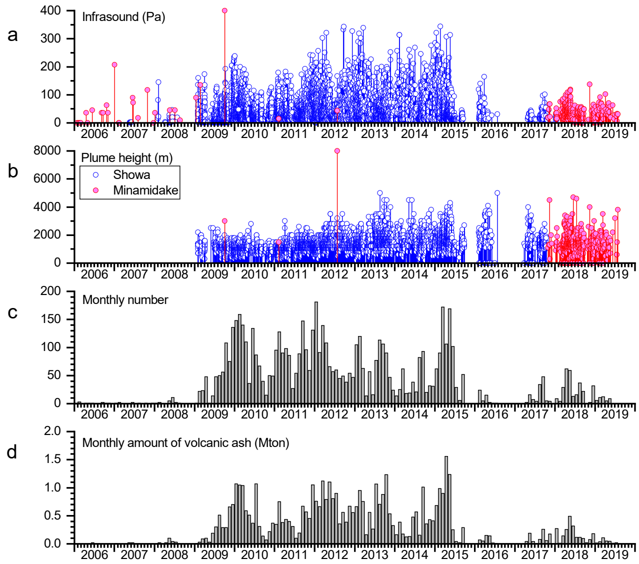

Fig. 4. Temporal change in eruptive activity during the period from 2006 to July 2019. (a) Amplitudes of infrasonic waves generated by Vulcanian eruption. The infrasonic waves are observed at the station AVOT (**Fig. 3**). (b) Plume height of Vulcanian eruptions mostly measured by JMA [30]. (c) Monthly number of Vulcanian eruption. (d) Monthly weight of volcanic ash ejected from the Minamidake and/or Showa craters. The monthly weight of volcanic ash is estimated from the sum of the patterns of decrease in volcanic ash weight according to distance from the crater, approximated by an exponentially decaying curve, along 8 directions [31]. The decrease patterns are determined by measurements at 58 points, which have been operated by the Kagoshima Prefectural government since 1978.

Eruptive activity was low in the initial stage. In 2008, only 18 Vulcanian eruptions occurred from February 3 to July 28. From February to April 2009, eruptive and dormant periods were alternatively repeated at a time interval of around two weeks. Eruptive activity gradually increased from July 2009. From the change in the monthly number of Vulcanian eruption and the weight of volcanic ash ejected from the crater, three episodes of increase in eruptivity are recognized. The first episode (Episode 1) was the eruptive activity during the period from December 2009 to March 2010, when more than 130 Vulcanian eruptions occurred per month. The monthly weight of volcanic ash exceeded 1 Mt during the period from January to March 2010. Episode 2 starting in December 2011 reached a peak with 181 events in January 2012 and continued to May 2012. The monthly weight of volcanic ash exceeded 1 Mt in December 2011, and March and May 2012. Episode 3 was marked by the eruptive activity during the period from January to June 2015. The monthly number of Vulcanian eruptions exceeded 100 from May to June 2015. The monthly weight of ash attained 1.56 Mt in April 2015, and this value was the largest during the activity at the Showa crater. Eruptive activity suddenly decreased in July 2015, and only 29 and 6 Vulcanian eruptions occurred in July and August 2015.

The intensity of the infrasonic waves generated by the Vulcanian eruptions correlated with the occurrence rate. The numbers of Vulcanian eruptions with infrasound larger than 200 Pa are 8 in the Episode 1, 14 in the Episode 2 and 20 in the Episode 3 (**Fig. 4(a)**). In contrast, the amplitudes of infrasonic waves were less than 40 Pa in October 2010 and June 2011, when the monthly number of explosions was only 15 and 27, respectively. A long-term trend of an increase in infrasound amplitude is recognized. Plume height also has a long-term tendency to increase. The plume height of only one Vulcanian eruption (April 9, 2009) exceeded 3000 m above the crater until 2011, however afterwards the plume height of 4 events exceeded 3000 m in 2012, and 16 in 2013. The plume of the Vulcanian eruption on August 18, 2013 reached an elevation of 5000 m above the crater, and this plume was the highest during the activity at the Showa crater. The trend of an increasing plume height continued and plume heights of 32 events exceeded 3000 m in 2015.

The temporal change in eruptive activity was compared with ground deformation, as shown in **Fig. 5**. The eruptions of Episodes 1–3 corresponded to ground inflation deformations, as shown by tensional strain at station HVOT and a slope distance change between the SVO and KUR stations (**Fig. 3**). When the tensional ground deformation began, eruptive activity simultaneously increased; in October 2009 (Episode 1), December 2011 (Episode 2) and January 2015 (Episode 3). The tensional strain reached peaks of 1.2×10^{-6} (in the radial component) in March 2010 (Episode 1), 1.5×10^{-6} in May 2012 (Episode 2) and 1.3×10^{-6} in June 2015 (Episode 3). The slope distance similarly increased by 1.4 cm in March 2010 (Episode 1), 1.2 cm in May 2012 (Episode 2) and 1.7 cm in June 2015 (Episode 3), when the episodes were

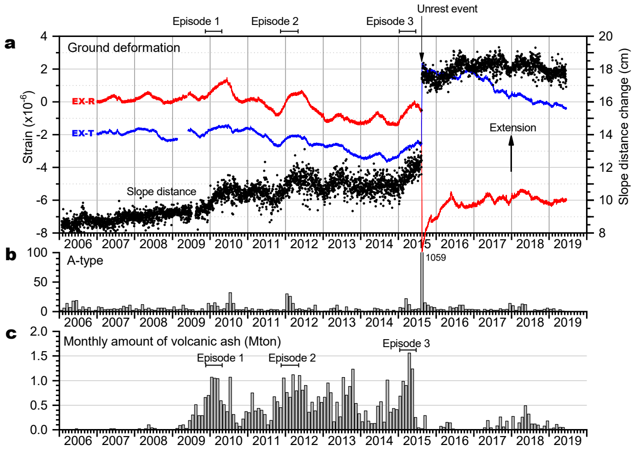

Fig. 5. Temporal change in volcanic activity during the period from 2006 to July 2019. (a) Ground deformation. Curves attached with "EX-R" and "EX-T" indicate strain changes in the direction to the crater and tangential to it, respectively, at the station HVOT (**Fig. 3**). Black dots are change in slope distance between SVOG and KURG (**Fig. 3**). (b) Monthly number of A-type earthquakes with amplitude ≥ 10 μm/s at the station HIK (**Fig. 3**). (c) Monthly weight of volcanic ash ejected from the Minamidake and/or Showa craters.

coming to an end. The ground deformation was modeled by multiple pressure sources; inflations sources at a depth of 10 km beneath the Aira caldera and 3 km beneath the Kitadake cone, and a deflation source at a shallow depth beneath Minamidake [32]. Such a simultaneous occurrence of an accumulation of magma and a discharge may be caused by a small open conduit connected to the Showa crater and a slightly larger intrusion of magma [24]. As the internal pressure of the open conduit did not change rapidly, the seismicity of an A-type earthquake, i.e., the shear fracture caused by over-pressure, was low during the period of frequent Vulcanian eruptions (**Fig. 5(b)**)

Prior to the initial events in February 2008 and Episode 1 in 2009, several phenomena showing an increase in activity were detected. The first one was an increase in the concentration of CO_2 and H_2 from hot spring water at station KUR. The concentration of CO_2 began to increase in July 2007 and attained 20% in January 2008. Fumarolic activity around the Showa crater also increased in January 2008, prior to the initial events in February 2008 [9]. Both the CO_2 and H_2 gas concentrations increased in March 2009 prior to the Episode 1. The H_2 gas concentration reached 3000 ppm in July 2009 but there was no increase in H_2 after this time.

The water-soluble Cl/SO_4 molar ratio of the ash samples increased prior to Episode 1 and showed large values associated with Episode 1 [33]. This suggests an intrusion of a new magma. The increase in Cl/SO_4 molar ratio sometimes appeared during eruptive activity at the Showa crater. Petrological analysis of the ejecta also shows an increase in magmatic activity. Juvenile materials such as unaltered scoria and pumice with fresh glass have been recognized since late September 2009. The whole-rock chemistry of these juvenile materials is similar to those from 1955 to 2000 but they are the most mafic (SiO_2 = 58.5–59.1 wt.%), indicating that the magma system, in which mafic magma was injected into silicic magma, has not changed [34].

The evolution of an underground structure caused by the intrusion and discharge of magma was detected by a repeat of several rounds of controlled seismic experiments [35]. A change of reflectivity was detected at a depth of 6.2 km, and the reflectivity change, which was interpreted to be caused by a velocity perturbation, was at a maximum in Episode 1 and a minimum in Episode 2.

From the multi-parameter monitoring, it is interpreted that a fresh magma was initially intruded during the precursory stages and during Episode 1.

During the period of high eruptivity at the Showa crater, the number of Vulcanian eruptions at the Minamidake crater were few. However, the Vulcanian eruptions which occurred at the Minamidake crater during this period is noteworthy. By the eruption on October 3, 2009, the amplitude of the infrasonic waves was 837 Pa at station HAR [24]. The volcanic plume produced by the eruption on July 24, 2012 reached 8000 m and volcanic ash of 0.25 Mt was discharged from the Minamidake crater [36]. This eruption was caused by rapid magma ascent with a much shorter stagnation period in the conduit which is interpreted from the groundmass textures of juvenile materials in the volcanic ash [37]. The Vulcanian eruption at the Minamidake crater was a large event with a rapid intrusion of magma.

3.4. Unrest Event with Dike Intrusion on August 15, 2015

In July 2015, eruptive activity suddenly declined, with only 29 Vulcanian eruptions occurring, however an unrest event suddenly occurred on August 15, 2015. An A-type earthquake began at 7 h, and the seismicity increased at 8:57 and 10:28 [38]. However, the seismicity decreased in the evening on August 15. This seismicity on the day was accompanied by 887 A-type earthquakes, including 4 felt earthquake and two large B-type earthquakes. Such a swarm of A-type earthquakes is the first in 47 years since the earthquake swarm in May 1968 [39]. Ground deformation showed a similar time progression. The strain changes at station AVOT began at 7 h and were followed by two accelerations at 8:54 and 10:28. The strain rate decreased at approximately 12 h and the strain changes nearly stopped at approximately 15 h. Ground deformation was the most rapid during the observation history of tilt and strain at HVOT since 1985 when continuous monitoring of ground deformation began. The radial tilt and strain attained 12 μrad and 8 μstrain, respectively, in nearly half a day. The progress of extensional deformation was also detected using the Global Navigation Satellite System (GNSS) [40].

The spatial distribution of the horizontal displacement of the event was different from Episodes 1–3 of which deformation was modeled using multiple Mogi's source [2], because of isotopically radial movement from the center [32]. The horizontal displacements of the unrest event were not isotropic. The northwestern flank of Sakurajima volcano showed movement in a northwest direction, with the southeastern flank displaying southeastward movement. The movements on the northeast and southwest flanks were much smaller than those on the northwest and southeast flanks. The displacements were accommodated by the extension of a tensile crack [41] with an opening 1.97 m that yielded a volume increase of 2.7×10^6 m^3. This was connected to the presence of a vertical dike with an NNE-SSW strike at a depth of 1.0 km below sea level beneath the Showa crater. The length and width of the dike is 2.3 and 0.6 km, respectively. These rapid extension events were interpreted to be an intrusion of dike-shaped magma beneath Sakurajima [38]. The deformation was detected by interferometric synthetic aperture radar (InSAR) [42] and they obtained 3D deformation data and a similar dike intrusion. The hypocenters of the A-type earthquake were roughly determined around the dike by the amplitude source location (ASL [43]) method [44] and hypocenter location analysis by the Double-Difference algorithm [45] showed that the swarm commenced at the upper tip of the dike and the hypocenter extended to the lower tip after 10:28 [46].

Responding to the sudden increase in seismicity and the rapid deformation, the Japan Meteorological Agency (JMA) upgraded the Volcanic Alert Level [47] from 3 to 4 and recommended an alert zone of 3 km from the summit, and 77 residents were evacuated from their own villages to safer shelters in Sakurajima. Fortunately, the intrusion event was not followed by eruptions and eruptive activity declined following the tendency of decreasing eruptivity from July 2015.

3.5. Post-Peak Eruptivity at the Showa Crater

Eruptive activity was at a lower level from September 2015, with no eruptions occurring after July 26, 2016 until an eruption at the Minamidake crater on March 25, 2017. From April 26, 2017 eruptions began to occur frequently at the Showa crater and continued to October the 13, 2017. Although most of them were smaller than the eruption in the peak period from 2009 to the first half of 2015, fountains of lava (**Fig. 6**) at the Showa crater and following chugging events (**Fig. 7**) are noted.

Volcanic ash was emitted frequently during the period from August 11 to 19, 2017, and subsequent lava fountain activity (**Fig. 6**) lasted for 12 hours from 22 h on August 22. Fragments of lava released continuously by the fountain reached a height of 200 m above the crater, and some of the fragments fell over the crater rim to the slope of the cone. The extension strain starting in late July accelerated from around 16 h on August 22 [9]. When the lava fountain started at 22 h, the extension reversed to contraction strain. The contraction strain stopped when the lava fountain terminated. As the volume change of the pressure source causing the strain change is estimated

Fig. 6. Lava fountain at Showa crater on August 23, 2017.

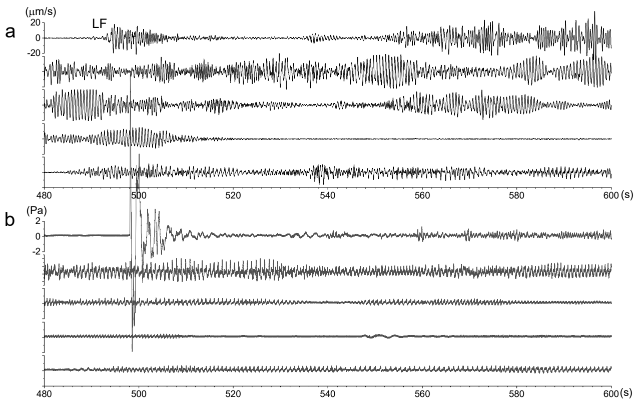

Fig. 7. (a) Seismogram and (b) infrasound associated with a chugging eruption began at 19:20 on August 23, 2017. LF indicates a low-frequency earthquake, which occurred at the onset of the eruption.

to be 1.9×10^5 m^3, the eruption rate is 4×10^5 m^3/day, which is comparable to the lava eruption rates of eruptions at Unzen [23] and Nishinoshima volcanoes [48] and is much larger than the eruption rate of 2×10^4 m^3/day during Episode 3 in 2015.

Immediately after the lava fountain stopped, an eruption type called "chugging" [49], that is initiated with a low-frequency earthquake and is followed by a harmonic tremor and infrasound (**Fig. 7**) with the intermittent ejection of lava fragments, repeated until August 25. It is inferred that the first chugging explosion occurred at 10:54 on August 23, however this type of phenomenon was clearly identified by 19:20. This eruption is quite similar to the eruptions at Karymsky volcano in 1997 and Sangay in 1998 [49]. As the chugging event is produced when debris are not completely ejected through the vent during the initial pulse and the fallback debris traps gas [49], the occurrence of chugging explosions may suggest a decline in eruptive activity.

3.6. Recurrence of Eruptivity at the Minamidake Crater

Although Vulcanian eruptions continued at the Showa crater until October 13, 2017, the eruptive activity moved to the Minamidake summit crater for the eruption on October 31, 2017. Subsequent eruptions occurred at the Minamidake crater (**Figs. 4(a)** and **(b)**). The amplitudes of the infrasonic wave generated by the Vulcanian eruptions at the Minamidake in this period were smaller than those at the Showa crater (**Fig. 4(a)**). On the other hand, the rate of higher plume elevation from Minamidake crater was larger than that from Showa crater. Showa crater's eruptions with a plume elevation of over 4000 m constituted 13 out of the 5657 eruptions whose volcanic height could be identified by the JMA, however the Minamidake crater's eruption plumes with an elevation of over 4000 m were 4 out of only 449 eruptions. A Vulcanian eruption on November 13, 2017 preceded by ground inflation (3×10^5 m^3 of volume increase of the pressure source) starting 6 days before, producing s volcanic plume that reached an elevation 4300 m above the crater, as revealed by an X-band multi-parameter (XMP) radar [50]. The Vulcanian eruption on June 16, 2018 produced pyroclastic flows reaching 1 km southwestward and a volcanic plume of 4700 m [51].

4. Forecasting Volcanic Eruptions

4.1. Inflation Prior to a Vulcanian Eruption

During the eruptive period at Minamidake crater, an upward tilt of the crater side and extensions in both radial and tangential strain were detected 10 min to 7 h prior to the start of the Vulcanian eruption, with an associated deflationary tilt and strain [52, 53]. Similarly, each Vulcanian eruption at the Showa crater was associated with ground inflation deformation prior to the eruptions and deflation afterwards [24]. Such ground deformation was detected for 89% of the eruptions. The ground deformation observation is the most useful tool for forecasting the Vulcanian eruptions, under the condition of no significant change in the seismicity of volcanic earthquakes.

The ground deformations associated with the Vulcanian eruptions at the Showa crater are different from those at Minamidake in their time series and source locations. Prior to most of the eruptions, extension strains are recorded in the tangential components of the extensometers, however, contraction strains are in the radial component, and this shows a shallower (0 to 1.5 km [24]) pressure source for the ground deformation than the pressure source related to the eruptions at the Minamidake crater (2–6 km [53] and 4 km [54]).

The deep pressure source, which was related to eruptions at the Minamidake crater, was also active in large eruptions at the Showa crater [24]. In such cases, larger strain changes were observed starting with significant increase and then following the suspension of the tensional strain one hour before the eruption. The suspension of tensional strain accompanied micro earthquake swarms similar to BH-type earthquakes [55] of which the seismicity accelerated immediately before the eruptions [56]. The seismicity showed an increase in the probability of occurrence of an eruption and an imminent eruption. In addition, emission rates of volcanic gas decreased with the progression of the ground deformation. The volume increase of a deformation source calculated using the strain records was of a comparable order of magnitude to the volume of the accumulated volcanic gas. The results suggest that the inflations before the explosions were caused by the gas accumulation [57].

4.2. Forecasting Pyroclastic Flows

Pyroclastic flows sometimes occurred from the Showa crater and reached a runout distance of ca. 1 km. The occurrence rate of pyroclastic flows from the Showa crater is larger than at Minamidake, because of a shallower depth of the crater bottom and a smaller size of the crater. The eruptions accompanying pyroclastic flows have larger ground deformation inflation with suspension lasting for a longer time period ($>$ 30 min), typically accompanying seismicity of BH-type. In a long-term tendency, most of the pyroclastic flows have occurred during a ground deformation deflation period (**Fig. 5**) [58].

4.3. Empirical Event Branch Logic Based on the Intrusion Rate of Magma

In the magma plumbing system from the deep magma chamber to the crater, the magma intrusion rate could be a useful parameter to forecast the scale and type of an eruption. For example, the Merapi Volcano in central Java, Indonesia, had repeated effusive eruptions (VEI 2) that generated pyroclastic flows due to collapse of the lava domes until the eruption in 2006. In 2010, an explosive eruption (VEI 4) occurred for the first time in 138 years. Costa et al. [59] inferred a difference in the ascent velocity of magma between the two types of eruption; slow ascent in 2006 and rapid in 2010, from petrological analysis. This interpretation is backed up by ground deformation data by Electronic Distance Measurement (EDM). The intrusion rates of the magma for the effusive eruption in 2006 was 0.38 Mm^3/day, while that for the explosive 2010 eruption was $3.16 \times Mm^3$/day [60].

The relation of the magma intrusion rate prior to eruptions with scales and types of eruption after the 20th century at Sakurajima is summarized as an empirical event branch logic [9]. It is estimated that the magma intrusion rate attained a level of approximately 10^8 m^3/day prior to the Plinian eruption in 1914 and was on the order of 10^6 m^3/day during the effusion of lava in the 1946 eruption. In cases of the intrusion of magma forming a new conduit, the intrusion rate immediately before the 1914 eruption exceeded 10^8 m^3/day, but only 10^6 m^3/day in the dike-forming event of August 15, 2015. The magma intrusion rates into a pre-existing conduit prior to eruptions at the Minamidake summit crater are ordered as follows: Vulcanian eruption (1×10^5 to 8×10^5 m^3/day) $>$ continuous emission of volcanic ash (approximately 1×10^5 m^3/day) $>$ Strombolian/lava fountain (0.2×10^5 to 2×10^5 m^3/day). The magma intrusion rate prior to Vulcanian eruptions at the Showa crater is smaller (approximately 10^4 m^3/day) than for eruptions at the Minamidake summit crater. However, the rate reached an order of 10^5 m^3/day prior to lava fountaining on August 22, 2017.

5. Detection and Forecasting Volcanic Ash Fall Deposit

5.1. Detection of Volcanic Ash by Remote Sensing Technology

XMP radars were installed to detect the volcanic plumes from the Kirishima, Sakurajima, Satsuma-Iwojima, Kuchinoerabujima and Suwanosejima volcanoes in 2017 [61]. The radars detected volcanic plumes ejected by Vulcanian eruptions in 2017 and 2018 at Shinmoedake volcano in the Kirishima volcano-complex, eruptions in 2018 and 2019 at the Kuchinoerabujima volcano and several Vulcanian eruptions at the Sakurajima and Suwanosejima volcanoes. The main advantage of XMP radar is its ability to detect volcanic ash clouds even in an invisible state due to fog covering the volcanoes. The volcanic cloud of the eruption on November 13, 2017 at Sakurajima was not visible due to weather clouds covering the summit, however the radars revealed the height of the volcanic plume reaching an elevation of 4.2–6.2 km [50]. Ku-band high-speed scanning Doppler radar could monitor the three-dimensional internal structure of a volcanic plume [62].

The GNSS can be applied to the detection of a volcanic plume by postfit phase residuals (PPR) of the GNSS signals between ground stations and the GNSS satellites after the application of basic GNSS data processing for daily or sub-daily coordinate estimation [63]. The signal-to-noise ratio (SNR) data in the GNSS data is also available without any data processing [64]. Both the PPR and SNR methods were applied to an eruption at Sakurajima on July 24, 2012, and an anomalous increase of PPR paths were detected in the sky approximately 3000 m high above the crater to the west whereas a decrease in SNR was detected in the path passing just above the crater [65]. The anomalous PPR was also detected in the Vulcanian eruption on November 13, 2017 and the intersection of the anomalous increase of PPR paths coincide with the plume height detected by XMP radar [50].

5.2. Forecasting Volcanic Ash

Based on the PUFF model [66], Tanaka and Iguchi [67] proposed a method to forecast the transport and deposition of ash, using the discharge rate of volcanic ash and the plume height of a Vulcanian eruption. The discharge rate of volcanic ash is estimated using co-eruptive seismic amplitude and ground deformation, and the rate is formulated by a linear combination of seismic amplitude in a specific frequency band (2–3 Hz) and the volume change of the pressure source [31]. The height of the plume is obtained from the discharge of volcanic ash in a time interval, under the assumption of $1/4$ power law between plume height and flux [68] with the coefficient empirically determined [67]. The advantage of this method is to forecast the transport of ash and ash-fall deposition in quasi-real time only from seismic and ground deformation observations as conventional monitoring methods and a wind field based on the Grid Point Value (GPV) of wind field forecasted by the JMA. The usefulness of this method is shown in Tanaka and Iguchi [67].

6. Application of Research Results of Forecasting a Volcanic Eruption to Volcanic Hazard Mitigation

Uplift of the west rim (BM. 2474) of the Aira caldera is frequently used for evaluation of the possibility of an occurrence of a large-scale eruption (VEI 4 or 5) at Sakurajima volcano. The location has continued to be uplifted by 10 cm since resumption in 1993 and the uplift since 1915 exceeded 70 cm [69]. From the measurement, the accumulated amount of magma in Aira caldera since 1915 has reached the amount equivalent to that of the 1914 eruption. Hence, when we modelled the disaster prevention measures we assumed an eruption on the scale of the 1914 eruption. Since the seismicity of cumulative energy prior to the 1914 eruption, reached an order of 10^{14} J [14], it is markedly larger than the other increases in seismicity. For example, 10^{9} J [38] with the unrest event on August 15, 2015, the cumulative seismic energy could be a condition for countermeasure decision making. Based on the estimation of the magnitude scale of the precursory seismicity (Section 2.2), one magnitude 5 volcanic earthquake or two magnitude 4 volcanic earthquakes become a condition to upgrade the volcanic alert level to 5 (evacuation) in the criterion of the volcanic alert level issued by the JMA [70].

At the Sakurajima volcano, the local governments of Kagoshima Prefecture and Kagoshima City have run various crisis management training courses. One is an evacuation drill for residents to move off the island of Sakurajima by ferry boats. The other is desktop training for disaster prevention practitioners to respond to the crisis and to share information. This desktop training is conducted with various kinds of scenarios and situations taking place during the progression of volcanic activity. The scenario of the progression of volcanic activity was updated by records [9] of both past and present eruptive activity.

The Regional Disaster Prevention Plan for Kagoshima city includes not only the evacuation of the residents on the island of Sakurajima, but also expands the plan to the evacuation of residents in downtown Kagoshima, in case of a massive tephra fall. Goto [71] simulated the evacuation to estimate the population and the time required for the residents in the wider urbanized area to evacuate to a distant area with less-ash fall. The preliminary simulation of an optimum evacuation shows that the number of evacuees amounts to 800 thousand and such a large evacuation will take 50 hours. However, taking into account the questionnaire replies on evacuation intention from residents and adding information on volcanic activity and evacuation orders, the evacuated population decreases to 130 thousand and the evacuation time is reduced to over 4 hours in the case of massive tephra fall in the densely populated area by an easterly wind. On the other hand, the urbanized area effected by tephra fall and its population strongly depends on the wind conditions. The simulation taking account of recent long-term wind conditions reveals that the population requiring evacuation is the largest in summer when volcanic ash is transported to the downtown of Kagoshima by a dominant easterly wind [72].

In addition, a plan of early recovery from volcanic ash impact was examined. Based on the volume and extent of the ash fall deposit and the restriction of road traffic due to the eruption at Shinmoedake in 2011, the relation between them was approximated by a functional fragility curve, and the probability distribution of traffic restriction was formulated by the extent of the ash fall deposit [73]. The formulation allows us to understand the initial decrease rate of traffic due to ash fall, which is forecasted by the method described in Section 5.2 [67]. The functional fragility curve obtained here is also applicable to other volcanoes and can be used for hazard assessment before an eruption. Furthermore, the optimal traffic network recovery analysis using road cleaning time, traffic, and the traffic reduction rate for all roads assist the early recovery of traffic [73].

7. Further Study for Forecasting Hazards Due to a Large-Scale Eruption

The uplift of the ground of Aira caldera continues. Regarding the rate of uplift, it is forecasted that the ground subsided after the 1914 eruption will be restored to the state just before the 1914 eruption in 10 to 20 years. The magma with the eruptive potential of a VEI 5 eruption has already been stored beneath the Aira caldera in the past 100 year. Therefore, it is important to understand changes in volcanic activity regarding the imminence of a large-scale eruption. Two tectonic earthquakes (M5.7 and M5.9), which could be regarded as "distal earthquakes" [74] occurred 20 km west of Sakurajima half a year before the 1914 eruption. As the eruption approached, the area where abnormal phenomena were detected became localized and these phenomena increased in intensity. It is necessary to study the seismic activity transition from the Aira caldera to the depth of the lower crust and upper mantle in the range of about 50 km, and to understand the ground movement in the northeastern and southwestern of Sakurajima, where increased seismicity was frequently detected.

We have made an immediate forecast of the impact of ash fall by a summit eruption with a VEI < 2 [67]. However, it is necessary to consider several types of hazards associated with an eruption of a VEI 4 and 5 at Sakurajima. These are massive tephra fall, pyroclastic flows, lava flows, debris flows and so on. Although research on the forecasting occurrence of pyroclastic flows has been conducted until now, it is necessary to extend the research to forecast the runout distance of pyroclastic flows. The potential volume of a pyroclastic flow is estimated by the seismic energy of a precursory volcanic earthquake [75], and the runout distance can be obtained by a numerical simulation (e.g., [76]). This implies that the hazardous area is directly forecasted by the monitoring data, and the hazard map could be updated by daily monitoring. In addition, research on forecasting debris flows, which occur even after the eruptive activity declines, is necessary. Since thick volcanic ash will be deposited widely by a large-scale eruption, the area of debris flow occurrence will extend to about 30 km from Sakurajima. It is necessary to evaluate the debris flow hazard even in areas where they are assumed not to occur. In fact, after the 1914 eruption, debris flows and flooding frequently occurred in a wide area (10 to 45 km from Sakurajima) of the Osumi Peninsula [77]. A concept of debris flow potential [78] based on the amount of pyroclastic material in the upper catchment of rivers is valuable to evaluate the probability of debris flows and their continuation.

Research on a more advanced evacuation is necessary for a large-scale eruption. Large scale eruptions often mean that many residents must evacuate to locations far from their homes. When the Merapi Volcano erupted in November 2010 a restricted zone was set up 20 km from the summit and more than 400 thousand residents were evacuated from the zone [79]. If an evacuation was needed as a countermeasure against the massive tephra fall by a future large-scale eruption of Sakurajima, long-distance evacuation is necessary for a larger number of residents. To increase resilience, a recovery plan of infrastructure is important. Issues concerning volcanic ash removal, such as the opening of roads after ash fall, have already focused government attention, and it is necessary to propose an efficient order of removal of volcanic ash on roads depending on the distribution of an ash-fall deposit. The recovery of transport networks is a diverse subject as this concerns not only roads, but also railway, aircraft, sea transportation etc. Therefore, research that considers their characteristics is necessary. Regarding the spreading of volcanic ash, which is a hazard to air routes, there is a possibility of it spreading throughout Japan. We cannot afford to dismiss volcanic disasters as a specific regional problem.

After the tragic eruption of Ontake volcano in 2014, countermeasures of volcanic disaster seem to be concentrated on the high-risk zone near craters despite the small scale. However, larger scale eruptions, when evacuation is needed, are not rare phenomena. After 1974 when the volcanic eruption prediction project was launched, eruptions, which forced residents to evacuate, occurred at Mt. Tokachi, Mt. Usu, Izu Oshima, Miyakejima, Mt. Unzen and Kuchinoerabujima volcanoes. Large-scale eruptions of Sakurajima include problems both with volcanoes and urban areas, but the situation is different at Izu Oshima, Miyakejima, and Kuchinoerabujima volcanoes, which are remote islands. The threat of a large-scale eruption is by no means the only problem associated with Sakurajima. As a wide range of differences in geographical and social environments must be considered, it is necessary to conduct a variety of research to improve volcanic disaster measures.

8. Conclusion

We present an understanding of the characteristics of volcanic activity of Sakurajima volcano and improve on the methods for forecasting an eruption at the volcano by continuous observation, surveys in the recent 15 years, and a reexamination of historic records. Forecasting the scale of an eruption and real-time evaluation of discharge rate of volcanic ash are available to model transportation and deposition of the ash, for which detection technology has been well developed by using radar, lidar and GNSS. Evaluation of the imminence of eruptions and forecasting their scale are used for the improvement of planning and drilling volcanic disaster measures.

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