Journal of Natural Disaster Science, Volume 38, Number 1, 2017, pp133-144

Vertical ground deformation related to the 2014 and 2015 eruptions at Kuchierabujima Volcano, Japan detected by repeated precise leveling surveys

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(Received : Feb. 7, 2017 Accepted : June 2, 2017)

Abstract

We conducted precise leveling surveys in Kuchierabujima Volcano, southwest Japan seven times after the occurrence of the 3 August 2014 eruption, in order to detect the vertical ground deformation associated with the eruptions that occurred in 2014 and 2015. The first survey data obtained in August 2014 suggest that vertical displacements associated with the 3 August 2014 eruption were not remarkable on the leveling route, which is located > 2.3 km away from Shindake crater. On the other hand, the obvious ground uplift toward the central part of the volcanic edifice was detected during the period between August 2014 and March 2015 surveys. The results of the pressure source analysis suggest that the rapid magma input occurred at a relatively large depth (optimally 7.0 km) and led to the large eruption on May 29, 2015. The ground uplift remained unchanged until at least October 2015, even after the eruptions on 29 May and 18 June 2015. During the period between June and September 2016 surveys, a significant ground subsidence was observed, suggesting that most of the stored magma was removed during this period.

Keywords：Kuchierabujima Volcano, eruption, repeated precise leveling surveys, vertical ground deformation

1. Introduction

Kuchierabujima Volcano, located south of Kyushu Island, southwest Japan, is an active island volcano (Fig. 1). The volcano has repeated phreatomagmatic or phreatic eruptions at a summit crater of Shindake or at a fissure on the east of the crater at a few year to a few decade intervals since 1841, before which no historic eruptions have been recorded. Although no eruptions had occurred after September 1980, the volcano erupted at Shindake crater on August 3, 2014 after 34 years of dormancy (Iguchi et al., 2017, in this issue; Tameguri et al., 2016).

Before the 3 August 2014 eruption, the increase of activity of volcanic earthquakes had been repeatedly observed, especially after the increase in July 1999. Most of the hypocenters were located at a depth shallower than 500 m beneath Shindake crater (Yamamoto et al., 1997; Iguchi et al., 2007; Triastuty et al., 2009). GPS campaign observations that had been conducted since 1995 detected inflations of the ground around Shindake crater, and the pressure sources were located initially at a depth around sea level beneath the crater, which became shallower over time (Iguchi et al., 2002, 2007). Furthermore, the continuous GPS observation started in 2004 revealed that the ground inflations occurred in association with the increase of activity of volcanic earthquakes (Saito and Iguchi, 2006). Kanda et al. (2010) observed the total intensity of the geomagnetic field at the summit area since 2000. They indicated that the estimated volcanomagnetic field variations were caused by the thermal demagnetization that occurred in the shallow part beneath Shindake crater and changed in concordance with the increase in seismicity. Thus the 3 August 2014 eruption occurred after various long-term precursory activities that had been gradually progressing (Iguchi et al., 2017, in this issue; Tameguri et al., 2016).

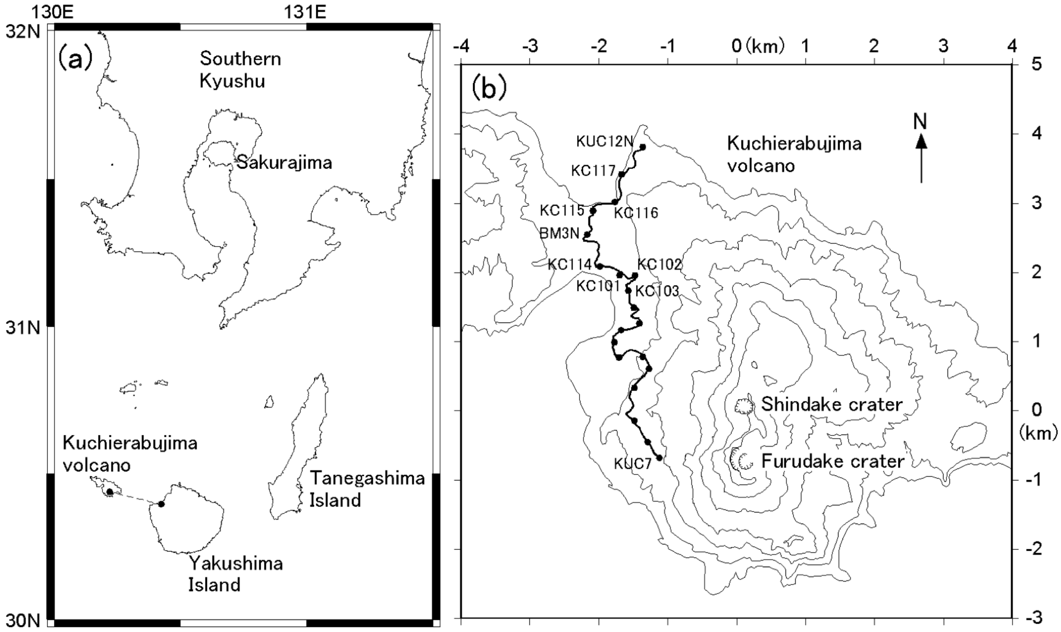

Fig. 1. (a) Location map of Kuchierabujima Volcano. Solid circles with a broken line denote the locations of GNSS stations (Nanakama station in Kuchierabujima operated by Japan Meteorological Agency and Kamiyaku2 station in Yakushima Island operated by Geospatial Information Authority of Japan) and the baseline whose length changes are discussed in the text. (b) Leveling benchmarks (solid circles) and leveling route (solid curve) of Kuchierabujima Volcano. The topographic contour interval is 100 m.

After the 3 August 2014 eruption, various kinds of observation data showed a further increase of volcanic activity (Iguchi et al., 2017, in this issue; Tameguri et al., 2016). These include the remarkable increase of SO_2 emissions since December 2014 (Mori et al., 2017, in this issue), shortening of the slope distance between the GNSS station in Kuchierabujima and that in Yakushima Island (Fig. 1a) during the period from December 2014 to January 2015, which is recognized as inflation of the volcano (Iguchi et al., 2017, in this issue), volcanic glow above Shindake crater observed on and after March 24, 2015 by JMA high-sensitivity monitoring camera (Japan Meteorological Agency, 2015), increase in the activity of volcanic earthquakes especially since May 2015 and the occurrence of felt earthquakes on January 24, 2015 and on May 23, 2015 (Iguchi et al., 2017, in this issue; Tameguri et al., 2016). These remarkable precursory activities led to the large eruption on May 29, 2015, when all the residents in Kuchierabujima evacuated from the island (Iguchi et al., 2017, in this issue; Tameguri et al., 2016). Another eruption occurred on June 18, 2015 in which ash-fall was observed in Yakushima and Tanegashima Islands (Fig. 1a) (Japan Meteorological Agency, 2015). However, the details of the eruption were unknown due to the bad weather and insufficient observation system due to the destruction caused by the 3 August 2014 eruption.

A precise leveling survey is a classical technique, but the most accurate geodetic method in measuring the vertical displacements of the ground. Therefore, it has been applied to various kinds of volcanic deformation studies (e.g. Dzurisin et al., 2002; Kimata et al., 2004; Yamamoto et al., 2013; Murase et al., 2016). On Kuchierabujima Volcano, Disaster Prevention Research Institute (DPRI), Kyoto University installed 20 leveling benchmarks around the northwestern foot of the volcano in May 1996, along the route of about 7.5 km long (Fig. 1b). Since then, precise leveling surveys have been repeated seven times before the 3 August 2014 eruption, including the May 1996, August 1996, September 1999, November 2000, December 2001, December 2006 and December 2008 surveys. The results of these repeated leveling surveys indicate that the vertical ground deformation was generally small, although relatively large (within 5 mm) uplift or subsidence was occasionally observed along the southern half of the leveling route between benchmarks KC103 and KUC7 (Fig. 1b), which are located relatively close to Shindake crater (Iguchi et al., 2002; Yamamoto and Sonoda, 2014). Iguchi et al. (2002) pointed out that the vertical displacements expected from the shallow pressure source inferred from the GPS campaign data were not inconsistent with the small displacements observed by the repeated leveling surveys. Along the leveling route north of KC103, the observed vertical displacements were smaller than about 2 mm (Yamamoto and Sonoda, 2014).

We conducted precise leveling surveys in Kuchierabujima Volcano repeatedly after the occurrence of the 3 August 2014 eruption. In this paper, we present the results of these surveys and discuss the vertical ground deformation related to the 2014 and 2015 eruptions, in order to assess the current status of the volcanic activity.

2. Observations

Just after the occurrence of the 3 August 2014 eruption, we conducted a precise leveling survey along the above-mentioned leveling route during the period of August 19-21, 2014, in order to detect the vertical ground deformation associated with this event. In this survey, we measured only the northern half of the leveling route (from KUC12N to KC103 in Fig. 1b and in Table 1), since the southern part of the leveling route is located in the off-limits area assigned due to the eruption. Since then, we have repeated the leveling surveys only along the northern half of the leveling route during the periods of March 4-5, 2015, July 29-30, 2015 (after the 29 May 2015 and the 18 June 2015 eruptions), October 7, 2015, March 24-25, 2016, June 22-23, 2016 and September 14-15, 2016. As to the July and October 2015 surveys, we measured only the benchmarks between KUC12N and KC101, due to the widening of the off-limits area associated with the 29 May 2015 eruption.

Table 1. List of benchmark coordinates used in this study.

Benchmark No.	Latitude (^oN)	Longitude (^oE)	Altitude (m)
KUC12N	30.47955	130.20028	28
KC117	30.47598	130.19708	26
KC116	30.47242	130.19605	10
KC115	30.47123	130.19275	40
BM3N	30.46817	130.19183	47
KC114	30.46405	130.19378	18
KC101	30.46290	130.19673	36
KC103	30.46087	130.19808	62

Table 2. Relative heights of benchmarks along the Kuchierabujima leveling route referring to the benchmark KUC12N, which is located at the northern end of the leveling route.

Benchmark No.	2008.12* (m)	2014.08 (m)	2015.03 (m)	2015.07 (m)	2015.10 (m)	2016.03 (m)	2016.06 (m)	2016.09 (m)
KUC12N		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
KC117	-2.4964	-2.4964	-2.4962	-2.4969	-2.4970	-2.4972	-2.4966	-2.4973
KC116	-17.8994	-17.9001	-17.8996	-17.9001	-17.8998	-17.9003	-17.8993	-17.9006
KC115	12.1495	12.1489	12.1501	12.1500	12.1502	12.1493	12.1501	12.1487
BM3N	19.1579	19.1568	19.1578	19.1585	19.1585	19.1575	19.1587	19.1566
KC114	-9.6960	-9.6972	-9.6949	-9.6960	-9.6952	-9.6960	-9.6944	-9.6968
KC101	7.5017	7.5009	7.5026	7.5030	7.5028	7.5024	7.5040	7.5009
KC103		34.3405	34.3430			34.3424	34.3434	34.3404
M.S.E.**	±0.36	±0.21	±0.16	±0.28	±0.12	±0.22	±0.20	±0.14

* The results of the December 2008 survey are taken from Takayama et al. (personal communications) in order to calculate the relative vertical displacements during the period between the December 2008 and August 2014 surveys. Since KUC12N is replaced between December 2008 and August 2014, the relative heights of benchmarks in the December 2008 survey are calculated referring to benchmark KC117 and the height of KC117 in the December 2008 survey is assumed as that in the August 2014 survey.

** Mean square error (mm/km)

The leveling instruments used in these surveys were a digital level (Leica DNA03) and Invar bar-coded leveling staffs (Leica GPCL3). We conducted precise leveling surveys, so as to keep the misclosure of the round-trip survey below the allowable limit of $2.5 \times L^{1/2}$ mm according to the first order leveling survey regulation defined by Geospatial Information Authority of Japan, where L is the distance in kilometers along the leveling route between the two measured benchmarks. The horizontality of the line of sight of the level and circular level of the leveling staffs were checked and adjusted before each survey, in order to decrease the measurement errors. As a result of these preparatory calibrations and careful measurements, mean square errors of the surveys were achieved with good accuracy ranging from ±0.12 to ±0.28 mm/km (Table 2).

3. Results of the leveling surveys

From the data obtained in each leveling survey, we calculated the relative height of each benchmark referring to benchmark KUC12N, which is located at the northern end of the leveling route and is the farthest benchmark from Shindake crater (Table 2). The calculated relative height of each benchmark was then compared with that of the previous survey, resulting in the relative vertical displacement of the benchmark between the successive surveys (Fig. 2). The error bar in Fig. 2 denotes the error of the vertical displacement of each benchmark calculated as the root mean square of the relative height errors of the benchmark in the two surveys concerned, where the relative height error of each benchmark is estimated from the misclosures of round trip surveys by accumulating from the reference benchmark (Kimata et al., 2004; Murase et al., 2016). In each survey, we measured the air temperatures and made a correction for the thermal expansion of our Invar bar-coded leveling staffs. Therefore, the measured data are basically free from such effects. If the expansion coefficient of the leveling staff has an uncertainty of 4.0×10^{-8} /℃ (in the case of our leveling staffs), the scale error in the maximum height difference of our benchmarks (about 60 m in Fig. 2h) is estimated to be 0.024 mm, where the temperature difference is assumed to be 10 ℃. This means that the scale error is negligible in our measured data.

The resultant displacements during the period from December 2008 to August 19-21, 2014 (just after the occurrence of the 3 August 2014 eruption) show a slight ground subsidence toward the south (i.e. toward the central part of the volcanic edifice including Shindake crater) (Fig. 2a). However, the amounts of the subsidence are less than 1.2 mm and are generally within the estimated errors, implying that the ground deformation associated with the 3 August 2014 eruption is not remarkable along the northern half of the leveling route.

The displacements during the period from August 2014 to March 2015 (Fig. 2b) indicate the obvious ground uplift, the amount of which is increasing toward the south or toward the central part of the volcanic edifice. The amount of uplift at the southern end of the leveling route (KC103) reaches 2.5 mm referring to KUC12N, which is much larger than the estimated errors. Since the leveling route was established, it is the first time that obvious ground deformation was observed along the northern half of the leveling route, which is located more than 2.3 km farther apart from Shindake crater. It suggests that subsurface inflation at a relatively large depth beneath the volcanic edifice was progressing in the preparation period of the 29 May 2015 eruption.

During the period from March 2015 to July 2015 in which the 29 May 2015 and the 8 June 2015 eruptions occurred (Fig. 2c), we cannot find clear ground deformation. This suggests that the ground uplift observed in the previous period (Fig. 2b) was not affected by these two eruptions. Some benchmarks seem to deform locally in this period, although the displacements are generally small. This is supposed to reflect the circumstantial changes around the benchmarks caused by the small landslides etc. because the land was not maintained due to the evacuation of all the residents from Kuchierabujima. During the following period between July 2015 and October 2015, the vertical displacements indicate no notable deformation (Fig. 2d). Thus the uplift was preserved.

During the period between October 2015 and March 2016, a subtle (less than 1 mm) ground subsidence toward the south is obtained (Fig. 2e). On the contrary, the ground uplift was measured in the following period of March-June 2016 (Fig. 2f). In the most recent period between June 2016 and September 2016, we observed significant ground subsidence toward the south, where the amount of maximum subsidence was as much as 3.1 mm at KC101.

Figure 3 represents the cumulative vertical displacements of the benchmarks referring to benchmark KUC12N since the 19-21 August 2014 survey. It is clearly displayed that the ground uplift observed during the period between August 2014 and March 2015 (solid squares) was preserved with relatively minor fluctuations in the following periods from March 2015 to June 2016. Then the ground returned to almost the same level in the 19-21 August 2014 survey during the period between June 2016 and September 2016.

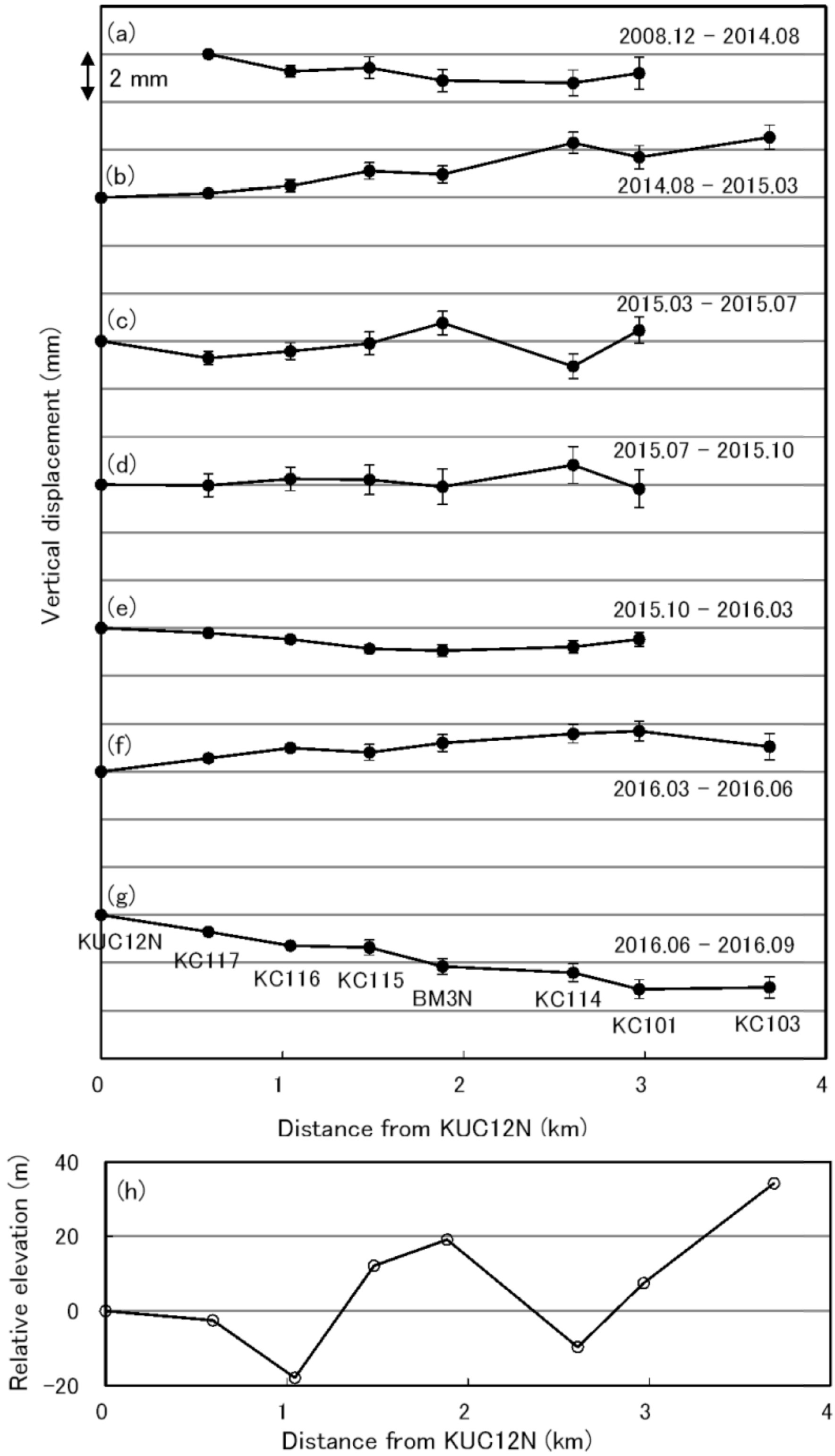

Fig. 2. Vertical displacements of the benchmarks in Kuchierabujima Volcano referring to benchmark KUC12N, which is located at the northern end of the leveling route during the periods between (a) December 2008 and August 2014, (b) August 2014 and March 2015, (c) March 2015 and July 2015, (d) July 2015 and October 2015, (e) October 2015 and March 2016, (f) March 2016 and June 2016 and (g) June 2016 and September 2016. The results of the December 2008 survey are taken from Takayama et al. (personal communications) in order to calculate the vertical displacements during the period between the December 2008 and August 2014 surveys (see footnotes of Table 2). Error bars denote the errors of the vertical displacements of the benchmarks (see text). (h) Relative elevations of the benchmarks referring to benchmark KUC12N.

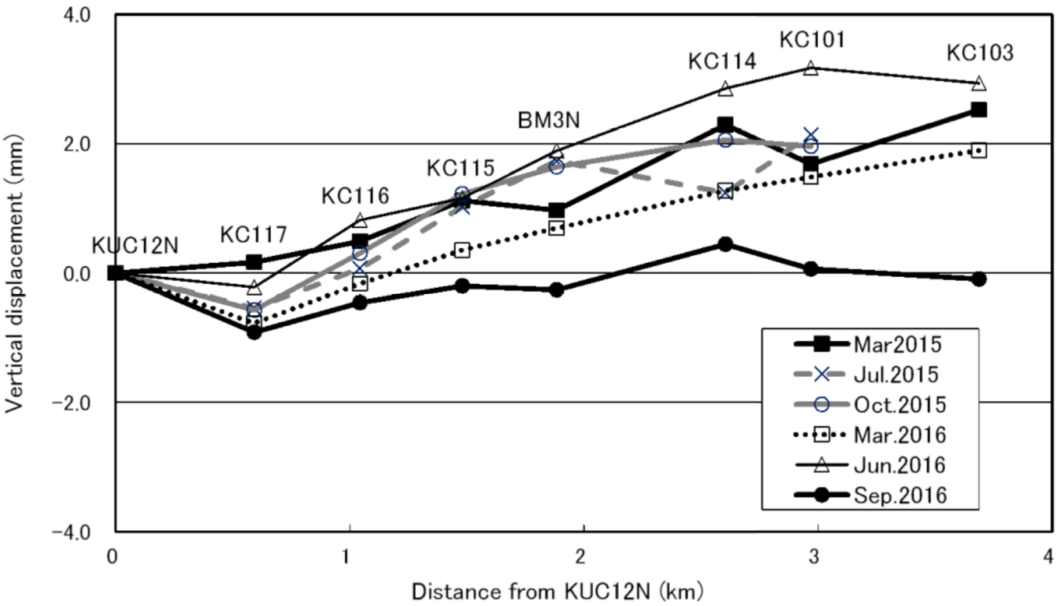

Fig. 3. Cumulative vertical displacements of the benchmarks in Kuchierabujima Volcano since the August 2014 survey referring to benchmark KUC12N, which is located at the northern end of the leveling route.

4. Discussion

4.1 Secular change of vertical ground deformation since 1996

Since May 1996 when the leveling benchmarks were newly installed, some benchmarks were accidentally broken or became useless, whereas the benchmarks of KC117, KC116, KC115, KC114 and KC101 in the northern half of the leveling route have been continuously measured until the latest leveling survey. Using the data observed at these benchmarks, we can obtain the secular changes of the relative heights of the benchmarks throughout the observation periods. In Fig. 4, we show the secular changes in the relative heights of benchmark KC101 (Fig. 4a) and KC114 (Fig. 4b) referring to benchmarks KC117, KC116 and KC115 resulting from repeated leveling surveys since May 1996.

During the period from May 1996 to August 2014 surveys, the relative heights change gradually. The relative heights of KC101 and KC114 referring to KC116 or KC115 (open triangles and circles in Figs. 4a and 4b) show a tendency of long-term ground uplift, while those referring to KC117 (open squares in Figs. 4a and 4b) show a tendency of long-term ground subsidence, with some shorter uplift and subsidence fluctuations. One of the probable causes of these long-term height changes is the secular height changes of the reference benchmarks, and further longer data acquisition will be needed to confirm the cause of the long-term deformation.

Compared with the gradual height changes before the August 2014 survey, the relative height changes during the period between August 2014 and March 2015 surveys (gray shaded in Fig. 4) indicate the significantly rapid and large ground uplift toward the central part of the volcanic edifice. During the period between August 2014 and March 2015, other observation data indicated remarkable signals related to the increase of volcanic activity, including the significant increase of SO_2 emission rate, shortening of the slope distance between the GNSS stations in Kuchierabujima and in Yakushima Island (ground inflation of the volcano), increase in the activity of volcanic earthquakes and the occurrence of felt earthquakes (Iguchi et al., 2017, in this issue; Mori et al., 2017, in this issue; Tameguri et al., 2016). It is inferred that the rapid magma input to the volcanic edifice occurred before the large eruption on May 29, 2015. Such rapid and large height changes during the period between August 2014 and March 2015 are distinguishable from the other changes measured before the August 2014 survey, suggesting the possibility of detecting the precursory ground deformation of the next large eruption if a similar deformation is observed along the northern half of the leveling route. In Fig. 4, we can also identify rapid and large ground subsidence during the period of June-September 2016 (Figs. 2g and 3).

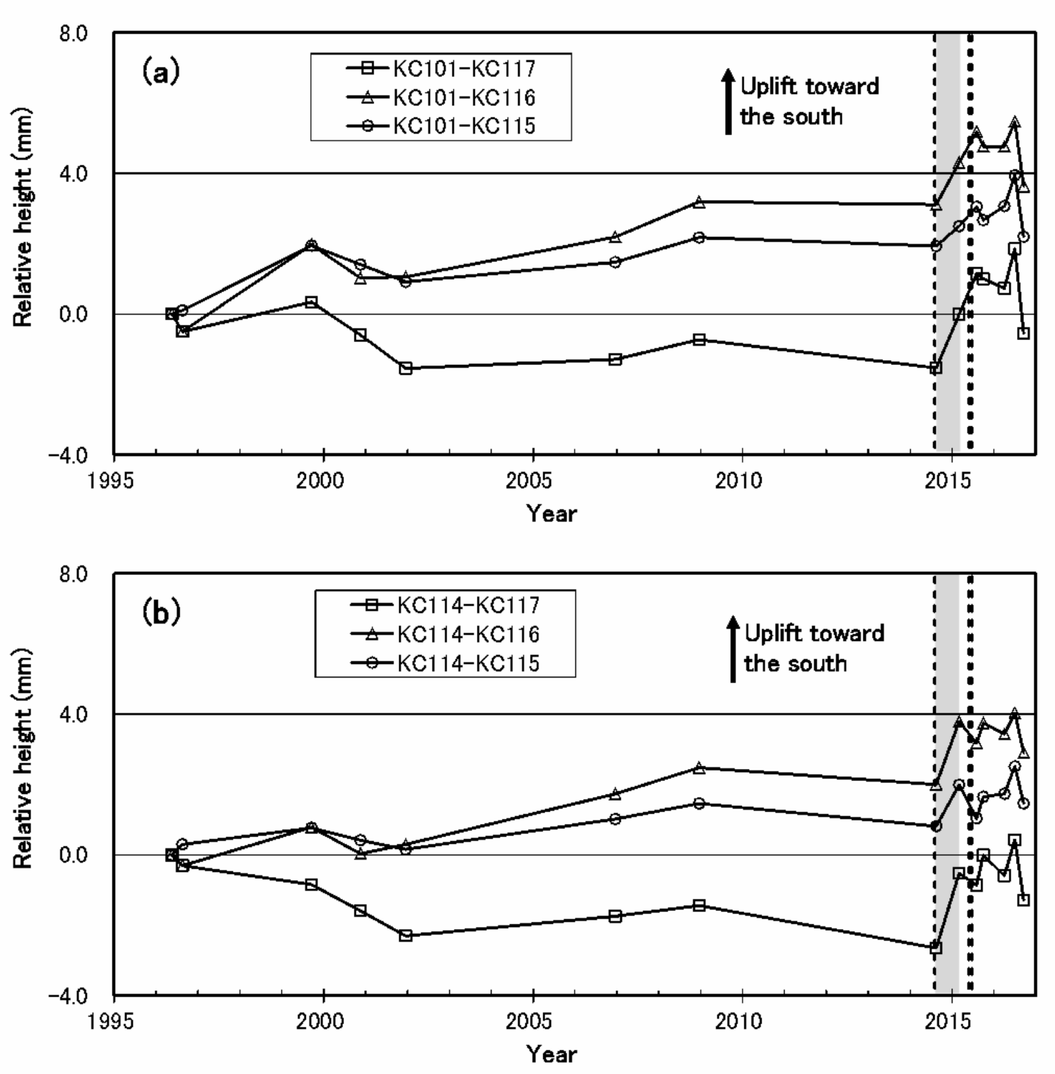

Fig. 4. (a) Secular changes of relative heights of benchmark KC101 referring to benchmarks KC117 (open squares), KC116 (open triangles) and KC115 (open circles), respectively, since May 1996. Gray shaded zones denote the period between August 2014 and March 2015 surveys. The three vertical broken lines indicate the timing of the 3 August 2014, the 29 May 2015 and the 18 June 2015 eruptions. (b) Similar to (a) but for the secular changes of relative heights of benchmark KC114.

4.2 Pressure source analysis based on Mogi's model

The relative vertical displacements during the period from August 2014 to March 2015 (Fig. 2b) that indicate the obvious ground uplift increasing toward the central part of the volcanic edifice were analyzed based on a spherical source model (Mogi, 1958). In the calculation, the effects of topography along the leveling route were considered by replacing the source depth with source depth plus benchmark elevation (Williams and Wadge, 1998). Our leveling data suggest that the inflation source was located south of the leveling route. However, it is difficult to determine the horizontal location of the source exactly, because the geometry of our leveling route was a nearly straight line and in addition, our leveling data were available only along the northern half of the leveling route that is located apart from the center of the volcanic edifice, the candidate area of the source location. Thus we assumed the horizontal source location to be beneath the active Shindake crater, and searched for the optimal source depth so as to minimize the residual sum of squares. The searched source depth ranged from 0 to 30 km below sea level, with a depth step of 0.1 km. Given the depth, the volume change at the pressure source was calculated by the least square fit of the model to the observed data, so the volume change was not searched.

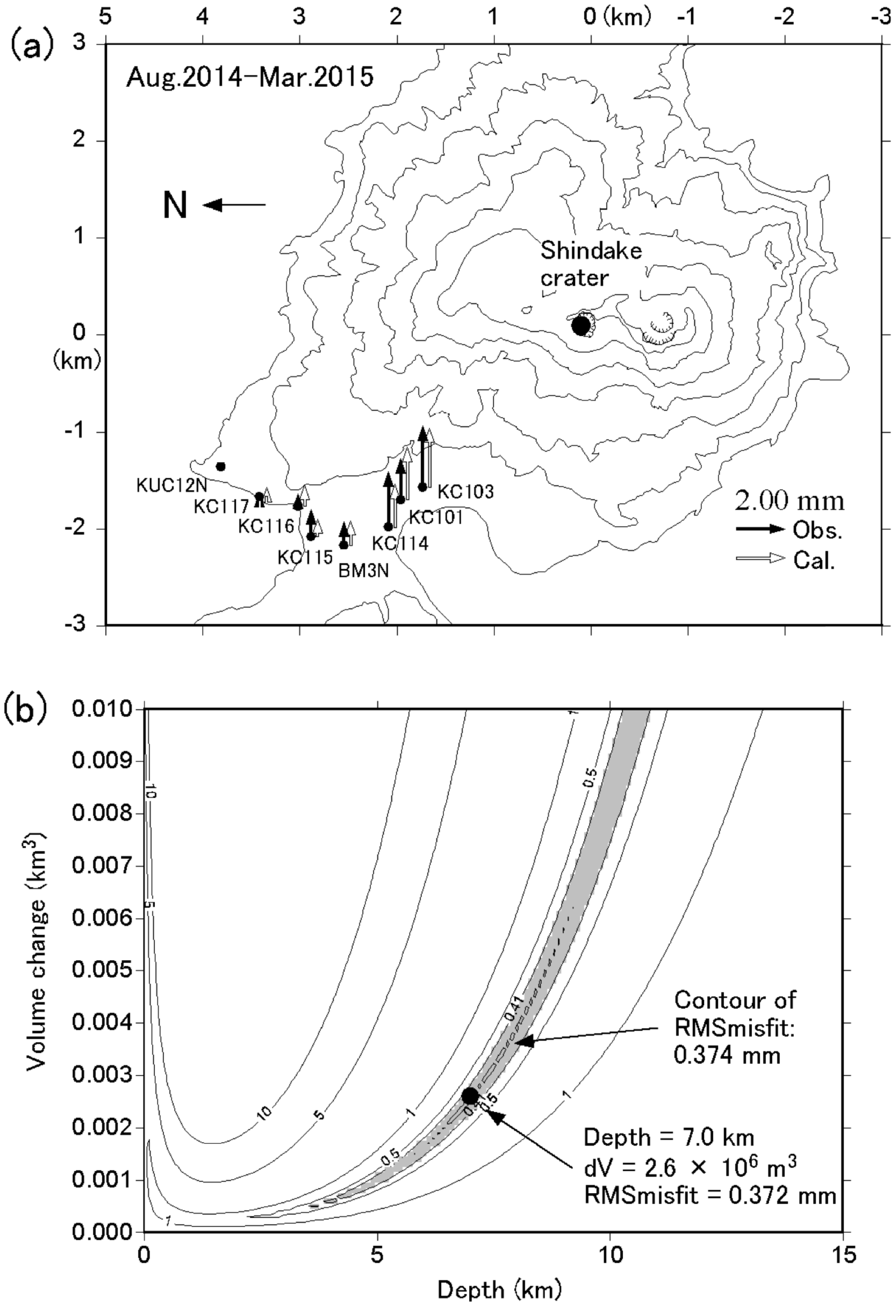

Fig. 5. (a) Comparison between measured vertical displacements during the period from August 2014 to March 2015 (solid arrows) and theoretical vertical displacements calculated by using the optimal pressure source (open arrows), respectively, where upward arrows indicate the ground uplifts. The large solid circle denotes the assumed horizontal location of the pressure source. (b) The contour plot of the root mean square (RMS) misfit in millimeters as a function of the depth and volume change of the pressure source. The large solid circle denotes the location of the optimal source parameters. The shaded zone is the region where the RMS misfit is less than 0.41 mm, representing the 68% confidence region estimated from the F-test (Arnadottir and Segall, 1994).

The optimal depth of the inflation source was determined to be 7.0 km below sea level. The volume increase of this pressure source was estimated to be about 2.6×10^6 m^3 (Table 3). The theoretical vertical displacements deduced from the optimal source accounted for the observed data fairly well (Fig. 5a). According to the F-test (Arnadottir and Segall, 1994), the 68% confidence intervals for the source parameters were estimated to be less than 0.41 mm (root mean square (RMS) misfits) in our case. Figure 5b is a contour plot of RMS misfit in millimeters calculated as a function of depth and volume change of the pressure source. Here, we can see an approximate view of the RMS misfit changes corresponding to variations of the volume change of the pressure source, although the volume change was not searched in our pressure source analysis. The large solid circle denotes the location of the optimal source parameters and the shaded zone shows the region where the RMS misfit was less than 0.41 mm. The shaded zone has an elongated shape as the volume change enlarges according to the depth increase. It extends from a depth of 3.5 km (volume increase of 4.7×10^5 m^3) to a depth of 24.8 km (volume increase of 2.5×10^8 m^3 : not shown in Fig. 5b). Figure 5 indicates that the optimal source is a plausible model that sufficiently explains the observed data, although the source depth is practically unconstrained by the data.

Table 3. Estimated volume changes of the pressure source located at 7.0 km depth beneath Shindake crater and root mean square (RMS) misfits.

Leveling survey interval	Volume change (m^3)	RMS misfit (mm)
Aug.2014 ~ Mar.2015	$+2.6 \times 10^6$	0.37
Mar.2015 ~ Jul.2015	-2.1×10^5	0.71
Jul.2015 ~ Oct.2015	$+3.3 \times 10^5$	0.36
Oct.2015 ~ Mar.2016	-1.1×10^6	0.40
Mar.2016 ~ Jun.2016	$+1.9 \times 10^6$	0.43
Jun.2016 ~ Sep.2016	-3.6×10^6	0.37

Before the 3 August 2014 eruption, the inflation sources had been located at shallower depths than 100 m below sea level beneath Shindake crater by using the data of GPS observations (Iguchi et al., 2002, 2007; Saito and Iguchi, 2006). The volume increases at these sources were estimated as ranging from 6.2×10^3 m^3 to 1.7×10^5 m^3. Although the source depth and the volume increase estimated in this study were unconstrained, the depth of the pressure source and its volume increase during the period between August 2014 and March 2015 were significantly larger than those before the August 2014 eruption under the assumption that the source was located beneath Shindake crater. A deeper source with a larger volume increase was originally supported by the fact that obvious ground uplift was detected along the northern half of the leveling route located apart from Shindake crater.

In this study period, we also observed relatively remarkable ground uplift during the period of March-June 2016 (Fig. 2f) and ground subsidence during the period of June-September 2016 (Fig. 2g). Attempting to analyze the data of these two periods by the same pressure source calculation process used in the period between August 2014 and March 2015, we obtained the optimal source depths and volume changes of 30.0 km and 4.0×10^8 m^3 for March-June 2016 data and 14.3 km and -4.3×10^7 m^3 for June-September 2016 data, respectively. These are much larger depths and volume changes than those obtained during the period between August 2014 and March 2015, and the source depths are also unconstrained by the data. Therefore, in the following discussion, we would rather additionally assume the source depth to be 7.0 km than determine the source depth variations, in order to compare the results with those during the period between August 2014 and March 2015. We only calculated the optimal volume changes at the pressure source by the least square fit of the model to the observed data.

In Table 3, we show the estimated volume changes of the pressure source at 7.0 km depth beneath Shindake crater of the two periods as well as those during the periods of March-July 2015, July-October 2015 and October 2015-March 2016, in which minor vertical displacements were observed. The RMS misfits of these estimations were 0.36-0.71 mm (Table 3), similar to the amounts of the vertical displacement errors (Fig. 2), suggesting that these sources are among possible models that explain the observed data.

The cumulative volume changes since the August 2014 survey were calculated from Table 3 and displayed in Fig. 6. It was inferred that even after the 29 May and 18 June 2015 eruptions about 2-3 × 10^6 m^3 magma remained until October 2015. The amount of the ejected magma associated with the 29 May 2015 eruption was estimated as 66-110 × 10^4 tons (2.6-4.4 × 10^5 m^3, where the density of magma was assumed to be 2500 kg/m^3) inferred from the volcanic plume heights (Meteorological Research Institute of Japan, 2015). Removal of the order of 10^5 m^3 magma from the pressure source at 7 km depth does not conflict with our estimates in Fig. 6 (and with observed vertical displacements). It is not necessary that the removal of magma from the source at 7 km depth was simultaneous with the eruption. Considering that the volcanic glow was observed above Shindake crater on and after March 24, 2015 by a JMA high-sensitivity monitoring camera (Japan Meteorological Agency, 2015), part of the magma was supposed to have moved from 7 km depth to the shallow part beneath Shindake crater in late March 2015. In addition, we calculated the expected slope distance change on the baseline between the GNSS stations in Kuchierabujima and Yakushima Islands (Fig. 1a) assuming some depths and volume changes of the Mogi sources beneath Shindake crater. It is suggested that a few millimeters slope distance shortening observed during the period from December 2014 to January 2015 (Iguchi et al., 2017, in this issue) was not produced by our optimal source parameters during the period between August 2014 and March 2015 (depth of 7 km and volume increase of 2.6 × 10^6 m^3: this source produces about 0.2 mm slope distance elongation), but was caused by another shallower inflation source. This result also supports the magma movement to the shallow part beneath Shindake crater.

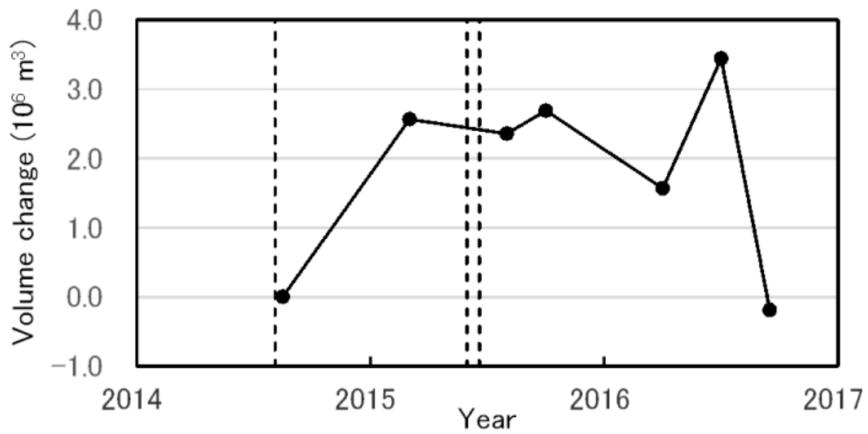

Fig. 6. Cumulative volume change since August 2014 survey at the pressure source located at 7.0 km depth beneath Shindake crater. The three vertical broken lines indicate the timing of the 3 August 2014, the 29 May 2015 and the 18 June 2015 eruptions.

After 1-2 × 10^6 m^3 volume decrease and increase in the following periods from October 2015 through March 2016 to June 2016, most of the remaining magma appears to have been removed during the period of June-September 2016. Since no magma ejection associated with the eruptions was observed during the period of June-September 2016, one of the possible causes of the volume decrease was magma drain back to deeper than 7 km, although no other supporting evidence of the magma drain back was found. Contraction of the baseline length of GNSS stations had been observed across Shindake crater since January 2016, and it continued at least until July 2016 after that the data were missed due to the GNSS station problems (Japan Meteorological Agency, 2016). This might be a signal that the magma drain back began at a shallow part beneath Shindake crater in early 2016. In order to clarify the cause of the volume decrease, successive monitoring by repeated precise leveling surveys is needed.

5. Conclusions

The vertical ground deformation related with the 2014 and 2015 eruptions at Kuchierabujima Volcano was revealed by the precise leveling surveys conducted repeatedly after the occurrence of the 3 August 2014 eruption. In the surveys, we measured only the northern half of the leveling route, which was located more than 2.3 km apart from Shindake crater, since the southern part of the leveling route was in an off-limits area assigned due to the eruptions.

The results of the August 2014 survey suggest that the vertical displacements associated with the 3 August 2014 eruption were not remarkable along the northern half of the leveling route. On the other hand, the obvious ground uplift toward the central part of the volcanic edifice was detected during the period between August 2014 and March 2015 surveys. The ground uplift remained unchanged until around October 2015, even after the eruptions on 29 May and 18 June 2015. After the following relatively minor ground subsidence and uplift, significant ground subsidence toward the central part of the volcanic edifice was observed during the period between June and September 2016 and the ground returned to almost the same level of that in the August 2014 survey.

From the analysis based on Mogi's model assuming that the horizontal source location to be beneath Shindake crater, the optimal depth of the inflation source was estimated to be 7.0 km below sea level with a volume increase of 2.6×10^6 m^3 by using the obvious uplift data during the period from August 2014 to March 2015. The depth of the pressure source and its volume increase were significantly larger than those before the August 2014 eruption inferred from the GPS data. During the period from August 2014 to March 2015, other observation data, including the SO_2 emission rate, GNSS and seismicity simultaneously indicated remarkable signals related to the increase of volcanic activity. It is suggested that the rapid magma input to the volcanic edifice occurred and led to the large eruption on May 29, 2015. The results of the source volume change calculations in the following periods suggest that most of the stored magma before the 29 May 2015 eruption appeared to be removed during the period of June-September 2016. Since no eruption was observed during the period of June-September 2016, one of the possible causes of the volume decrease was magma draining back to the depths.

Repeated precise leveling surveys are an important and useful technique for assessing the eruptive activity at Kuchierabujima Volcano. In order to evaluate the potential for the following eruption, successive monitoring with repeated precise leveling surveys is needed.

Acknowledgements

We thank the staff of Sakurajima Volcano Research Center, Disaster Prevention Research Institute, Kyoto University, for help and assistance with the observations. The leveling surveys were conducted with the support of Yakushima town and Japan Meteorological Agency. We are also grateful to two anonymous reviewers and a sub-editor for constructive and valuable comments and suggestions. Some figures were drawn using GMT software (Wessel and Smith, 1995). This study was supported by MEXT KAKENHI Grant Number 15H05794 and by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan, under its Earthquake and Volcano Hazards Observation and Research Program.

References

Arnadottir, T. and Segall, P., 1994. The 1998 Loma Prieta earthquake imaged from inversion of geodetic data, J. Geophy. Res., 99, 21835-21855.

Dzurisin, D., Poland, M. P. and Burgmann, R., 2002. Steady subsidence of Medicine Lake volcano, northern California, revealed by repeated leveling surveys, J. Geophy. Res., 107, 2372, doi:10.1029/2001JB000893.

Iguchi, M., Yamamoto, K., Miki, D., Takayama, T., Teraishi, M., Sonoda, Y., Fujiki, S., Onizawa, S., Suzuki, A., Yakiwara, H. and Hirano, S., 2002. Recent ground deformation at Kuchierabujima volcano, Ann. Disast. Prev. Res. Inst., Kyoto Univ., 45B, 601-608 (in Japanese with English abstract).

Iguchi, M., Saito, E., Tameguri, T., Triastuty, H. and Yamazaki, T., 2007. Evaluation of volcanic activity of Kuchinoerabujima in 2006., Ann. Disast. Prev. Res. Inst., Kyoto Univ., 50B, 349-358 (in Japanese with English abstract).

Iguchi, M., Nakamichi, H., Tameguri, T., Yamamoto, K., Mori, T., Ohminato, T. and Saito, E., 2017. Contribution of monitoring data to decision making for evacuation from the eruptions in 2014 and 2015 at Kuchinoerabujima volcano, Jour. Nat. Disast. Sci., (in this issue).

Japan Meteorological Agency, 2015. Kuchierabujima volcano, Coordinating Committee for Prediction of Volcanic Eruption (in Japanese).

Japan Meteorological Agency, 2016. Kuchierabujima volcano, Coordinating Committee for Prediction of Volcanic Eruption (in Japanese).

Kanda, W., Utsugi, M., Tanaka, Y., Hashimoto, T., Fujii, I., Hasenaka, T. and Shigeno, N., 2010. A heating process of Kuchi-erabu-jima volcano, Japan, as inferred from geomagnetic field variations and electrical structure, Jour. Volcanol. Geotherm. Res., 189, 158-171.

Kimata, F., Miyajima, R., Murase, M., Darwaman, D., Ito, T., Ohata, Y., Irwan, M., Takano, K., Ibrahim, F., Koyama, E., Tsuji, H., Takayama, T., Uchida, K., Okada, J., Solim, D. and Anderson, H., 2004. Ground uplift detected by precise leveling in the Ontake earthquake swarm area, central Japan in 2002-2004, Earth. Planets. Space., 56, e45-e48.

Meteorological Research Institute of Japan, 2015. Kuchierabujima volcano, Coordinating Committee for Prediction of Volcanic Eruption (in Japanese).

Mogi, K., 1958. Relations between the eruption of various volcanoes and deformations of the ground surfaces around them, Bull. Earthq. Res. Inst., 36, 99-134.

Mori, T., Morita, M., Iguchi, M. and Fukuoka Regional Headquarters, 2017. Sulfer dioxide flux monitoring using a public ferry after the 2014 eruption of Kuchinoerabujima volcano, Japan, Jour. Nat. Disast. Sci., (in this issue).

Murase, M., Kimata, F., Yamanaka, Y., Horikawa, S., Matsuhiro, K., Matsushima, T., Mori, H., Ohkura, T., Yoshikawa, S., Miyajima, R., Inoue, H., Mishima, T., Sonoda, T., Uchida, K., Yamamoto, K. and Nakamichi, H., 2016. Preparatory process preceding the 2014 eruption of Mount Ontake volcano, Japan: insights from precise leveling measurements, Earth. Planets. Space., 68, 68:9, doi:10.1186/s40623-016-0386-4.

Saito, E. and Iguchi, M., 2006. Ground deformation detection at Kuchinoerabujima volcano by continuous GPS with simple atmospheric correction, Bull. Volcanol. Soc. Japan., 51, 21-30 (in Japanese with English abstract).

Tameguri, T., Iguchi, M., Nakamichi, H. and Yamamoto, K., 2016. Disaster research of Kuchinoerabujima eruptions in 2014-2015, Ann. Disast. Prev. Res. Inst., 59A, 85-90 (in Japanese with English abstract).

Triastuty, H., Iguchi, M., Tameguri, T., 2009. Temporal change of characteristics of shallow volcano-tectonic earthquakes associated with increase in volcanic activity at Kuchinoerabujima volcano, Japan, Jour. Volcanol. Geotherm. Res., 187, 1-12.

Wessel, P. and Smith, W.H.F., 1995. New version of the Generic Mapping Tools released, EOS Trans. Amer. Geophys. Union., 76, 329.

Williams, C.A. and Wadge, G., 1998. The effects of topography on magma chamber deformation models: Application to Mt. Etna and radar interferometry, Geophys. Res. Lett., 25, 1549-1552.

Yamamoto, K., Iguchi, M., Takayama, T. and Ishihara, K., 1997. Increase in seismic activity in 1996 at Kuchierabujima volcano, Ann. Disast. Prev. Res. Inst., 40B-1, 39-47 (in Japanese with English abstract).

Yamamoto, K., Sonoda, T., Takayama, T., Ichikawa, N., Ohkura, T., Yoshikawa, S., Inoue, H, Matsushima, T., Uchida, K. and Nakamoto, M., 2013. Vertical ground deformation associated with the volcanic activity of Sakurajima volcano, Japan during 1996-2010 as revealed by repeated precise leveling surveys, Bull. Volcanol. Soc. Japan., 58, 137-151.

Yamamoto, K. and Sonoda, T., 2014. Vertical ground deformation at Kuchierabujima volcano measured by precise leveling surveys, Abstracts of 2014 Fall Meeting of Volcanological Society of Japan, P2-37 (in Japanese).