

Inflation of the Aira Caldera prior to the 1999 Eruptive Activity at Sakurajima Volcano Detected by GPS Network in South Kyushu

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Synopsis

The GPS data observed by 7 campaigns of Kyoto University and GEONET data in south Kyushu during 1996-2002 were analyzed to reveal characteristics of ground deformation caused by volcanic activity of Sakurajima. Outward radial pattern of horizontal displacement from the center of Aira caldera was detected in a circular area of 25 km radius during the successive two periods of January 1998–January 1999 and January–December 1999. Locations of the pressure sources are estimated at depths of 8-9 km beneath the Aira caldera. The intensity of the source for each period is 2×10^6 and total volume change of the source during the two years is $2 \times 10^7 \text{ m}^3$. The magma supply rate during inflation periods of 10 million cubic meters per year is in good agreement with the supply rate in typical inflation stage at Sakurajima. Temporal changes in slope distances by continuous GPS data show that the significant inflation started in December 1997 and finished in August 1999. Increase eruptive activity from October 1999 may be caused by magma intrusion as inferred by GPS observation.

Key words: GPS, pressure source, magma supply, volcanic activity

1. Introduction

Ground deformation associated with volcanic activity provides us information on location of magma reservoir or dike (Dvorak and Dzurisin, 1997), and volume of magma supplied to volcanoes (e.g., Ishihara, 1981; 1993; Delaney and McTigue, 1994). Sakurajima volcano is one of the most favorite test fields for the study of magma supply system from ground deformation observation data because of its high level activity and long history of measurements. The volcano is an andesitic stratovolcano, situated at the southern rim of Aira caldera, southern Kyushu, Japan, and has repeated flank and summit eruptions during historic times.

The last large flank eruption occurred in 1914, accompanied with remarkable subsidence around Aira caldera and at Sakurajima (Omori, 1916). By examining the pattern of depression after the eruption, some researchers proposed models of source causing

the deformation. Mogi (1958) applied a small spherical pressure source of Yamakawa (1955) and estimated the pressure source of the ground deformation located at a depth of 10 km beneath the center of Aira caldera. Composite or modified models were proposed to explain the pattern of the ground deformation (Yokoyama, 1974; 1986; Hashimoto and Tada, 1988).

In 1955, eruptive activity characterized by explosive eruption of Vulcanian type started at the summit crater of Minamidake. Yoshikawa (1961) proposed two pressure sources of Mogi model for the inflation pattern of vertical displacements and estimated that the pressure sources were located at a depth of 10 km beneath Aira caldera and a depth of 4 km beneath Sakurajima volcano. Eto and Nakamura (1986) applied the two pressure source model to subsiding vertical displacements, which started in 1974, and estimated the locations of the sources which were almost the same position as those estimated by Yoshikawa (1961).

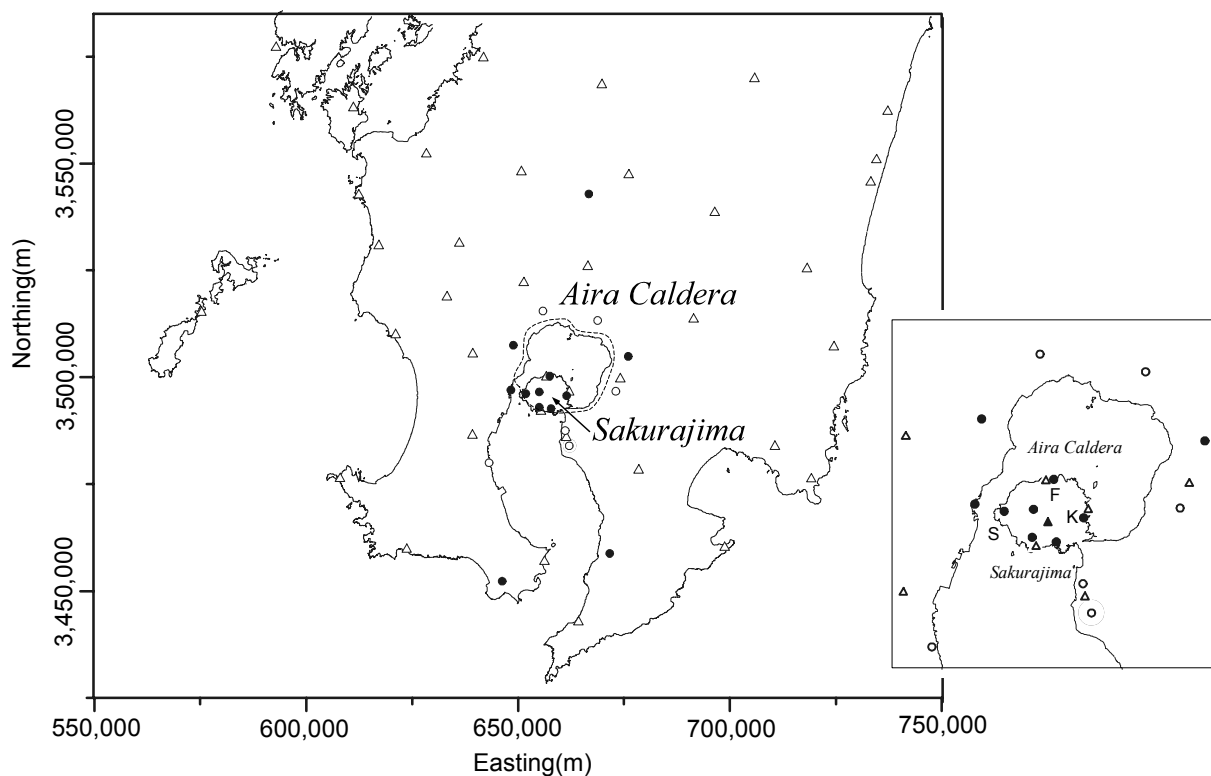


Fig. 1 Locations of GPS stations. Solid circles denote continuous GPS stations installed by Sakurajima Volcano Research Center. GPS campaigns have been repeated at stations represented by open circles. GEONET stations are shown by open triangles. Coordinate system is referred to UTM, Zone 52. Right figure shows enlargement of Sakurajima and Aira caldera. Solid triangle represents the summit crater of Sakurajima. S: SVOG, K: KURG, F: FUTG GPS station.

In 1990's, the eruptive activity of Sakurajima volcano declined. The deflative deformation turned to inflation around 1993 as measured by the EDM data (Eto et al., 1998b) and the leveling data (Eto et al., 1998a).

Sakurajima Volcano Research Center installed a GPS monitoring system in Sakurajima in 1994 and analyzed baselines with automated calculation system. By using the GPS data for the period of 1995 – 1997, Kamo et al. (1997) also detected horizontal extension of Sakurajima and located a pressure source at a depth of 5 km in northern part of Sakurajima. Iguchi and Ishihara (1999) showed that the inflation rates of Sakurajima and Aira caldera were not constant during 1995-1999, suggesting intermittent supply of magma beneath Aira caldera.

In the previous studies, horizontal displacements only in Sakurajima area were analyzed. The estimated locations of the pressure source causing horizontal displacements were somewhat different from those obtained by the precise leveling. In this paper, the GPS data obtained by temporary and continuous stations in south Kyushu are analyzed to detect an area which is

affected by the proposed pressure source beneath Aira caldera and to reveal the pattern of horizontal displacement in South Kyushu during the period from 1996 to 2002. Then, locations of pressure sources are estimated based on Mogi model and compared with those estimated by the previous studies. Finally, the inflative ground deformation prior to minor increase of eruptive activity in 1999 was discussed.

2. Data

Twelve field GPS static surveys were done by Sakurajima Volcano Research Center, Kyoto University in December 1996, May 1997, January 1998, June 1998, January 1999, June 1999, December 1999, June 2000, December 2000, June 2001, December 2001, and December 2002. Here, the data obtained in the 7 winter seasons were used to reduce the atmospheric error by assuming equal atmospheric noise level. Locations of stations used in this paper were shown in Fig. 1. Six GPS receivers (Leica SR399) were temporarily installed for 3 – 4 days in cooperation with 12 permanent GPS

stations (Leica SR299E). The measuring session length was typically 12 hours during 18:00 – 06:00 with 15 seconds sampling interval. Adding data at 29 stations of

GEONET (GPS Earth Observation Network system operated by Geographical Survey Institute), the data at 46 GPS stations were totally analyzed.

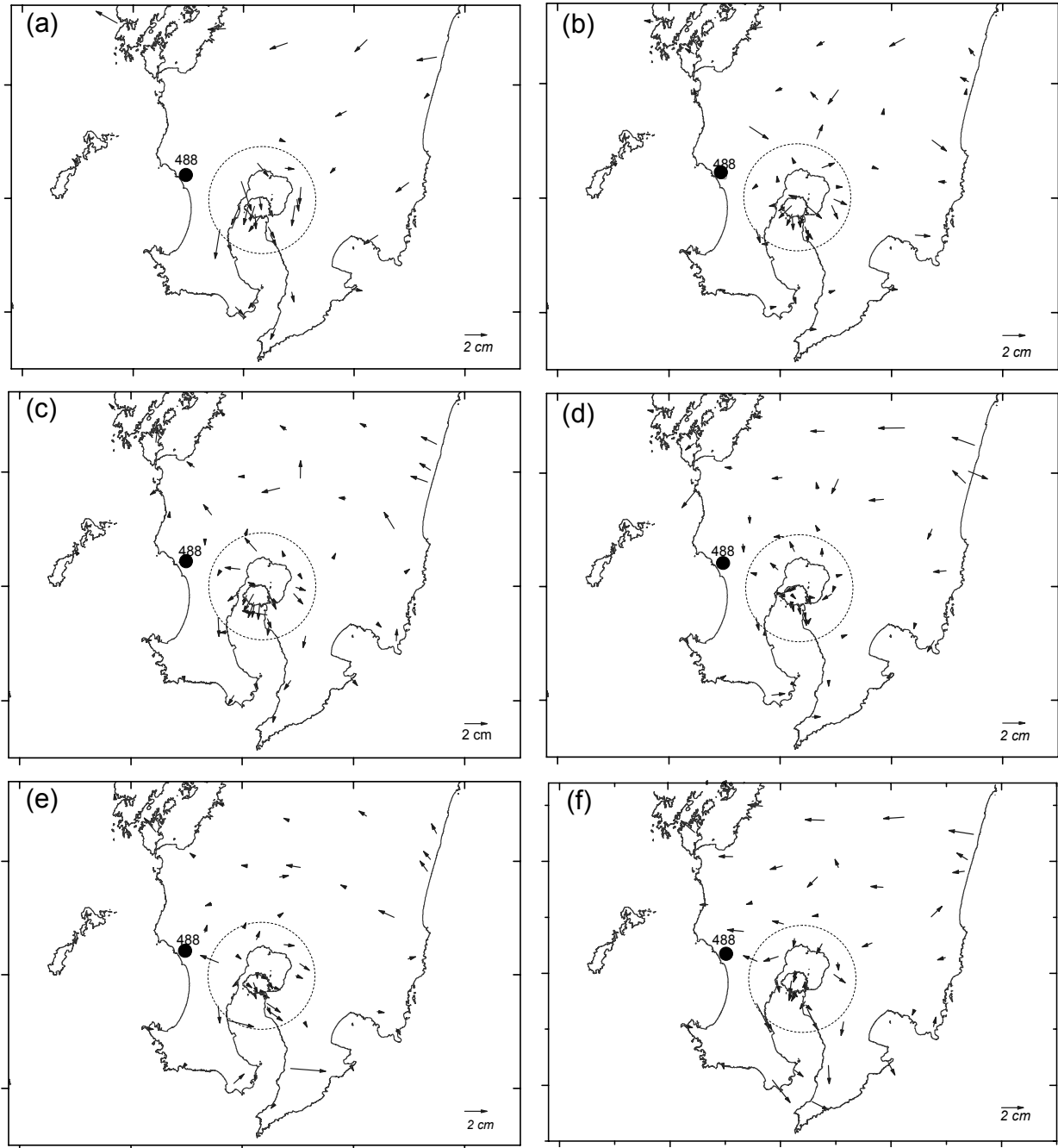


Fig. 2 Horizontal displacements. Station 0488 west of Aira caldera is used as reference, as denoted by solid circle. The area in radius of 25 km from caldera center is shown by dashed circle in each figure. (a) December 1996 – January 1998, (b) January 1998 – January 1999, (c) January – December 1999, (d) December 1999 – December 2000, (e) December 2000 – December 2001 and (f) December 2001 – December 2002.

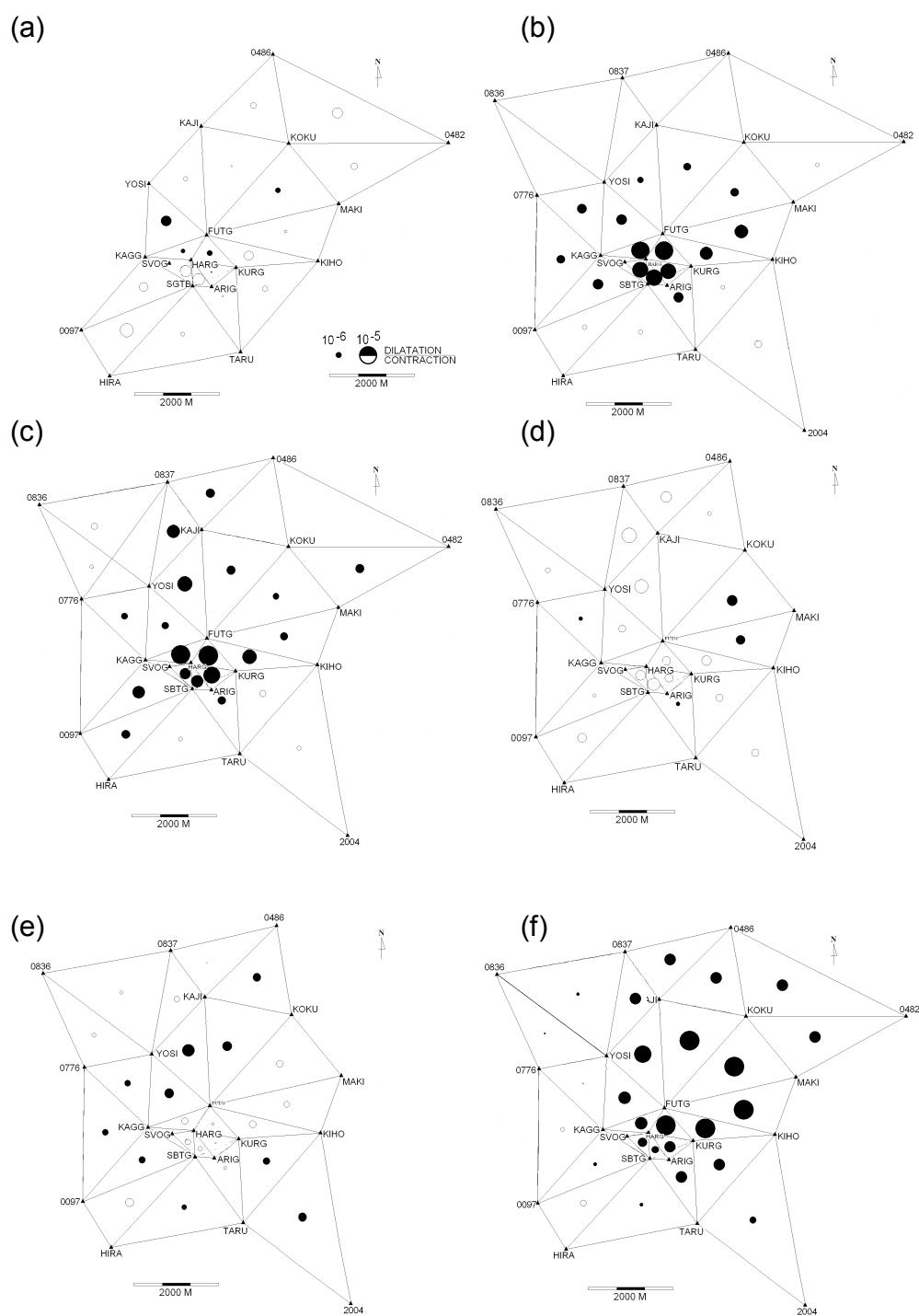


Fig. 3 Distribution of dilatation in triangulation network. (a) December 1996 - January 1998, (b) January 1998 - January 1999, (c) January - December 1999, (d) December 1999 - December 2000, (e) December 2000 - December 2001 and (f) December 2001 - December 2002. Solid and open circles represent dilatation and contraction, respectively.

The data were analyzed with SKI-Pro version 2.1, Leica Geosystems software. The station coordinates were estimated by baseline analysis, in which linear combination of the two GPS carrier phases (L1 and L2) was used with fixing ambiguities for baselines shorter than 20 km, and without fixing ambiguities (float) for baselines longer than 20 km. Precise ephemeris was retrieved in the calculation. Errors for the coordinate estimation range from 0.1 to 0.8 mm for the baselines. After all the calculations were completed, coordinate system in WGS84 was transformed into UTM, Zone 52.

3. Characteristics of ground deformation around Sakurajima and Aira Caldera

3.1 Horizontal displacement

For baseline analysis to detect horizontal displacements, GEONET station 0488 was treated as reference. Most of the stations moved to southeast in southern part of Kyushu (see Appendix). The 0488 station has the typical trend of displacement and it is sufficiently distant from Sakurajima volcano and Aira caldera, the target area in this study. Although we attempted to analyze baselines by using the other stations in South Kyushu as reference, the station 0488 provided the least errors in the baseline calculation. Horizontal displacements were obtained during the following periods; January 1996-January 1998, January 1998- January 1999, January 1999-December 1999, December 1999-December 2000, December 2000-December 2001, and December 2001-December 2002 periods (Fig.2).

The horizontal displacements in the period of December 1996-January 1998 indicate southward movements (Fig. 2a). In the period of January 1998–January 1999, an outward radial pattern of the horizontal displacement can be recognized in a circular area of approximately 25 km radius from the center of Aira caldera (Fig. 2b). During January-December 1999, the similar pattern is seen with displacements more than 2cm in Sakurajima and around Aira caldera (Fig. 2c). In the period of December 1999–December 2000, the radial pattern is also recognized, although the displacement is smaller (<1cm) than the previous ones (Fig. 2d). The horizontal displacements in December 2000–December 2001 are mostly small in the circular area of the Aira caldera (Fig. 2e) as well as in the December 2001-December 2002 period (Fig.2f). Among the 6 periods, we found the remarkable outward radial pattern of the horizontal vector in two periods, January 1998-January

1999 and January 1999-December 1999 (Figs. 2b and 2c).

Horizontal displacements in the northern part of South Kyushu have a similar pattern during whole periods, mostly indicating westward movement.

3.2 Strain

Strain components are computed in the triangulation networks according to Jaeger(1962). Dilatations in the triangulations are shown in Fig. 3. Minor contraction occurred during the period December 1996-January 1998. In the periods of January 1998-January 1999 and January 1999-December 1999, dilatations attained more than 10^{-5} in the triangulation networks in Sakurajima (Figs. 3b and 3c), and turned minor contraction in the periods December 1999-December 2000 and December 2001. In December 2001-December 2002, dilatation occurred at northern part of Aira caldera. Dilatation components are larger than maximum shear strains around Sakurajima. Principal strain axes are oriented to east-west.

4. Estimation of pressure source

Outward radial pattern of the horizontal displacement and dilatation of triangulation inside the area of Aira caldera indicated inflation of the ground Aira caldera in periods of January 1998-January 1999 and January 1999- December 1999. The locations of the sources causing the inflation for the two periods were estimated.

4.1 Method

Yamakawa (1955) calculated surface ground deformation caused by a spherical source in an ideal semi-infinite elastic crust, and Mogi (1958) applied the model to the ground deformation associated with the 1914 Sakurajima eruption and estimated the location of the pressure source. Assuming $\lambda = \mu$ (λ and μ : Lamé's constants), the horizontal displacement Δd and the vertical one Δh of the surface at a horizontal distance d from a small spherical pressure source at a depth f are expressed as follow:

$$\Delta d = \frac{3a^3P}{4\mu} \frac{d}{(d^2 + f^2)^{3/2}}, \quad (1)$$

$$\Delta h = \frac{3a^3P}{4\mu} \frac{f}{(d^2 + f^2)^{3/2}}, \quad (2)$$

where a and P denotes radius of the spherical source, and change of the hydro-static pressure in the source, respectively.

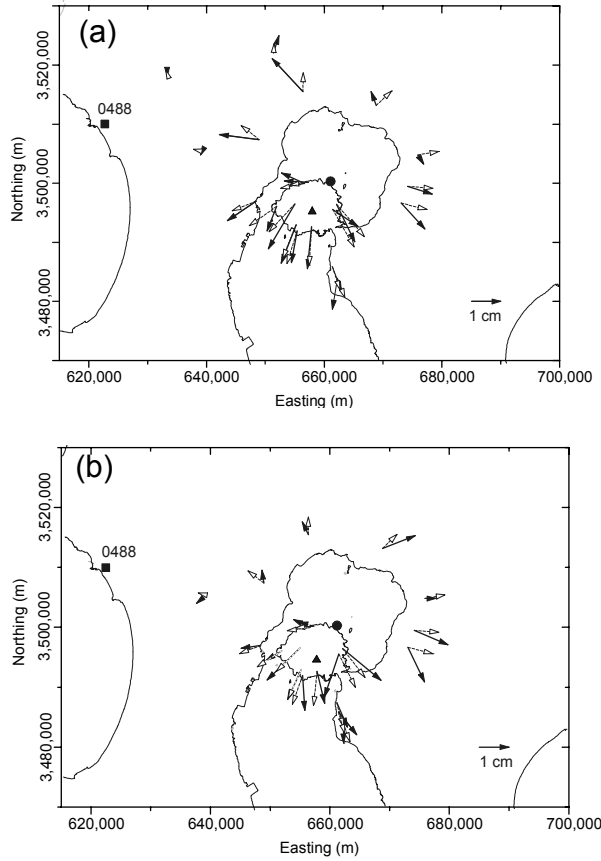


Fig. 4 Location of pressure source, (a) during the period from January 1998 to January 1999 and (b) during the period January to December 1999. Dot denotes location of the source. Bold arrows are observed horizontal displacements and dashed ones are calculated ones. Triangle and square represent the summit crater of Minamidake and reference station, respectively.

A grid search method is used to locate the pressure source. The source location is determined so as to minimize square sum of residual between the observed and the calculated horizontal displacement. Putting

$$k = \frac{3a^3 P}{4\mu},$$

Horizontal displacement Δd is simplified as:

$$\Delta d = k \frac{d}{(d^2 + f^2)^{3/2}}. \quad (3)$$

The horizontal distance of the i -th station from the source located at (x_s, y_s) is expressed as:

$$d_i = \sqrt{(y_i - y_s)^2 + (x_i - x_s)^2}. \quad (4)$$

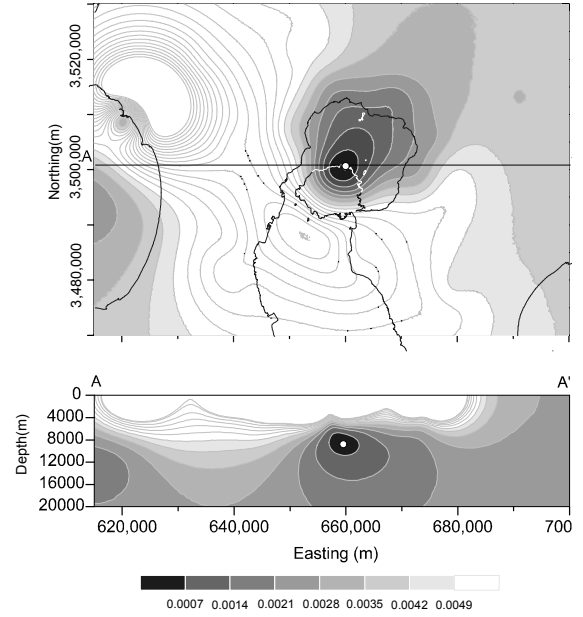


Fig.5 Spatial distribution of residual in grid search for the period of January-December 1999. Top is horizontal distribution at the depth of 8.2 km, and the bottom is vertical cross-section of A-A', which includes location giving minimum residual.

Displacement at the i -th rover station by baseline analysis is a relative displacement from a reference station. Thus the calculated displacement $\Delta \mathbf{d}_{calc,i}$ at the i -th rover station is subtracted by the displacement at the reference.

$$\begin{aligned} \Delta \mathbf{d}_{calc,i} &= \Delta \mathbf{d}_i - \Delta \mathbf{d}_{i ref} \\ &= k \left(\frac{d_i}{(d_i^2 + f^2)^{3/2}} \mathbf{e}_i - \frac{d_{ref}}{(d_{ref}^2 + f^2)^{3/2}} \mathbf{e}_{ref} \right), \quad (5) \end{aligned}$$

where $\mathbf{e}_i$ and $\mathbf{e}_{ref}$ are unit vectors directed from the source to the i -th station and the reference station, respectively, and $\mathbf{d}_i$ and $\mathbf{d}_{ref}$ are horizontal displacement vectors of the i -th station and the reference station, respectively. The $\Delta \mathbf{d}_{calc,i}$ has two components $(\Delta d_{x,i}, \Delta d_{y,i})$, and they are represented as,

$$\Delta d_{x,i} = \Delta d_i \frac{x_i - x_s}{d_i} - \Delta d_{ref} \frac{x_{ref} - x_s}{d_{ref}}, \quad (6)$$

$$\Delta d_{y,i} = \Delta d_i \frac{y_i - y_s}{d_i} - \Delta d_{ref} \frac{y_{ref} - y_s}{d_{ref}}. \quad (7)$$

Then, the squared sum R of residual is defined as follows,

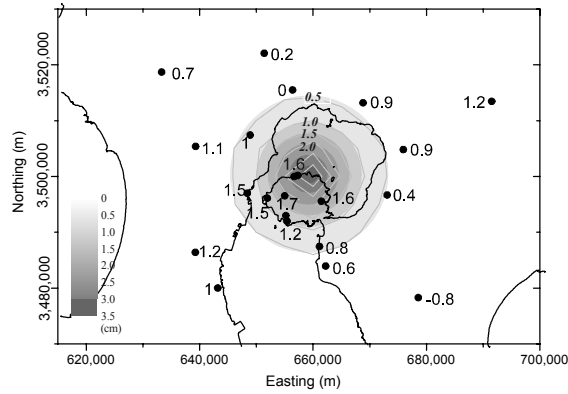


Fig.6 The vertical displacement around Aira caldera caused by spherical point source at the depth of 8.2 km. Black dots and the values denote station location and the observed vertical displacement in the period of January-December 1999, respectively. The 0488 station is fixed.

$$R = \sqrt{\sum_{i=1}^N R_{x,i}^2 + \sum_{i=1}^N R_{y,i}^2},$$

where

$$\begin{aligned} R_{x,i} &= (\Delta d_x)_{obs,i} - \Delta d_{x,i} \\ R_{y,i} &= (\Delta d_y)_{obs,i} - \Delta d_{y,i} \end{aligned} \quad (8).$$

Grid search was done to minimize R with varying parameters of intensity k and location (x_s, y_s, f) of source.

4.2 Results

Locations of pressure sources based on Mogi's model were determined for two periods, January 1998 – January 1999 and January 1999 – December 1999 when remarkable radial pattern of horizontal displacements were detected. The ranges of variable parameters are listed in Table 1. The coordinates of the sources and the values of intensity k giving minimum residual are listed in Table 2. Fig. 4 shows estimated locations of the pressure sources for the 2 periods. The pressure sources are obtained at similar location, at depths of 8.6 km and 8.2 km beneath northern part of Sakurajima, that is, near the center of Aira caldera in the period January 1998-January 1999 and January-December 1999, respectively. Intensities of sources are also similar, $2.3 \times 10^6 \text{ m}^3$ and $2.3 \times 10^6 \text{ m}^3$, respectively. Theoretical horizontal displacements are compared with observed ones. The theoretical vectors coincide with observed ones fairly well except at a few stations. Distribution of residual at grid point for the period from January to December 1999

is shown in Fig. 5. Residual are comparably small (0.0004 m) in the region of 2km radius from the best-fit location.

Table 1 Parameters of grid search.

Parameter	Range	Step
Easting	615,000 – 700,000 m	100 m
Northing	3,470,000 – 3,530,000 m	100 m
Depth	0 – 30,000 m	100 m
Intensity	$10^6 - 10^7 \text{ m}^3$	100 m^3

Table 2 Coordinates of the sources and the values of intensity k to give minimum residual

Pressure Source	Jan98-Jan99	Jan-Dec99
Easting (m)	659,600	659,200
Northing (m)	3,500,200	3,500,300
Depth (m)	8,600	8,200
Intensity ($\times 10^6 \text{ m}^3$)	2.279	2.3941
Residual ($\times 10^{-4} \text{ m}$)	4.7356	5.8645

5. Discussions

5.1 Pressure source location compared to the previous study

Using horizontal displacements by GPS, locations of pressure sources are estimated at depths 8 – 9 km beneath the center of Aira caldera. Kamo et al. (1997) estimated the pressure source at a depth of 5 km by using the GPS data only in Sakurajima. Although the measurement period was different, the wide GPS network in this study may provide better depth in source estimation. The locations of the source in this study almost coincide with those ($\approx 10 \text{ km}$) estimated from vertical displacements data (Mogi, 1958; Yoshikawa, 1961; Eto and Nakamura, 1986; Eto et al., 1998a).

5.2 Vertical displacement

Vertical displacements observed by GPS in this study are examined comparing with change in elevation difference measured by the precise leveling that was conducted at western and northern part of Sakurajima volcano. The benchmark 27 (BM27) of the precise leveling is located close to the GPS station FUTG and was uplifted by 30.4 mm referred to BM15 which is close to SVOG during the period from July 1998 to October 2001 (Yamamoto, pers. comm., unpublished data). Meanwhile, in the period of January 1998 to December 2001, FUTG was uplifted by 37 mm referred to SVOG. Considering the precision of vertical component measured by GPS, it coincides well with that measured by the precise leveling. Next, the observed vertical displacements by GPS are compared with the

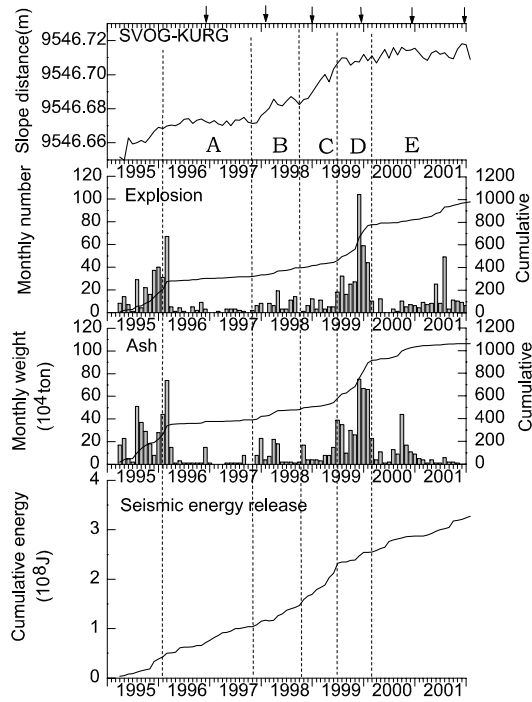


Fig.7 Temporal change of slope distance between station SVOG and KURG (top column), monthly number of explosive eruption and its cumulative change (second), monthly weight volcanic ash ejected from the summit crater and its cumulative change (third) and cumulative seismic energy released by A-type earthquake (fourth) during the period from April 1995 to December 2002. Symbols A, B, C, D, and E partitioned by vertical lines denote the periods of volcanic activity defined by deformation, eruptive and seismic activity. Arrows in the top show six GPS surveys.

theoretical ones expected by the pressure source estimated from the horizontal displacement distribution. The observed vertical displacements during the period from January 1999 and December 1999 are shown in Fig. 6. Station 0488 is fixed. During the period, the pressure source is estimated to be located at the depth of 8.2 km around northern part of Sakurajima with intensity $k = 2.4 \times 10^6 \text{ m}^3$. Contours of the uplifting by the source are also shown in Fig. 6. The center of uplift is located in northern part of Sakurajima and the measured vertical displacements coincide with those calculated from Mogi's model. The vertical displacements show consistent results with the model derived from the horizontal ones, especially with precision of 1 cm in Sakurajima area.

5.3 Volume estimation of intruded magma

Inflation of the ground of Sakurajima and Aira Caldera was detected during two periods of January 1998 – January 1999 and January 1999 to December 1999. According to Delaney and McTigue (1994), in case of Poisson's ratio of 0.25 ($\lambda = \mu$), the volume change ΔV_p is calculated as follow:

$$\Delta V_p = 1.33\pi k. \quad (9)$$

The intensities k of the source were estimated to be 2.3×10^6 and $2.4 \times 10^6 \text{ m}^3$ in the periods of January 1998 – January 1999 and January 1999 - December 1999, respectively. Consequently, the total volume change of the source during the two years was $2.0 \times 10^7 \text{ m}^3$. Sakurajima Volcano Research Center estimated total weight of volcanic ash ejected from the summit crater from distribution of ash-fall deposit in Kagoshima Prefecture (Ishihara and Eto, 1979). Weight of the ash was 5×10^6 ton during the same period. When density of Sakurajima magma is assumed to be 2500 kg/m^3 , the weight of volcanic ash corresponds to $2 \times 10^6 \text{ m}^3$ of magma in volume. It is inferred that magma of $2.2 \times 10^7 \text{ m}^3$ was supplied to the magma reservoir beneath Aira caldera during the two years. Therefore, annual rate of magma supply is $1.1 \times 10^7 \text{ m}^3$. Eto et al. (1998a) estimated annual rate of volume of magma supplied to the magma reservoir during December 1991 - October 1996 as $1 \times 10^7 \text{ m}^3$. The volumes estimated in this study during inflation periods are almost equal to those in the previous years.

5.4 Relation with the volcanic activity of Sakurajima

Although inflation was found during the period from January 1998 to December 1999, no remarkable ground deformations were detected in the period December 1996-January 1998 and after December 1999 in this study. When did the inflation start and finish? Daily slope distances have been calculated by automated GPS monitoring system at Sakurajima Volcano Research Center (Kamo et al., 1997). Monthly average of the slope distance between SVOG and KURG is shown in the top column of Fig. 7. The baseline length is relatively stable from the beginning of 1996 to November 1997. It is recognized that extension of the baseline began in December 1997 and ends in August 1999. The baseline lengths become stable after August 1999. In order to show the relationship between ground deformation and eruptive and seismic activities of Sakurajima volcano, monthly number of explosive eruption and the weight of ash ejected from the summit crater and cumulative seismic energy released by volcanic A-type earthquakes are shown in Fig. 7. Monthly number of explosions and the ejected ash began

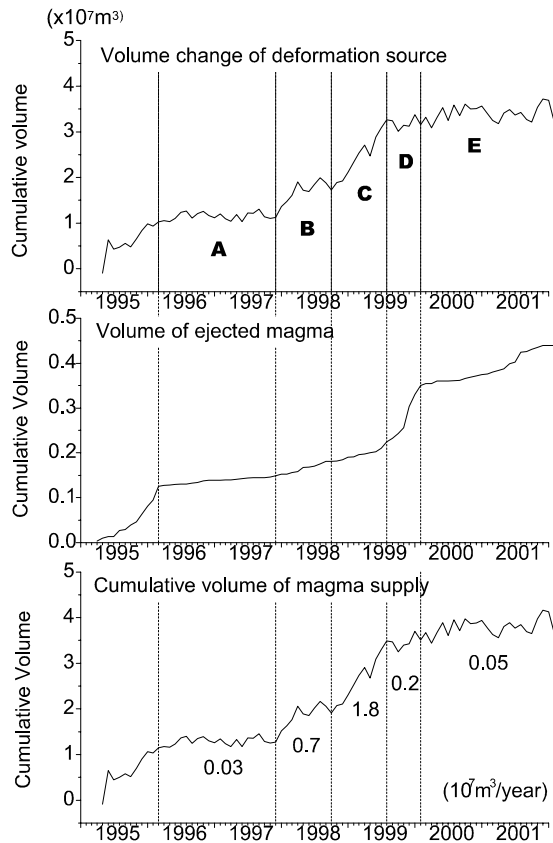


Fig. 8 Cumulative volume change of the deformation source (top), cumulative volume of ejected magma (middle) and cumulative volume of magma supply (bottom). Periods A, B, C, D, and E are the same as Fig. 7.

to increase in August 1999 when extension of the baseline terminated. Seismicity of volcanic earthquakes also corresponds well to the ground deformation. In October 1998, the seismic energy release rate increases from $4 \times 10^7 \text{ J/year}$ to $1 \times 10^8 \text{ J/year}$. With special attention to temporal change in extension rate of the slope distance, the extension rate also increases in October 1998 from 1cm/year to 2cm/year. These facts suggests that, as precursors of increase in the eruptive activity from October 1999, inflation started in December 1997 and the inflation rate increased in October 1998 accompanied by increase in seismicity of A-type earthquakes.

According to the same method as described in the section 5.3, monthly intrusion volume of magma to the magma reservoir was estimated from volume change of the deformation source and the ejected magma volume.

Monthly volume change of deformation source was calculated from temporal change in slope distance. As derived from Eqs.(1) and (9), volume change of source is proportional to horizontal displacement. During the period from January 1998 to December 1999, volume of the pressure source increased by $2.0 \times 10^7 \text{ m}^3$ and the location did not move. The slope distance between SVOG and KURG extended by 2.4cm during the same period. Therefore, the relation of volume change of the source ΔV_p with the slope distance change of SVOG-KURG L can be formulated by

$$\Delta V_p = 8.3 \times 10^6 \Delta L \quad (10)$$

Monthly intrusion volume of magma to the magma reservoir was calculated by adding volume change of the deformation source and the ejected magma volume. Fig. 8 shows cumulative volume supplied to the magma reservoir. Based on the temporal change in slope distance, eruptive activity, and seismicity of A-type earthquakes, the volcanic activity can be divided into 5 periods. Supplied volume magma and volcanic activity for each period are described as follows;

Period A. February 1996 – November 1997.

Slope distance did not change. Very few eruptions occurred and monthly weight of volcanic ash ejected from the summit crater was less than 10 ton. Magma supply rate $0.03 \times 10^7 \text{ m}^3$ is considered to be below the detection level.

Period B. December 1997 –September 1998.

Grounds of Sakurajima and Aira caldera inflated, and the eruptive activity slightly increased. Magma was supplied to the magma reservoir beneath Aira caldera at a rate of $0.7 \times 10^7 \text{ m}^3/\text{year}$.

Period C. October 1998 –July 1999. Inflation rate of the ground deformation increased, and magma supply rate increased to $1.8 \times 10^7 \text{ m}^3/\text{year}$. Seismic energy release rate of A-type earthquakes also increased. The A-type earthquakes occurred at depths 2-4km beneath the summit crater. This suggests that magma was stored in the magma reservoir beneath Aira caldera and a part of the magma migrated to the summit, accumulating stress in the rocks around the magma reservoir.

Period D. August 1999 –February 2000.

Eruptive activity reached its peak during the periods examined in this study, and volcanic ash ejected from the summit crater attained 750 thousands ton in December 1999. In contrast, inflation of the ground nearly stopped and the release rate of seismic energy turned to the normal level. It is inferred that stress in the magma reservoir and rocks around it was released by ejection of magma while eruptions.

Period E. After March 2000. No remarkable ground deformation has been detected and the ejection rate of volcanic ash has decreased compared with the previous periods. Very few amount of magma has been supplied to the magma reservoir.

At the end of 2002, ground around Aira caldera seem to be inflated a little and we need continuous slope distance data after this period to make sure this inflation is continued.

6. Conclusions

Horizontal displacements measured by 7 GPS campaigns in South Kyushu area were analyzed during inflation stage of Sakurajima volcano. The following results were obtained:

- 1) Outward radial pattern of horizontal displacement from the center of Aira caldera was detected in a circular area of 25 km radius from the center of the caldera during the period of January 1998 – December 1999.
- 2) Location of the pressure sources are estimated at depth of 8.6 km and 8.2 km beneath the Aira caldera for the periods of January 1998 – January 1999 and January 1999 – December 1999, respectively. The intensity of the source for each period is 2×10^6 , which deduces that total volume change during the two years is $2 \times 10^7 \text{ m}^3$.
- 3) Analysis of the continuous GPS monitoring data shows that the inflation started in December 1997 and finished in August 1999. High rate inflation stage in October 1998- July 1999 was accompanied with increase in seismicity of A-type earthquakes beneath the summit. The inflation appeared to occur prior to the peak of eruptive activity during August 1999 – February 2000. In conclusion, minor increase in eruptive activity in 1999 is possibly induced by the magma supply which started in December 1997 and terminated in August 1999.

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Appendix

In order to pick up characteristic pattern of horizontal displacements caused by regional stress, GEONET data and the GPS data in this study are analyzed with fixing station 0450 at Fukuoka, North Kyushu, during the period from January 1998 to

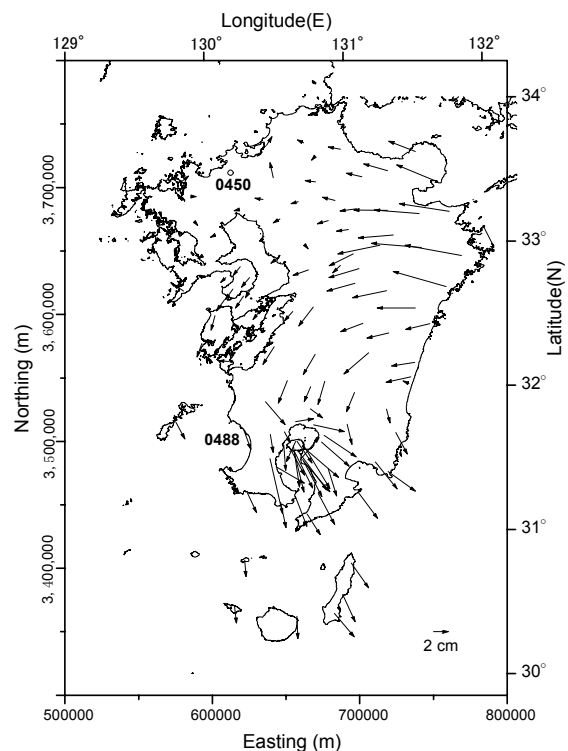


Fig. A1 Horizontal displacement fixing 0450 station in north Kyushu during the period from January 1998 to December 2001

December 2001. Fig. A1 shows the horizontal displacements. Northeastern part of Kyushu moved westward by 10cm for 4 years. The directions gradually rotate southwest in the central Kyushu and they change to southeast in South Kyushu, southern region from 32°N. Horizontal movements by 4-6cm were observed in Central and South Kyushu area. Westward movement of northeastern part of Kyushu is caused by northwest movement of Philippine Sea Plate. Southeast movement of South Kyushu is derived by back-arc spreading of Okinawa Trough (e.g., Tada, 1984; Harada and Shimura, 1979). Disturbance of regular pattern of horizontal vectors is recognized around Aira caldera. Some of them are not oriented to southeast and amount of displacements is 2-3cm.

要旨

1993年から地盤の膨張が検出されている始良カルデラおよび桜島周辺において1996年12月から約1年毎に、GPS連続観測網と連動したGPS稠密臨時観測を7回行い、南九州地域における桜島の火山活動に伴う水平変位の特徴的なパターンを明らかにすることを目的として、これらのGPSデータに国土地理院のGEONETデータを加えて解析を行った。(1)1998年1月～1999年1月および1999年1月～1999年12月の連続する2期間において、始良カルデラの中心から半径25kmの範囲内で、カルデラ外側へ向かう放射状の変位パターンが見られる。(2)単一圧力源の茂木モデルを仮定すると、観測された放射状変

位を最もよく説明する圧力源の位置は、始良カルデラ中心の深さ 8〜9km に推定される。(3)この 2 期間の圧力源における体積変化は、 $2 \times 10^7 \text{m}^3$ と推定され、山頂火口から放出された火山灰量を考慮すると $1.1 \times 10^7 \text{m}^3$ のマグマが約 1 年の各期間に圧力源へ供給されたことになる。このマグマ供給率は、桜島における典型的な地盤膨張時の供給率とほぼ一致する。(4)GPS 連続観測データに見られる斜距離の時間変化から、顕著な膨張は 1997 年 12 月に始まり、1999 年 8 月に終わったことが示された。また、基線長の急激な伸びが観測された 1998 年 10 月以降、A 型地震にも増加傾向が見られる。1999 年 8 月に膨張が止まった後は、爆発的噴火活動が顕著に増加し、1999 年 12 月にそのピークを迎える。1999 年にやや活発化した桜島火山の噴火活動は、1997 年 12 月に始まり 1999 年 8 月に終わったマグマ供給に誘発された可能性があると考えられる。

キーワード: GPS, 茂木モデル, マグマ供給システム, 火山活動