Article

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Vertical Ground Deformation Associated with the Volcanic Activity of Sakurajima Volcano, Japan during 1996–2010 as Revealed by Repeated Precise Leveling Surveys

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The recent vertical ground deformation in Sakurajima volcano and around Aira caldera associated with the volcanic activity of this volcano is revealed by the repeated precise leveling surveys conducted in October-December 2007, November 2009 and April and November 2010. The ground uplifts are detected in Sakurajima volcano and around Aira caldera to be centered in the caldera during the period from 1996 to 2010, as the previous results during the period from 1991 to 1996. From the analysis based on a spherical source (Mogi's) model, the inflation source is located at 8.8 km - 10.8 km depth with the volume change rates of $6.5–8.2 \times 10^6$ m^3/year beneath the center of Aira caldera generally through the period of 1996–2010. It is indicated that the magma storage at the inflation source inferred at 10 km depth beneath Aira caldera is progressed during the period. In the period of 2007–2009, a shallow inflation source is located at 4.3 km depth with a volume change rate of about 0.6×10^6 m^3/year beneath the northern part of Sakurajima. It suggests the magma movement towards shallow part of Sakurajima volcano from 10 km depth beneath Aira caldera, although the estimated amount of magma input is as small as about 2.0×10^6 m^3.The magma storage at the magma reservoir beneath Aira caldera has continued since around 1991 when the eruptive activity of Sakurajima volcano was gradually decayed. Explosive eruptions are increasing at Showa crater in Sakurajima volcano especially since 2009. However continuing ground uplifts are observed until November 2010. It is suggested that the amount of supplied magma overcomes that of ejected magma at the magma supply system beneath Aira caldera in spite of the increasing volcanic activity. Considering the estimated volume increase at the inflation sources and the volume of the ejected magma based on the observed amount of the ash-fall deposits, it is indicated that the total of about 1.2×10^8 m^3 magma is inferred to have additionally stored beneath Aira caldera during the period from 1991 to 2010. The ground uplift around the northern part of Sakurajima caused by the progressing magma storage at the time of November 2010 recovers and further exceeds the height level in around 1973, when the intense summit eruptions during the 1970s and the 1980s started. These results suggest the immanent potential of the next intensive eruptive activity of this volcano.

Key words: Sakurajima volcano, Aira caldera, precise leveling survey, vertical ground deformation

1. Introduction

Sakurajima volcano is an andesitic stratovolcano located in southern Kyushu, Japan (Fig. 1). It is situated on the southern rim of Aira caldera. At this volcano, the flank eruptions with the lava flows and the summit eruptions have been repeated during historic times, including the great eruption in 1914. The current eruptive activity at the summit crater of Minamidake began in 1955, which is characterized by violent explosive eruptions of a Vulcanian type, as well as the intermittent emissions of volcanic ash. In addition, the eruptive activity at Showa crater on the eastern slope of the volcano started in June 2006 and the activity has increased in recent years. The total number of explosive eruptions since 1955 exceeds 9500 in 2010.

Repeated precise leveling surveys have been conducted in and around Sakurajima volcano since 1957 (Eto, 1967; Eto *et al.*, 1997; Yoshikawa, 1961). The results suggested that the ground deformation associated with the eruptive

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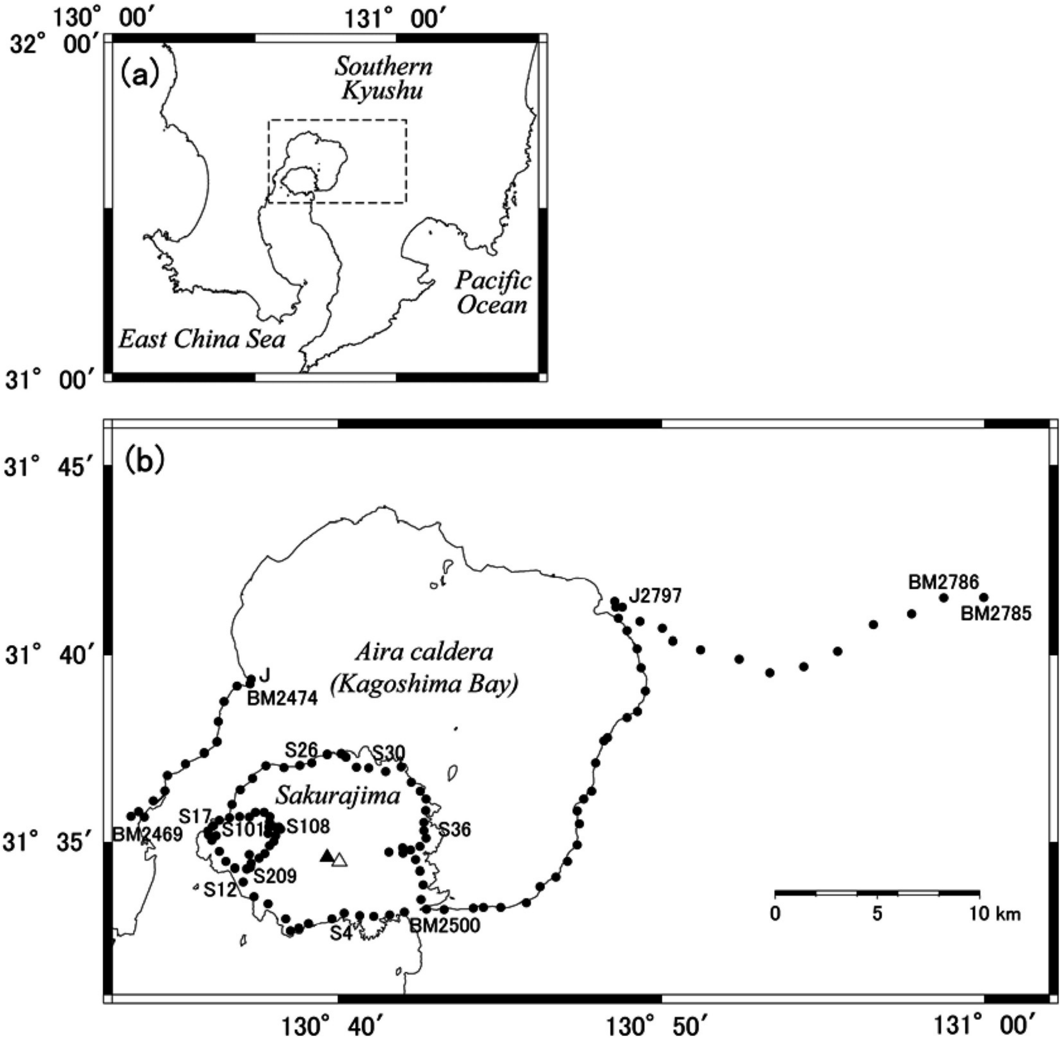

Fig. 1. (a) Location map of Sakurajima volcano. Dashed box indicates the area shown in (b). (b) Leveling bench marks measured in this study (solid circles). Solid and open triangles indicate the locations of the active summit and Showa craters of Sakurajima volcano, respectively.

activity reflects the phenomena of magma storage and/or ejection at the deep primary magma reservoir inferred at about 10 km depth beneath Aira caldera and at the secondary one inferred at about 3 km depth beneath Sakurajima volcano (Eto, 1989). The ground subsidence around the northern and the central parts of Sakurajima had continued due to the pressure decrease both at the primary and the secondary magma reservoirs associated with the intense eruptive activity since 1973. The ground around the northern part of Sakurajima was observed to be uplifted when the eruptive activity of Sakurajima volcano was gradually decayed since around 1991–1996 (Eto *et al.*, 1997).

We conducted the repeated precise leveling surveys in Sakurajima volcano and around Aira caldera in 2007, 2009 and 2010. In this paper, we discuss the recent vertical ground deformation associated with the volcanic activity of this volcano.

2. Description of the leveling surveys

In Table 1, the descriptions of our leveling surveys, including measured leveling routes, conducting organizations and used leveling equipments are summarized. The leveling routes measured in the October-December 2007 survey are about 98 km long in total (Table 1 and Fig. 1b). The leveling surveys were conducted by the Geographical Survey Institute[1] (GSI) and by the joint university team (Yamamoto *et al.*, 2008).

Table 1. List of leveling surveys.

Period	Routes	Organizations	Equipments
Oct.-Dec., 2007	Sakurajima coast route*1 Sakurajima western flank route*2 Kagoshima Bay eastern coast route*3 Soo route*4	Kyoto University Kyushu University Geographical Survey Institute	Wild NA3003, NA3000 and GPCL3 Zeiss DiNi12 and LD13
Nov., 2009	Sakurajima coast route*1 Sakurajima western flank route*2 Kagoshima Bay western coast route (11 km long: BM.2469 - BM.2474 - BM.J)	Kyoto University Kyushu University	Wild NA3003, NA3000 and GPCL3
Apr., 2010	Sakurajima coast route (12 km long: BM.S.17 - BM.S.30) Sakurajima western flank route (5 km long: BM.S.101 - BM.S.108)	Kyoto University Kyushu University	Wild NA3003, NA3000 and GPCL3
Nov., 2010	Sakurajima coast route*1 Sakurajima western flank route*2	Kyoto University Kyushu University	Wild NA3003, NA3000 and GPCL3

Sakurajima coast route*1 (37 km long: BM.S.17 - BM.S.26 - BM.S.36 - BM.S.4 - BM.S.17)
Sakurajima western flank route*2 (11 km long: BM.S.101 - BM.S.108 - BM.S.209)
Kagoshima Bay eastern coast route*3 (25km long: BM.2500 - BM.J.2797)
Soo route*4 (25 km long: BM.J.2797 - BM.2785)

In the November 2009, April 2010 and November 2010 surveys, Sakurajima coast route and Sakurajima western flank route were repeatedly measured by the joint university team (Table 1 and Fig. 1b). In addition, we measured Kagoshima Bay western coast route in the November 2009 survey (Yamamoto *et al.*, 2010). In the November 2010 survey, a new leveling route of about 8 km long was constructed around the northern flank of this volcano (not shown in Table 1 and Fig. 1b) and was also measured. The vertical displacements along this new route will be obtained at the next survey.

The leveling instruments used in these surveys were digital levels (Wild NA3003 and NA3000) and Invar bar coded leveling staffs (Wild GPCL3) for the measurements by the university team and a digital level (Zeiss DiNi12) and Invar bar coded staffs (Zeiss LD13) for the 2007 measurements by GSI. We conducted the precise leveling surveys, so as to keep the difference error of double-run below the allowable limit of $2.5\times L^{1/2}$ mm and to keep also the closed error of the level-circuit within $2.0\times S^{1/2}$ mm if the leveling route is closed, where L is the distance in kilometers along the leveling route between the measured two bench marks and S is that of the level-circuit. The horizontality of the line of sight of levels and circular level of the leveling staffs were checked and adjusted before each survey, in order to decrease the measurement errors. As a result, mean square errors of the surveys were achieved with a good accuracy as the range from ±0.30 to ±0.62 mm/km (Table s 2, 3, 4 and 5).

[1] English appellation of the GSI is changed to Geospatial Information Authority of Japan, from 1 April 2010.

3. Results of the leveling surveys

From the data obtained in each leveling survey, we calculated the relative height of each bench mark referred to the reference bench mark BM.S.17 which is located at the western coast of Sakurajima (Tables 2, 3 and 4), except for Kagoshima Bay western coast route where the reference bench mark is BM.2469 located in Kagoshima city to the west of Sakurajima (Table 5). We measured Sakurajima western flank route in the November 2009 survey, but only the relative heights of bench marks between BM.S.101 and BM.OBS are shown in Table 3 and are discussed here due to the large measurement errors. The calculated relative heights of the bench marks were then compared with those of the previous surveys, resulting in the relative vertical displacements of the bench marks between the corresponding surveys.

3–1 Vertical displacements during the period from 1996 to 2007

Fig. 2 represents the relative vertical displacements of the bench marks during the period from October 1996 to October–December 2007, where the 1996 data are taken from Eto *et al.* (1997) and partly (from BM.J.2797 to BM. 2785) from the 1997 survey results conducted by GSI. In

Table 2. Relative heights of bench marks along Sakurajima coast route referred to BM.S.17 which is located at the western coast of Sakurajima. Asterisk shows replaced bench marks.

Bench Mark No.	Latitude (°N)	Longitude (°E)	Oct.-Dec.,2007 (m)	Nov.,2009 (m)	Apr.,2010 (m)	Nov.,2010 (m)
S.17	31.5941	130.5994	0.0000	0.0000	0.0000	0.0000
S.18	31.5968	130.6030	0.7028	0.7021	0.7020	0.7026
S.19	31.5979	130.6082	4.0359	4.0347	4.0347	4.0373
S.20	31.6045	130.6100	1.8928	1.8933	1.8942	1.8973
S.21	31.6103	130.6138	2.7344*	2.7364	2.7381	2.7415
S.22	31.6154	130.6201	1.1368*	1.1399	1.1429	1.1462
S.23	31.6209	130.6269	2.1321	2.1356	2.1402	2.1431
S.24	31.6202	130.6363	3.6736	3.6791	3.6835	3.6853
S.25	31.6211	130.6444	6.1798	6.1854	6.1910	6.2427*
S.26	31.6223	130.6505	1.7197	1.7265	1.7332	1.7347
S.26'	31.6258	130.6585	1.8954	1.9019	1.9088	1.9108
S.27	31.6262	130.6659	2.0161	2.0226	2.0297	2.0327
S.28	31.6248	130.6683	13.1964*	13.2029	13.2106	13.2131
S.28'	31.6204	130.6736	62.2881	62.2942	62.3018	62.3025
S.29	31.6200	130.6798	86.1038*	86.1092	86.1166	86.1187
S.30	31.6185	130.6887	77.8672	77.8697	77.8772	77.8802
S.31	31.6205	130.6968	28.5579	28.5586		28.5702
S.32	31.6142	130.7017	11.1119	11.1099		11.1192
S.33	31.6096	130.7066	35.9496	35.9478		35.9545
S.34	31.6065	130.7096	19.0574	19.0537		19.0583
S.35	31.6003	130.7087	46.2843*	46.2761		46.2806
S.36	31.5919	130.7086	27.0716	27.0564		27.0577
S.36'	31.5888	130.7095	48.5310	48.5154		48.5170
S.37	31.5851	130.7063	33.4896	33.4793		33.4813
S.38	31.5791	130.7040	73.4871*	73.4829		73.4869
S.39	31.5744	130.7064	54.7339	54.7272		54.7305
S.40	31.5682	130.7080	38.2158*	38.2142		38.2179
S.41	31.5619	130.7077	42.6088*	42.6063		42.6102
S.42	31.5577	130.7039	-	31.8362*		31.8391
BM.2500	31.5562	130.6984	21.2821	21.2800		21.2829
S.1	31.5549	130.6908	40.5569	40.5550		40.5571
S.2	31.5542	130.6826	47.8287	47.8231		47.8262
S.3	31.5546	130.6753	53.9868	53.9794		53.9815
S.4	31.5552	130.6671	28.3440	28.3370		28.3393
S.6	31.5532	130.6614	23.3880	23.3799		23.3811
S.7	31.5511	130.6490	32.7513	32.7465		32.7475
S.7'	31.5491	130.6439	51.2615	51.2592		51.2597
S.8	31.5479	130.6396	66.0404*	66.0383		66.0386
S.9	31.5532	130.6372	44.2037	44.2020		44.2024
S.10	31.5599	130.6280	37.3792	37.3780		37.3787
S.11	31.5631	130.6207	15.7052	15.7037		15.7038
S.12	31.5689	130.6154	18.5696	18.5688		18.5688
S.13	31.5757	130.6108	8.2779	8.2783		8.2788
S.13-1	31.5785	130.6062	30.0094	30.0093		30.0086
S.14-1	31.5830	130.6029	34.3054	34.3038		34.3037
S.15-1	31.5875	130.5996	18.3718	18.3702		18.3708
S.16	31.5918	130.5969	2.8043	2.8027		2.8027
Closed error (mm)			-1.9	-0.6		2.5
Mean square error (mm / km)			±0.45	±0.38	±0.54	±0.43

Table 3. Relative heights of bench marks along Sakurajima western flank route referred to BM.S. 17 which is located at the western coast of Sakurajima. Asterisk shows replaced bench marks.

Bench Mark No.	Latitude (°N)	Longitude (°E)	Oct.-Dec.,2007 (m)	Nov.,2009 (m)	Apr.,2010 (m)	Nov.,2010 (m)
S.17	31.5941	130.5994	0.0000	0.0000	0.0000	0.0000
S.101	31.5985	130.6135	27.4336*	27.4320	27.4308	27.4346
S.102	31.5983	130.6179	56.6256*	56.6247	56.6234	56.6269
S.103	31.6003	130.6219	92.0678	92.0683	92.0685	92.0715
S.103'	31.6003	130.6261	144.2994	144.2990	144.3004	144.3029
S.104	31.5984	130.6290	182.7510	182.7500	182.7523	182.7536
S.105	31.5965	130.6289	212.0841*	212.0821	212.0847	212.0862
S.105'	31.5937	130.6284	252.0355	252.0325	252.0352	252.0358
S.106	31.5909	130.6281	281.2413	281.2369	281.2394	281.2398
S.107	31.5945	130.6322	340.0369*	340.0329	340.0361	340.0358
S.108	31.5927	130.6345	384.5472	384.5390	384.5412	384.5409
BM.OBS	31.5937	130.6336	405.3050	405.2984	405.3010	405.3011
S.201	31.5899	130.6320	342.9216*	342.9114		
S.202	31.5873	130.6313	298.0597*	298.0509		
S.203	31.5854	130.6288	257.8796*	257.8736		
S.204	31.5814	130.6267	218.0223	218.0169		
S.205	31.5800	130.6234	189.1680	189.1619		
S.206	31.5814	130.6183	163.9075	163.9025		
S.207	31.5777	130.6193	115.7694	115.7655		
S.208	31.5760	130.6189	81.4187	81.4139		
S.209	31.5752	130.6171	46.5392	46.5339		
Closed error (mm)			3.4	-0.9		
Mean square error (mm / km)			±0.50	±0.36	±0.57	±0.41

this figure, the vertical displacements during the period from December 1991 to October 1996 (Eto *et al.*, 1997) are also plotted for comparison (Figs. 2a and 2b). The resultant displacements inside Sakurajima (Fig. 2c) indicate the ground uplift at the northern part of Sakurajima, similar to those observed during 1991-1996 (Fig. 2a). We make clear that the amount of the ground uplift is increasing towards the center of Aira caldera in the displacements outside Sakurajima (Fig. 2e), especially between the bench marks of BM.J.2797 and BM.2785. The total amount of the maximum uplift at the northern part of Sakurajima during 1996-2007 is as much as about 14 cm referred to BM.2785, which is located the farther (about 30 km) apart from the center of Aira caldera. The uplift is thought to reflect the inflation of the deep primary magma reservoir beneath Aira caldera, suggesting that the magma storage at the deep primary magma reservoir is progressed during the study period. Eto *et al.* (1997) pointed out that the magma storage began since around 1993 when the eruptive activity at the summit crater of Sakurajima volcano was gradually decayed. On the other hand, the localized subsidence is seen around the bench marks of BM.S.36, BM.S.4 and BM.S.12 both in Figs. 2a and 2c (shaded zones in figures). The cause of this subsidence is thought to be the ground compaction due to the gravitational loading of the East Showa lava flow, the South Showa lava flow and the artificial mound from the lahar deposits, respectively (Eto *et al.*, 1997). Thus the ground subsidence is thought to be the phenomena which does not relate to the volcanic activity. The resultant displacements of the Sakurajima western flank route (Fig. 2d) are relatively small compared with those of the Sakurajima coast route (Fig. 2c).

3-2 Vertical displacements during the period from 2007 to 2010

Fig. 3 displays the relative vertical displacements of the bench marks during the periods from October-December 2007 through November 2009 and April 2010 to November 2010. The resultant displacements of the Sakurajima coast route during the period from October-December 2007 to November 2009 (Fig. 3a) indicate the ground uplift at the northern part of Sakurajima, similar to those observed during 1991-1996 (Fig. 2a) and 1996-2007 (Fig. 2c). However, the amount of uplift at the northern part of Sakurajima during this period is about 7 mm referred to BM.S.17, indicating that the uplift velocity was smaller than the half of those in previous periods. The localized subsidence, especially seen around BM.S.36 in Fig. 3a, seems relatively larger during this period compared with that measured in the previous periods. The resultant displacements of the Sakurajima western flank route (Fig. 3b) show the ground subsidence near the central part of this volcano.

Table 4. Relative heights of bench marks along Kagoshima Bay eastern coast route and Soo route referred to BM. S.17 which is located at the western coast of Sakurajima. Asterisk shows replaced bench marks.

Bench No.	Latitude (°N)	Longitude (°E)	Oct.-Dec.,2007 (m)
BM.2500	31.5562	130.6984	21.2821
K.01	31.5575	130.7097	8.3314*
BM.2499	31.5573	130.7189	7.4428
SF.2392	31.5579	130.7339	2.8167
BM.2498	31.5582	130.7390	2.5937
K.02	31.5582	130.7480	3.4008
BM.2497	31.5603	130.7613	3.9011
K.03	31.5675	130.7682	6.4989
BM.2496	31.5718	130.7765	6.1939
K.04	31.5785	130.7824	4.5666*
BM.2495	31.5858	130.7874	2.4955*
K.05	31.5952	130.7886	4.6791
BM.2494	31.6009	130.7874	2.6582
K.06	31.6062	130.7909	6.3708
SF.2393	31.6097	130.7949	6.2619
BM.2493	31.6238	130.7978	3.0754
K.08	31.6318	130.8012	4.2861
BM.2492	31.6332	130.8030	6.0749
K.09	31.6422	130.8132	4.0677
BM.2491	31.6449	130.8186	3.8495
K.11	31.6539	130.8225	1.1551*
BM.2490	31.6643	130.8204	1.8096
K.12	31.6726	130.8182	0.6448*
BM.2489	31.6805	130.8131	0.3588
K.13	31.6860	130.8086	18.2639
K.14	31.6909	130.8074	67.2212
J.2797	31.6909	130.8107	86.1057
BM.2796	31.6846	130.8198	162.1174
BM.2795	31.6816	130.8314	251.6041
BM.2794	31.6760	130.8368	334.8152
BM.2793	31.6722	130.8511	378.4260
BM.2792	31.6681	130.8710	365.5474
BM.2791	31.6620	130.8867	309.2557
BM.2790	31.6648	130.9043	299.2046
BM.2789	31.6715	130.9217	289.7993
BM.2788	31.6832	130.9402	290.9085
BM.2787	31.6879	130.9599	272.1631
BM.2786	31.6951	130.9763	239.6090
BM.2785	31.6952	130.9970	228.9219
Mean square error (mm / km)			±0.62

Table 5. Relative heights of bench marks along Kagoshima Bay western coast route referred to BM.2469 located in Kagoshima city to the west of Sakurajima. Asterisk shows replaced bench marks.

Bench Mark No.	Latitude (°N)	Longitude (°E)	Nov.,2009 (m)
BM.2469	31.5985	130.5573	0.0000*
BM.C	31.6005	130.5613	-0.9931*
BM.D	31.6053	130.5689	0.3952*
BM.2470	31.6099	130.5748	4.5719
BM.E	31.6167	130.5762	-0.0426*
BM.2471	31.6217	130.5855	6.7518
BM.G	31.6265	130.5952	6.0365
BM.2472	31.6313	130.6017	5.6855
BM.H	31.6404	130.6024	7.2405
BM.2473	31.6492	130.6054	2.5295
BM.I	31.6561	130.6120	4.6685
BM.2474	31.6571	130.6188	5.3114
BM.J	31.6591	130.6193	7.7571
Mean square error (mm / km)			±0.30

One explanation of the cause of this subsidence is that it reflects the deflation of the magma reservoir that is located beneath the summit crater, caused by the recent increase of the volume of the ejected magma associated with the eruptive activity at the summit and Showa craters. However we also suspect the cause partly by other effects such as artificial and/or natural mound from the lahar deposits, especially around BM.S.108.

We can find that the resultant displacements of the Sakurajima coast route during the period from November 2009 to November 2010 (Fig. 3c) also show the ground uplift at the northern part of Sakurajima. The amount of uplift at the northern part of Sakurajima during this period is about 11 mm referred to BM.S.17 and we can also find that the most of the uplift occurs during the period from November 2009 to April 2010. The uplift velocity during the period of November 2009–April 2010 is estimated to be larger than the twice of those in 1991–1996 (Fig. 2a) which is thought to be typical during the inflation stage of Aira caldera, while it decreased during the period of April–November 2010. It is suggested that the magma storage at the deep primary magma reservoir is rapidly progressed especially during the period of November 2009–April 2010. The resultant displacements of the part in the Sakurajima western flank route (Fig. 3d) are relatively small compared with those of the Sakurajima coast route (Fig. 3c) but show the slight ground uplift near the central part of this volcano during the period of November 2009–April 2010.

4. Discussion

4-1 Analysis based on Mogi's model and magma supply rates

The relative vertical displacements during the period from 1996 to 2007 are analyzed in the same method as Eto *et al.* (1997) based on a spherical source model (Mogi, 1958), in order to calculate the locations and the volume changes of one or two pressure sources. In the calculation, the relative vertical displacement data of the bench marks troubled during the study period and those observed the localized subsidence (around BM.S.36, BM.S.4 and BM.S.

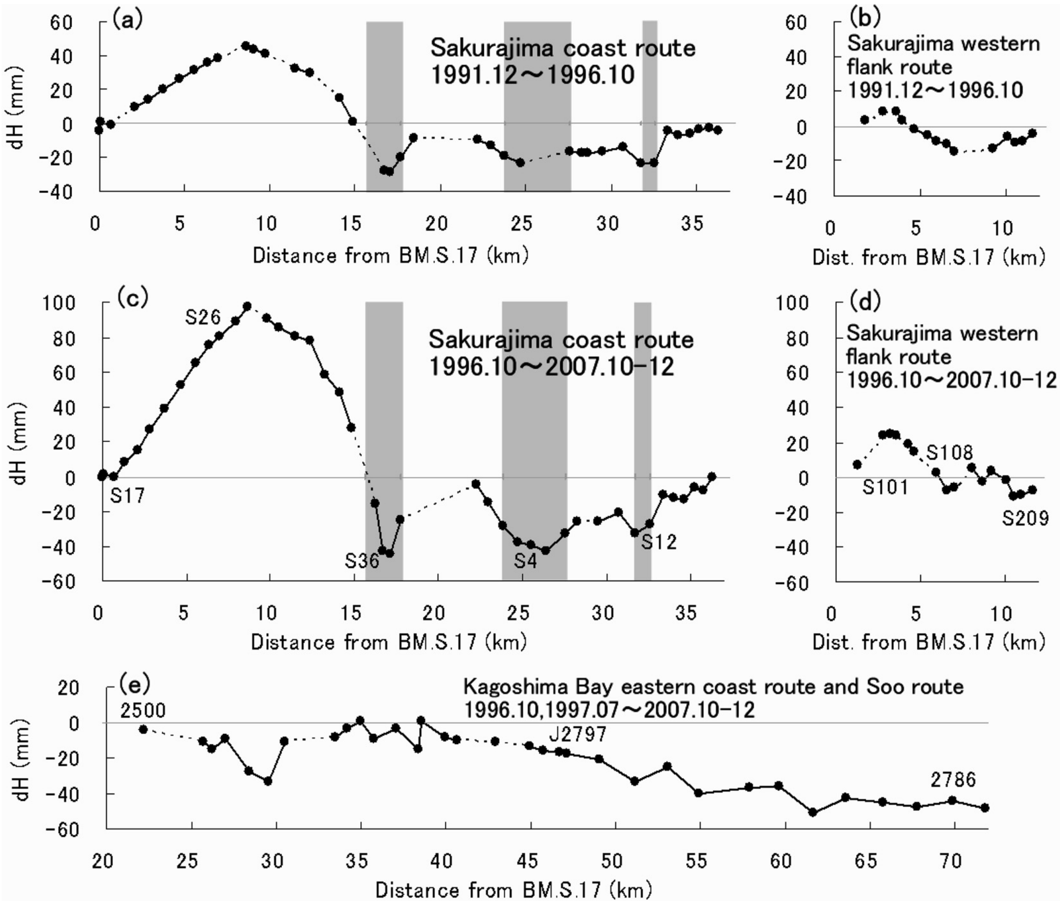

Fig. 2. Vertical displacements of the bench marks in Sakurajima volcano and around Aira caldera referred to BM.S.17 which is located at the western coast of Sakurajima. Shaded zones represent the regions where the localized subsidence is seen (see text). (a) and (b): Sakurajima coast route and Sakurajima western flank route, respectively during the period from December 1991 to October 1996 (Eto *et al.*, 1997); (c) and (d): Sakurajima coast route and Sakurajima western flank route, respectively during the period from October 1996 to October-December 2007; (e): Kagoshima Bay eastern coast route and Soo route during the period from October 1996, July 1997 to October-December 2007.

12) are eliminated. The results of the pressure source calculation are summarized in Table 6, in which those during the period 1991-1996 (Eto *et al.*, 1997) are also shown for comparison.

The inflation source is located beneath the center of Aira caldera (source A in Table 6) while the pressure source beneath the center of Sakurajima (source B in Table 6) cannot be found from the calculation, similar to the results obtained in the previous period of 1991-1996. The location of the calculated pressure source and the comparison between the measured and the theoretical vertical displacements are displayed in Fig. 4, in which the theoretical curve deduced from one inflation source accounts for the observed data fairly well. The estimated volume increase at the pressure source during the period 1996-2007 is about 7.2×10^{7} m^3 (i.e., 6.5×10^{6} m^3/year) (Table 6).

At Sakurajima volcano, monthly amounts of volcanic ash ejected by the summit eruptions have been estimated since 1978 (Eto, 1988). In the estimation, the empirical equations as a distribution function of ash-fall deposits are determined by using the observed monthly amount of ash-fall deposits at monitoring stations around the volcano and the integrations of the empirical equations result in the monthly mass of ash-fall deposits. The amounts of ejected ash-fall deposits have been compared with the deformation volumes calculated from the leveling data in order to evaluate the amounts of supplied magma at the magma reservoirs (Eto *et al.*, 1997).

Hereinafter, the similar discussion is made with the results during the period 1996-2007. The amount of the

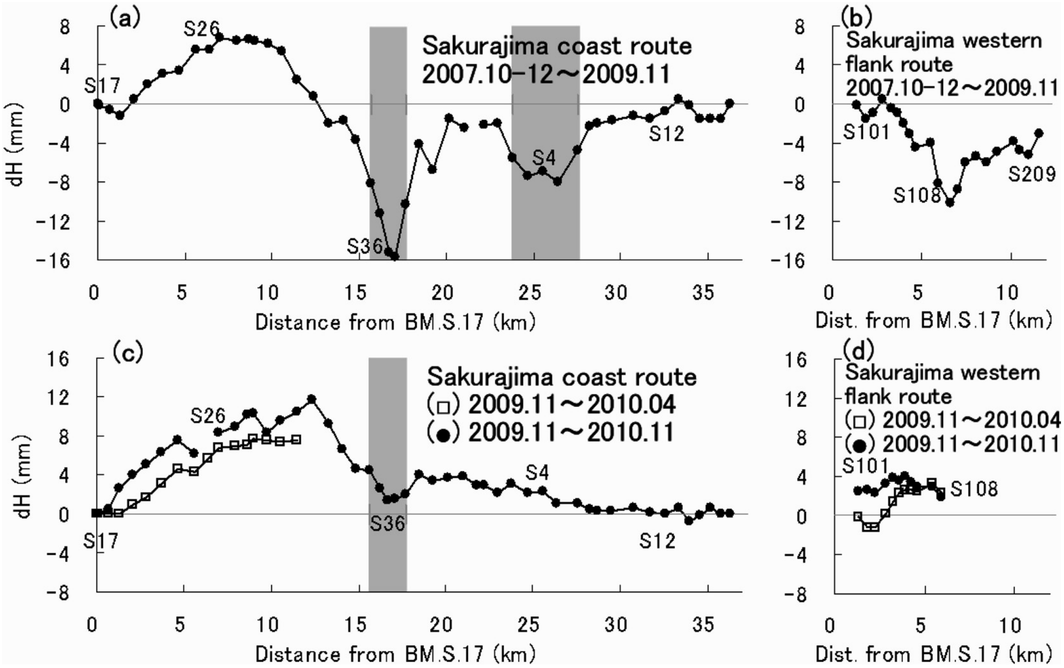

Fig. 3. Vertical displacements of the bench marks in Sakurajima volcano referred to BM.S.17 which is located at the western coast of Sakurajima. Shaded zones represent the regions where the localized subsidence is seen (see text). (a) and (b): Sakurajima coast route and Sakurajima western flank route, respectively during the period from October-December 2007 to November 2009; (c) and (d): Sakurajima coast route and Sakurajima western flank route, respectively during the period from November 2009 through April 2010 to November 2010.

Table 6. Results of the pressure source calculation. A and B: pressure sources beneath the center of Aira caldera and beneath the center of Sakurajima, respectively. X and Y: horizontal position of the pressure source, where the origin of the X,Y coordinates is at the center of the summit crater of Sakurajima volcano. Z: depth of the pressure source. Uzo is the vertical displacement above the pressure source. ΔVp is the deformation volume at the pressure source.

Leveling survey intervals	Dec.1991 ~ Oct.1996 (Eto et al., 1997)	Oct.1996 ~ Oct.-Dec.2007 (This study)	Oct.-Dec.2007 ~ Nov.2009 (This study)		Nov.2009 ~ Nov.2010 (This study)
Source	A	A	A	B	A
X (km)	0.4	1.8	-0.4	-1.6	2.9
Y (km)	9.0	9.7	3.2	0.6	8.1
Z (km)	9.5	8.8	4.3	1.5	10.8
Uzo (mm)	+102.7	+220.5	+13.7	-22.1	+16.9
ΔVp (m^3)	$+3.9\times10^7$	$+7.2\times10^7$	$+1.1\times10^6$	-2.1×10^5	$+8.2\times10^6$

ejected magma (where the density of magma is assumed to be 2.5 g/cm^3) based on the observed amount of the ash-fall deposits during the period 1996–2007 is estimated as about 2.8×10^6 m^3. Combined with the calculated volume increase at the pressure source, the total of about 7.5×10^7 m^3 magma is inferred to be supplied into the deep primary magma reservoir beneath Aira caldera. This amount corresponds to about 6.8×10^6 m^3/year of the average magma supply rate. The magma supply rate during the period of 1991–1996 was estimated as about 1.0×10^7 m^3/year (Eto *et al.*, 1997) and was equivalent to the typical average supply rate that had been investigated from the ground deformation in the non-eruptive period of 1919–1932 (Ishihara, 1981). In the period of 1996–2007, the magma supply rate is inferred to become slightly smaller than that in the previous period, or the typical average rate, suggesting that the almost ordinary but slightly smaller rate magma supplying process has been continued at the magma reservoir beneath Aira caldera.

Although the relative vertical displacements are avail-

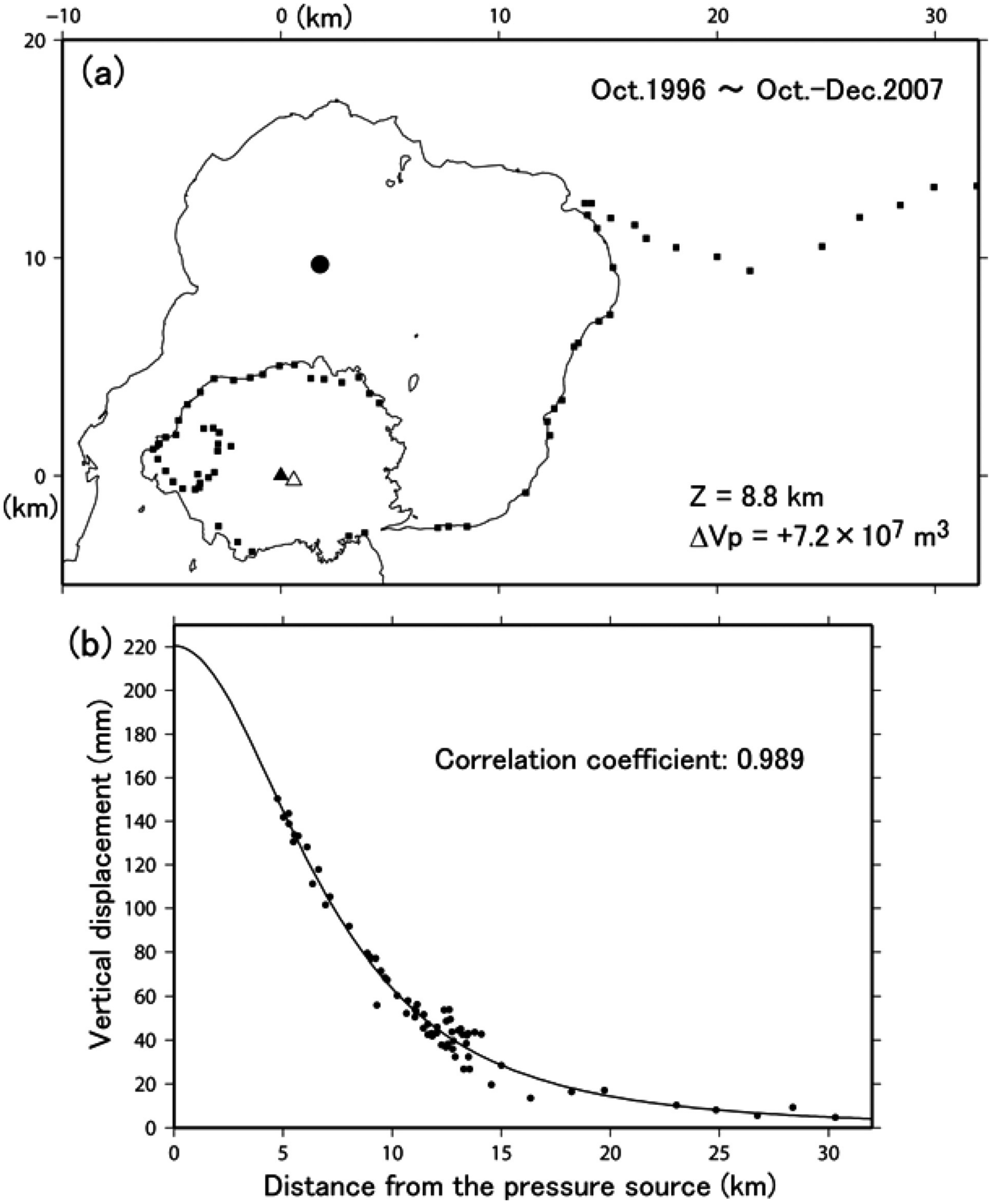

Fig. 4. (a) Horizontal location of the calculated pressure source (solid circle) by using the relative vertical displacement data during the period from 1996 to 2007. Z and ΔVp represent the depth and the deformation volume at the pressure source, respectively. Solid rectangles denote the bench marks used for the calculation. Solid and open triangles indicate the locations of the summit and Showa craters, respectively. (b) Comparison between measured vertical displacements (solid circles) and theoretical vertical displacements (solid line) versus radial distance from the pressure source.

able only in Sakurajima during 2007–2010, and the obtained displacements are as small as of about millimeter order, we also tried the pressure source calculations based on a spherical source model. The data of the bench marks troubled during the study periods and those observed the localized subsidence are also eliminated from the calculations. The results of the pressure source calculations are summarized in Table 6 and are displayed in Fig. 5.

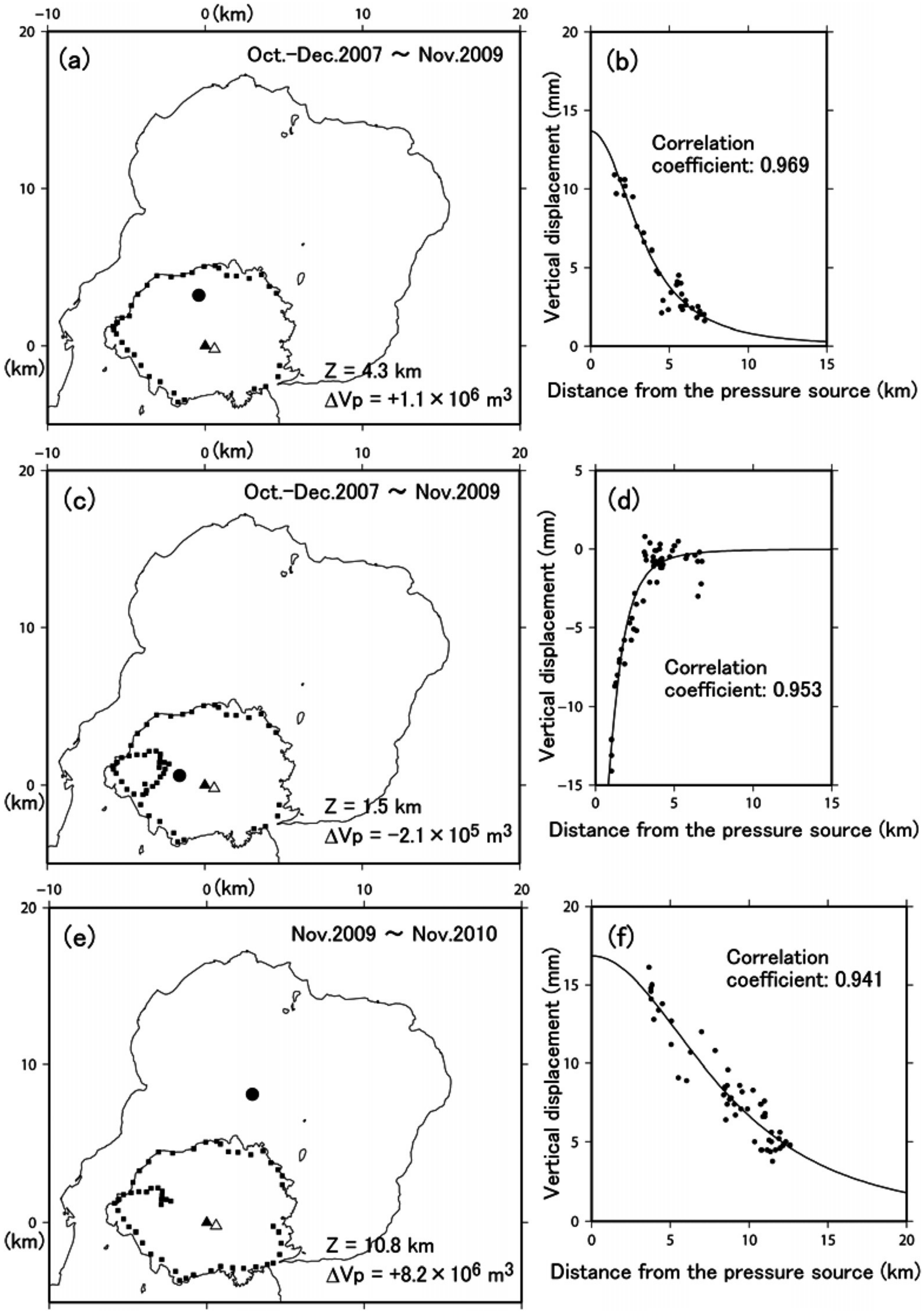

Fig. 5. (a), (c) and (e): same as Fig. 4a but by using the data during the period from October-December 2007 to November 2009 ((a): A-source and (c): B-source in Table 6) and those during the period from November 2009 to November 2010 ((e): A-source). (b), (d) and (f): same as Fig. 4b but by using the data during the period from October-December 2007 to November 2009 ((b): A-source and (d): B-source in Table 6) and those during the period from November 2009 to November 2010 ((f): A-source).

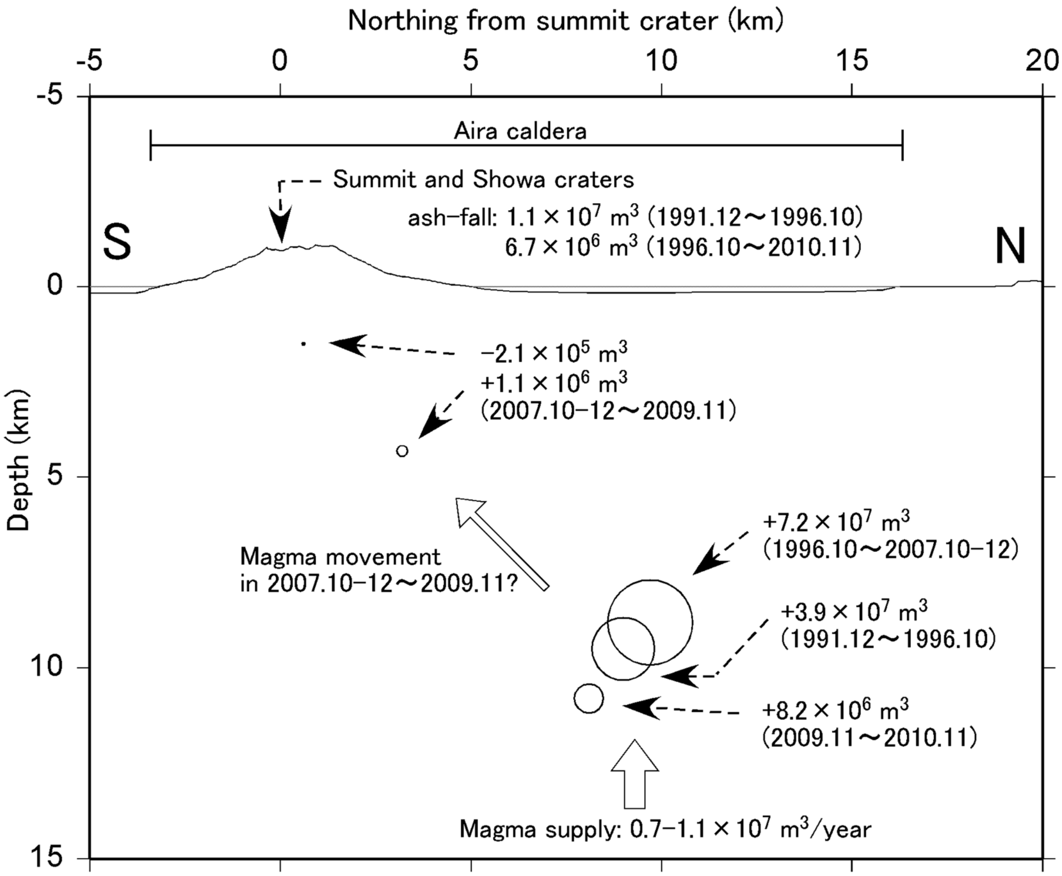

Fig. 6. Schematic illustration showing the locations of the calculated pressure sources projected onto North-South cross section crossing the summit crater of Sakurajima volcano (open circles) and inferred magma movement (see text for discussion). The results during the period of December 1991 - October 1996 (Eto *et al.*, 1997) are also plotted for comparison. The area of the each circle is drawn in proportion to the absolute deformation volume at the pressure source.

From the data during the period from October–December 2007 to November 2009, the inflation source is located at 4.3 km depth beneath the northern part of Sakurajima (Figs. 5a and 5b) and the deflation source is found at 1.5 km depth beneath the western flank of this volcano (Figs. 5c and 5d). The North-South cross sectional view of the locations of these pressure sources can be seen in Fig. 6 with that calculated during 1996–2007. We suppose that the inflation source at 4.3 km depth reflects the magma accumulation around the location (Figs. 5a and 6), whereas the estimated location and the shallow depth of the deflation source (Figs. 5c and 6) lead us to the speculation that it does not relate to the magma reservoir. The volume increase at the inflation source is estimated as about 1.1×10^6 m^3 (i.e., 0.6×10^6 m^3/year) (Table 6). While the amount of the ejected magma based on the observed amount of the ash-fall deposits during this period is estimated as about 0.9×10^6 m^3, the total of about 2.0×10^6 m^3 magma is inferred to be supplied into the inflation source. The averaged magma supply rate of about 1.0×10^6 m^3/year corresponds to one tenth of the typical magma supply rate mentioned above. The location of the inflation source seems to move shallower and closer to Sakurajima volcano compared with that in the previous period, which may suggest the magma movement towards shallow part of Sakurajima volcano from 10 km depth beneath Aira caldera, although the amount of magma input is small (Fig. 6).

During the period from November 2009 to November 2010, the inflation source is located beneath the center of Aira caldera (Fig. 5e), similar to the results calculated in the period of 1996–2007. The theoretical vertical displacements deduced from one inflation source account for the measured data with a good agreement (Fig. 5f). The estimated volume increase at the inflation source is about 8.2 $\times 10^6$ m^3 (Table 6) and the amount of the ejected magma based on the observed amount of the ash-fall deposits during the period is estimated as about 3.0×10^6 m^3,

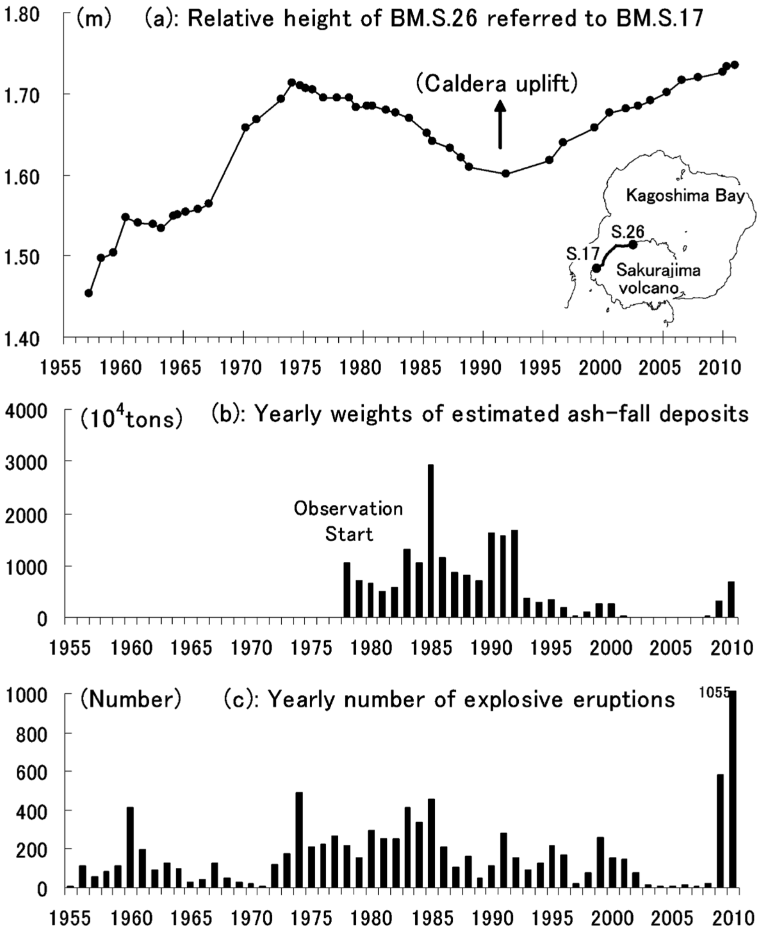

Fig. 7. (a) Relation among secular change of relative heights of BM.S.26 (located in northern Sakurajima) referred to BM.S. 17 (located in western Sakurajima), (b) yearly weights of estimated volcanic ash-fall deposits and (c) yearly number of explosive eruptions at the active summit and Showa craters of Sakurajima volcano.

resulting in the total of about 1.1×10^7 m^3 magma is inferred to be supplied into the deep primary magma reservoir beneath Aira caldera. The magma supply rate (of about 1.1×10^7 m^3/year) corresponds to nearly the same to the typical average supply rate suggested by Ishihara (1981). The magma supply rate may be doubled during the period between November 2009 and April 2010, considering that the most of the vertical displacements is produced during this period. These shorter period fluctuations of the magma supply rates may cause the fluctuations of eruptive activity and thus need the further examination of these relations.

Combined the results of this study with that of Eto *et al.* (1997), it is indicated that the total of about 1.4×10^8 m^3 magma is inferred to be supplied into the magma reservoir at about 10 km depth beneath Aira caldera (Fig. 6) during the magma accumulation period from 1991 to 2010. On the other hand, only about 0.2×10^8 m^3 of this supplied magma has been ejected by eruptive activity, resulting in the possibility that about 1.2×10^8 m^3 magma has additionally stored beneath Aira caldera during the period from 1991 to 2010.

4-2 Secular change of ground deformation and relation to the volcanic activity

The ground deformation around the northern part of Sakurajima located close to the center of Aira caldera well reflects the inflation or deflation process of the deep primary magma reservoir associated with the eruptive activity of this volcano. In Fig. 7, the secular vertical deformation of BM. S. 26 (located in northern part of Sakurajima) referred to BM.S.17 (located in western part of Sakurajima) resulted from the repeated leveling surveys is plotted since 1957 with yearly weights of estimated volcanic ash-fall deposits and yearly number of explosive eruptions at the summit and Showa craters of Sakurajima volcano. It is clearly seen that the ground uplift was

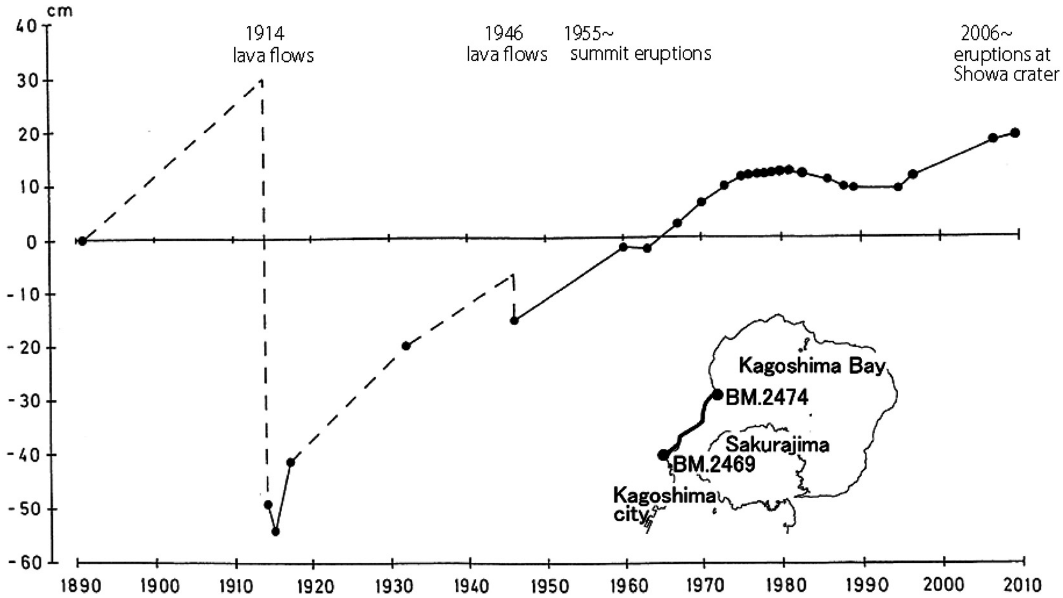

Fig. 8. Secular change of relative heights of BM.2474 (located at western coast of Kagoshima Bay) referred to BM.2469 (located in Kagoshima city to the west of Sakurajima) and volcanic activity of Sakurajima volcano (modified from Fig. 1 in Eto *et al.* (1997)).

detected around the northern part of Sakurajima during the period around 1967–1973, which is caused by the inflation of the primary magma reservoir associated with the magma storage during the period of decreasing eruptive activity. The ground subsidence was observed during the period around 1973–1991 due to the pressure decrease at the magma reservoir associated with the magma ejection during the period of intense eruptive activity. The ground uplift was identified again since around 1991 when the eruptive activity of this volcano was gradually decayed (Eto *et al.*, 1997). The current relative height of BM.S.26 in November 2010 recovers and further exceeds the height level in around 1973, suggesting that the volcano has the potential of the similar intense eruptive activity as that occurred during the 1970s and the 1980s. The increase of yearly number of explosive eruptions in 2009 and 2010 (Fig. 7c) is attributed to the recent increase of the eruptive activity at Showa crater, and the amount of magma ejection is correspondingly enlarged (Fig. 7b), while the uplift velocity momentary decreased during the period of April - November 2010 (Fig. 7a). However the continuing ground uplifts suggest that the amount of supplied magma overcomes that of ejected magma at the magma supply system beneath Aira caldera until November 2010. It is suggested to be necessary of ground deformation monitoring associated with the volcanic activity in order to evaluate the eruption potential of this volcano in the future.

Fig. 8 represents the secular change of the relative heights of BM.2474 (located at western coast of Kagoshima Bay) referred to BM. 2469 (located in Kagoshima city to the west of Sakurajima) resulted from the repeated leveling surveys since 1891, where BM.2474 is located relatively close to the center of Aira caldera and displays the uplift or subsidence associated with the inflation or deflation process of the deep primary magma reservoir. The leveling data are acquired during more than one hundred years and the lava flows of the 1914 great eruption and the 1946 eruption occurred on the way in this acquisition period (Eto, 1967; Eto *et al.*, 1997; Kamo, 1978; Omori, 1916; Sassa, 1956). The ground uplift of BM.2474 associated with the magma storage at the primary magma reservoir has progressed to be about 75 cm after the 1914 eruption to November 2009, and about 85 cm subsidence is inferred at the eruption (Sassa, 1956), where uplifts during 1891–1914 are assumed mainly from the averaged uplift rate measured during other periods of dormant eruptive activity. The ground subsidence at the eruption is suggested to be already recovered about 90 % for about 100 years after the eruption.

Lu *et al.* (2010) investigated the ground deformation at Okmok volcano, which is a basaltic central volcanic complex in Alaska, measured with InSAR observations from the end of the 1997 eruption to shortly before the onset of the 2008 eruption. From the source volume changes, they estimated that magma storage at about 3.5 km depth beneath the caldera floor had increased by $3.7–5.2 \times 10^7$ m^3 during 1997–2008, which corresponds to 85–100 % of the magma volume erupted in 1997 (i.e., the volume of magma withdrawn during the 1997 eruption was mostly replenished by 2008). They also suggested that the effects of continuing magma supply and vesiculation of stored magma caused a critical pressure threshold to be exceeded, triggering the 2008 eruption. The case of Okmok volcano is suggestive to other volcanoes including Sakurajima. If the magma storage is progressing and the resultant ground uplift around BM. 2474 continues at the recent rate, the relative height of BM. 2474 will reach the hypothesized height level at just before the 1914 eruption after about 10–20 years, suggesting that the volcano will gain the immanent potential of the similar eruptive activity as that occurred in 1914.

5. Conclusions

The vertical ground deformation in Sakurajima volcano and around Aira caldera associated with the volcanic activity of this volcano is revealed by the recent repeated precise leveling surveys conducted in October-December 2007, November 2009 and April and November 2010. We discuss the ground deformation in the period of 1991–2010 including previous leveling data. The results are summarized as follows:

(1) The ground uplifts are detected in Sakurajima volcano and around Aira caldera to be centered in the caldera during the period of 1996–2010. The uplifts are thought to reflect the magma storage at the magma reservoir beneath Aira caldera, and have continued since around 1991 when the eruptive activity of Sakurajima volcano was gradually decayed. Explosive eruptions are increasing in Sakurajima volcano since 2009. However continuing ground uplifts suggest that the amount of supplied magma overcomes that of ejected magma at the magma supply system beneath Aira caldera until November 2010.

(2) From the analysis based on Mogi's model, the inflation source is generally located at the 8.8–10.8 km depth with the volume change rates of $6.5\text{–}8.2 \times 10^6$ m^3/year beneath the center of Aira caldera through the period of 1996–2010. It is indicated that the magma storage beneath Aira caldera is progressed during the period. In the period of 2007–2009, a shallow inflation source is calculated at the 4.3 km depth with a volume change rate of about 0.6×10^6 m^3/year beneath the northern part of Sakurajima. It may suggest the magma migration towards shallow part of Sakurajima volcano from 10 km depth beneath Aira caldera.

(3) It is indicated that the total of about 1.2×10^8 m^3 magma is inferred to have additionally stored beneath Aira caldera during the period from 1991 to 2010. The progressing ground uplift of BM.S.26 around the northern part of Sakurajima due to the magma storage at the time of November 2010 recovers and further exceeds the height level in around 1973, when the intense summit eruptions during the 1970s and the 1980s started. The ground uplift of BM.2474 around the western coast of Kagoshima Bay is about 75 cm for about 100 years after the 1914 great eruption to November 2009, and already recovers about 90 % of the inferred ground subsidence at the eruption. These results suggest the immanent potential of the next intensive eruptive activity of this volcano.

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(Editorial handling Takeshi Hashimoto)

水準測量の繰返し観測による桜島火山の火山活動に伴う地盤上下変動（1996 年～2010 年）

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井上寛之・松島　健・内田和也・中元真美

桜島火山の活動に伴う最近の桜島および姶良カルデラ周辺域における地盤上下変動が，2007 年 10 月–12 月，2009 年 11 月，2010 年 4 月および 11 月と行われた精密水準測量の繰返し観測によって明らかとなった．姶良カルデラ周辺の地盤は，1996 年から 2010 年までの期間において，それ以前の 1991 年から 1996 年までの期間に得られていた結果と同様に，カルデラ内部を中心として隆起したことが確認された．球状圧力源（茂木）モデルに基づく解析を行った結果，1996 年–2010 年の期間において，姶良カルデラ中央部地下の深さ 8.8 km–10.8 km に増圧源の存在が推定された．この期間，姶良カルデラ地下に推定されるマグマ溜りにおいてマグマの貯留が進行したものと考えられる．2007 年–2009 年の期間においては，桜島北部地下の深さ 4.3 km に増圧源の存在が推定された．このことは，姶良カルデラの深さ 10 km から桜島の浅部方向へのマグマの移動が生じた可能性を示唆するが，そのマグマの移動量は小さい．姶良カルデラ地下におけるマグマの貯留は，桜島火山の山頂噴火活動が静穏化した 1991 年頃から継続している．2009 年以降，昭和火口における噴火活動が活発化する傾向にあるが，観測された地盤隆起の継続は，噴火活動が活発化しつつある 2010 年 11 月の時点においても姶良カルデラ地下においてマグマの供給量が放出量を上まっていることを示唆している．計算された増圧源において見積もられた容積増加量および観測降下火山灰量に基づき見積もられたマグマの放出量を考慮すると，1991 年から 2010 年までの期間において姶良カルデラの地下に約 $1.2\times10^8\ m^3$ のマグマが新たに蓄積されたことが推定される．また，マグマの蓄積に伴う桜島北部付近の 2010 年 11 月の時点における地盤隆起量は，1970 年代および 1980 年代の活発な山頂噴火活動が開始した 1973 年頃の状態を回復し更に隆起が継続した状態となっている．これらの結果は，桜島火山の次の大規模噴火活動についての潜在的なポテンシャルを示唆するものと考えられる．