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The Inflation-deflation History of Aira Caldera for the Last 120 Years and the Possibility of a Forthcoming Large Eruption at Sakurajima Volcano

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In order to assess the potential for future eruptive activity at Sakurajima volcano, southern Japan, ground deformation around northern Kagoshima Bay (i.e., Aira caldera), especially the height change between leveling stations 2474 and 2480, was re-analyzed. Prior to the large eruption in 1914 at Sakurajima volcano, a remarkable inflation was confirmed at Aira caldera, based on re-surveyed data that were not referred to in previous investigations. Considering those data, the upper limit of the magma storage at Aira caldera just before the 1914 eruption could be obtained. Although the 1914 eruption accompanied a remarkable deflation at Aira caldera, magma started to accumulate again and was likely to have exceeded the level observed in 1900 (14 years before the large eruption). Around the early 1970s, it approached the level before the 1914 eruption. After the ground uplift stopped and slightly reversed during a period of extremely frequent explosions at Sakurajima volcano in the 1970s and 1980s, the inflation seems to again be approaching the inferred level before the 1914 eruption, suggesting the possibility of the next large eruption. In addition, inconsistencies between the inferred amounts of magma supply and observed volumes of erupted materials were discussed and left for further study.

Key words: Sakurajima volcano, Aira caldera, eruption, inflation-deflation, leveling survey

1. Introduction

In January 1914, a large eruption occurred at Sakurajima volcano, located several kilometers from the harbor of Kagoshima City in Kyushu, southern Japan. During this Plinian type eruption, large amounts of volcanic ash and pumice were ejected from the summit crater and thickly covered the surrounding region (*e.g.*, Omori, 1914; Koto, 1916). In addition, lava flowed down to the coast from newly formed small craters on the west and southeast flanks of the volcano. After the occurrence of the eruption, sea water overflowed into the salt fields and the coastal region along the northern part of Kagoshima Bay. According to a subsequent leveling survey by the Land Survey of Japan (1915), a remarkable subsidence of the land was confirmed to have occurred over an area several tens of kilometers in diameter (Fig. 1). It was one of the most remarkable eruptive events in Japan during the last 100 years.

The depressed topography of the northern part of Kagoshima Bay was basically formed as a composite caldera, i.e., Aira caldera (*e.g.*, Aramaki, 1984), which was caused by great eruptions around 29 thousand years before present in calibrated radiocarbon age (*e.g.*, Okuno, 2002). After that, Sakurajima volcano was formed as a post caldera cone at the southern rim of the caldera. As discussed later, it is interesting that Sakurajima volcano was not located at the center of the subsidence accompanying the 1914 eruption of the volcano. Instead, the amount of subsidence at the benchmarks increased towards the center of Aira caldera, and similar movement was also found at triangulation points directed towards the same center (*e.g.*, Land Survey of Japan, 1915; Omori 1916b; Hashimoto and Tada, 1992). The co-eruptive subsidence of the ground strongly suggests that magma had accumulated gradually at Aira caldera, and that it pushed its way to Sakurajima volcano in 1914 (*e.g.*, Omori, 1916b; Sassa, 1956; Mogi, 1957; 1958; Kamo, 1994).

In previous discussions, however, the remarkable evidence of inflation prior to the 1914 eruption (Yamashina, 1997) was not considered. In order to discuss this pre-eruptive deformation and the inflation-deflation process at Aira caldera, the leveling survey data obtained by both the Land Survey of Japan (up to 1946) and the Geographical Survey Institute of Japan (1960 and later; recently named the Geospatial Information Authority of Japan) are reviewed in Section 2.

As indicated in Section 3, the present paper focuses on the height change at leveling station 2474 versus 2480 located 9.5 km north-northeast. Previously, however, the height change has been discussed for station 2474 versus 2469 located 8.5 km southwest (*e.g.*, Sassa, 1956; Kamo, 1994; Eto *et al.*, 1997; Yamamoto *et al.*, 2010). Here,

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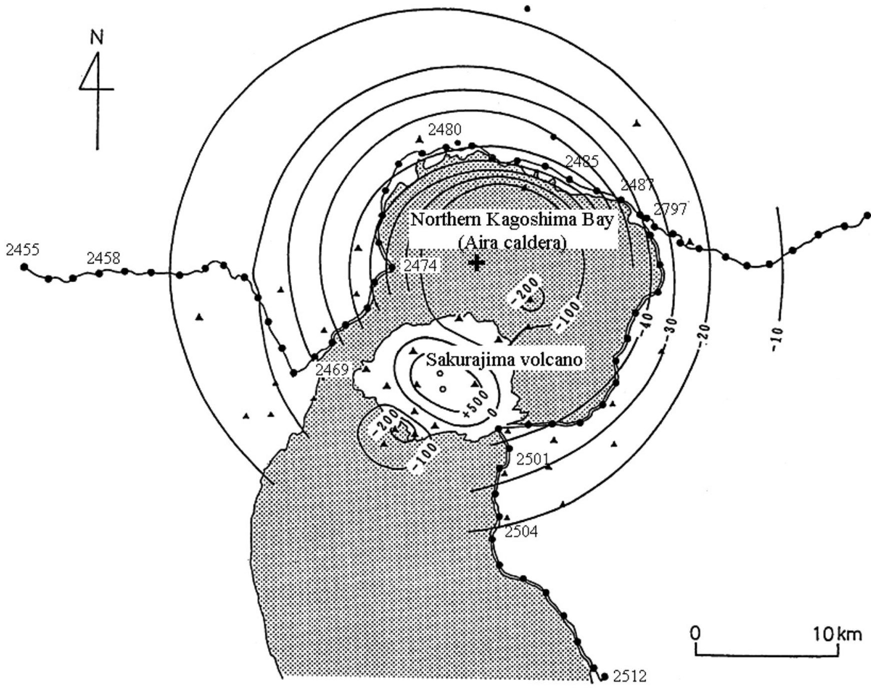

Fig. 1. Ground subsidence around northern Kagoshima Bay (i. e., Aira caldera) confirmed by leveling and partly triangulation surveys (Land Survey of Japan, 1915; Omori, 1916b). Solid circles and triangles are benchmarks and triangulation stations, respectively. Numerals along leveling routes represent the station numbers of benchmarks. Contour curves with intervals of 10 cm are the difference between the 1890s and 1914 drawn by Yamashina (1997). A cross marks the location of an inferred deflation source in 1914, and open circles at Sakurajima volcano are the summit craters.

from stations 2474 to 2469, the locations approach Sakurajima volcano. At this point, a secondary disturbance due to ground deformation originating at Sakurajima volcano might be included in the observed data at 2469. Another problem might be that a magnitude 7 earthquake occurred in this area several hours after the commencement of the 1914 eruption (*e.g.*, Omori, 1914). Although the exact location of the earthquake is not clear, it was probably not very far from the city of Kagoshima in which station 2469 is located (*e. g.*, Omori, 1922; Abe, 1981; Hashimoto and Tada, 1992). If so, coseismic deformation might also affect the height of 2469 and adjacent stations. Considering these possibilities, the observed data at 2480 may be preferable as a reference for discussing the height change at 2474, as well as the inflation-deflation process occurring at Aira caldera.

Owing to the present results, these problems are found to have not been serious because the patterns of the temporal height changes were essentially similar between 2474–2480 and 2474–2469 at least in the period after 1914. However, it is useful to examine the height change at 2474 versus 2480 because the data at 2480 witness the previous assumption that station 2474 would have uplifted gradually before the 1914 eruption with almost the same rate observed after the eruption. The data also suggest that Sakurajima volcano could now very likely be in a preparatory stage for a forthcoming large event.

Subsequently, the absolute height change at each location, the co-eruptive deflation in 1914, and the balance of magma supply and erupted materials for 120 years are analyzed in Sections 4 and 5. Section 6 will demonstrate that a large problem regarding a quantitative balance between magma storage and discharge at Aira caldera and Sakurajima volcano remains for further study.

2. Leveling data along Kagoshima Bay

2–1 First survey in 1892

In the Meiji era, more than 120 years ago, according to a national plan to establish a precise topographic map of the whole country, the Land Survey of Japan was initiated to survey the large number of leveling and triangulation points all over Japan. According to reports from the Land Survey of Japan (1915) and Omori (1916b), a leveling survey between the benchmarks at stations 2455–2488, 2797 (located between 2488 and 2489), and 2489–2512 located in Kagoshima Prefecture was carried out in

February, April, and May 1892.

This first survey in the Kagoshima area is sometimes referred to as having been carried out in 1891. This is probably because a report that collected the results of old leveling surveys (Geographical Survey Institute of Japan, 1975) indicated that the whole route from Kumamoto to Kagoshima Prefectures was surveyed in 1891. Although the survey of the route started in September 1891 at the southwestern part of Kumamoto Prefecture, it continued into the next year to complete the operation up to the southeastern end of the route on the southeastern coast of Kagoshima Bay.

2-2 Re-survey in 1900

Referring to the reports from the Land Survey of Japan (1915) and Omori (1916b), the heights of several leveling stations along the northwestern coast of Kagoshima Bay were not surveyed in 1892 but in 1900, without any explanation. This situation became clear from old documents left by the Land Survey of Japan (1891 and later, 1898) and also from the database compiled by the Geospatial Information Authority of Japan: After the first survey in 1892, the stone-pillar benchmarks buried at several leveling stations (i.e., 2475, 2476, 2478, and 2479) were found to be damaged or lost. In order to restore the damaged stations, they were re-installed and surveyed again in March 1900 along the route from stations 2472 to 2483. Consequently, the difference between 1892 and 1900 was also found at the stations not experiencing trouble over this period.

2-3 Leveling survey in 1897-1898 and later by Kyushu Railways

Referring to Omori (1916b), prior to the re-survey in 1900, it was reported that the benchmarks along the northwestern coast of Kagoshima Bay (stations 2470-2481, excepting 2478) were surveyed during September 1897 and May 1898 by Kyushu Railways to construct a new railway line connecting cities in Kumamoto and Kagoshima Prefectures. The leveling survey was also extended southwestwards along the leveling route including stations 2455, 2456, and 2469 during July 1912 and July 1913. After the 1914 eruption, they were all re-surveyed in April and May 1915. However, the survey must have been less accurate than those by the Land Survey of Japan. In fact, for example, a systematic southward-dipping trend of error might be included in the results for 1897-1898. Therefore, in the present paper, the results obtained by Kyushu Railways are not considered but are left for further discussion.

Incidentally, the relative heights of stations 2475, 2476, and 2479 in 1897-1898 were fairly different from the results in 1892, but rather close to those in 1900. Since the stone pillars were reported to be re-installed in 1900 at these stations (Land Survey of Japan, 1891 and later), the date of the survey or that of the re-installation itself may not be exact.

2-4 Repeated surveys in the post-eruptive period from 1914 to 1918

After the large eruption in 1914, the Land Survey of Japan began to re-survey the benchmarks around northern Kagoshima Bay and adjacent areas (i. e., stations from 2457 to 2512 and from 2794 to 2797). The results obtained during June and August 1914 proved a remarkable subsidence of the bay-side area (Land Survey of Japan, 1915; Omori, 1916b). In order to confirm the extent of the subsided areas, a re-survey was also carried out from December 1914 to April 1915 along the leveling routes towards the northwest in Kumamoto Prefecture and the northeast in Miyazaki Prefecture.

In this post-eruptive period, the benchmarks around northern Kagoshima Bay were again re-surveyed in February 1915 (stations 2468-2488 and 2793-2797; Omori, 1916b) and November-December 1918 (stations 2456-2512 and 2789-2797; Omori, 1920).

2-5 Repeated surveys from 1932 to 2006 and estimation of the missing data

Leveling surveys were repeated along northern Kagoshima Bay by the Land Survey of Japan in 1932 and 1946, and by the Geographical Survey Institute of Japan in 1960, 1962-1963, 1968, 1975, 1981, 1987, 1997, and 2006. The observed data for these years are available in the annual reports and special volumes published by the Geographical Survey Institute of Japan (1955-2008, 1974 and 1975). In this period, there is a large problem in which unexpected trouble occurred in many benchmarks, and it became necessary to interrupt the continuous observation of a possible uplift or subsidence at each station. Such a lack of data is, if necessary, compensated using the following assumptions.

First, the benchmark at station 2474 is considered. It is located on a little cape named Oosakinohana, penetrating northern Kagoshima Bay, and is known to have subsided the most in 1914 in the land area. In spite of its importance, troubles occurred there in 1932-1946, 1946-1960, 1963-1968, and 1968-1975. Fortunately, however, there seems to be a linear trend between the amounts of deformation at the respective stations in sections both 2470-2474 and 2474-2478. Therefore, any missing observation at 2474 could be estimated from the data at stations 2470 to 2478 using the method of least-square fitting to straight lines. In order to determine the estimation error, the same process is applied to the periods for which the deformation at 2474 is known. The results indicate that the difference between the calculation and observation is usually within several millimeters as seen in Fig. 2.

The present paper also focuses on the deformation at 2480. This point is close to the northwestern-most part of Kagoshima Bay and had the least subsidence in this region along the leveling route at the time of the 1914 eruption. The station was fairly stable but was lost once during 1946 and 1960. Since the deformations at stations 2478, 2479, and 2480 are similar for almost every period, the missing value can be estimated from those at 2478 and/or 2479. The estimation error also seems to be within several millimeters as seen in Fig. 3.

2–6 Surveys by university members

During and after the 1970s, leveling surveys along the routes within Sakurajima volcano and around northern Kagoshima Bay were repeated by the Sakurajima Volcanological Observatory of the Kyoto University, the Earthquake Research Institute of the University of Tokyo and other cooperating organizations. Based on these surveys, detailed temporal changes in the ground were observed with respect to the eruptive activity at Sakurajima volcano (*e.g.*, Eto, 1989b; Miyazaki, 1990; Eto *et al.*, 1997; Yamamoto *et al.*, 2010). These surveys, however, did not include the section focused on by the present paper, i. e., the stations from 2474 to 2480. Therefore, their results are not referred to in the following discussions.

3. 120-year history of the relative height change between 2474 and 2480

3–1 Inflation prior to the large eruption in 1914

The extrapolation discussed in Section 2 enables plotting the progress of the height change at 2474 versus 2480 during almost 120 years, as seen in Fig. 4. The present result supports the previous ones obtained for station 2474 compared with 2469 (*e.g.*, Sassa, 1956; Kamo, 1994; Eto *et al.*, 1997; Yamamoto *et al.*, 2010). In those previous results, however, the pre-eruptive uplift at 2474 from the 1890s to 1914 was not proved directly by the evidence of leveling survey, but inferred from the analogy of the uplift observed during 1918 and the 1960s, and probably the tidal

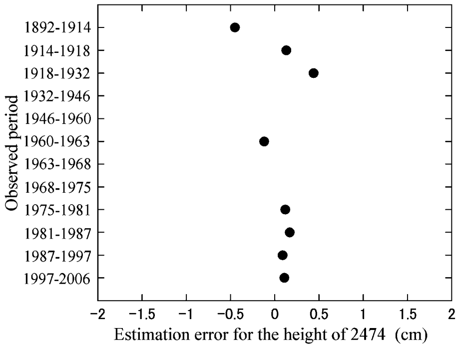

Fig. 2. Difference of the height of station 2474 between the observation and calculation obtained from the data at adjacent stations from 2470 to 2473 and/or from 2475 to 2478.

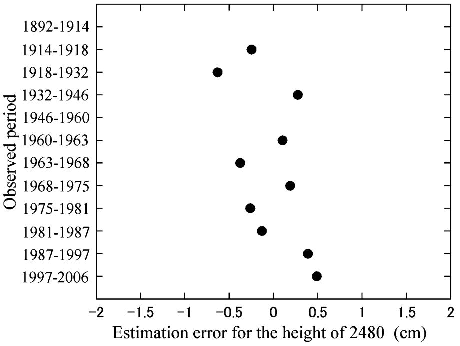

Fig. 3. Difference of the heights between stations 2480 and 2478 and/or 2479, representing an estimation error of missing data at 2480.

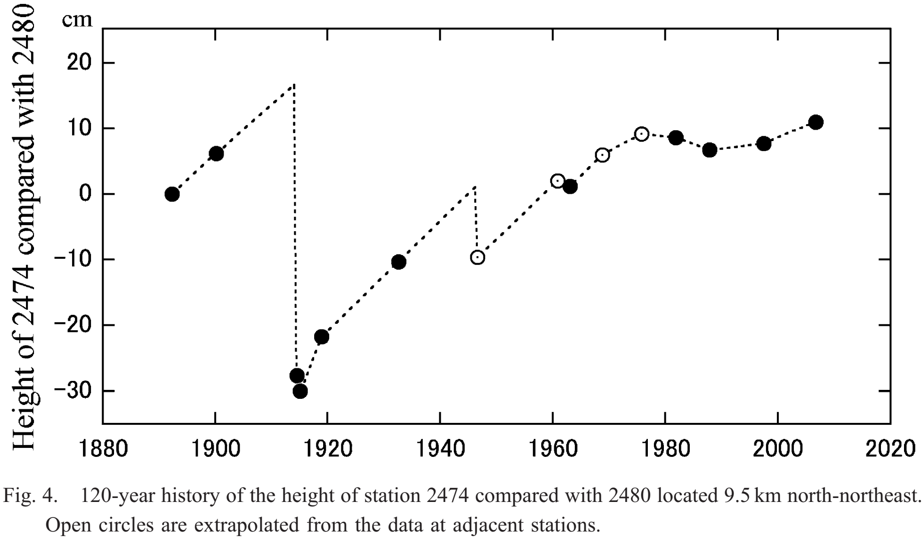

Fig. 4. 120-year history of the height of station 2474 compared with 2480 located 9.5 km north-northeast. Open circles are extrapolated from the data at adjacent stations.

Table 1. Inferred heights of benchmarks around northern Kagoshima Bay in February-April 1892, March 1900, and June-July 1914 obtained in the present paper based on the results of the leveling survey by the Land Survey of Japan (referring mainly to the database stored in the Geospatial Information Authority of Japan). Height changes during 1892−1900, 1900−1914, and 1892−1914 are also shown. However, the absolute values of heights and height changes at each station are not so accurate and errors of several millimeters or more might be included. Here, it is assumed that the height of 2797 was 88.2230 m in 1914, and that the height change at station 2751 was negligible between 1892 and 1914.

Benchmark	Inferred height (m)			Height change (m)		
	1892	1900	1914	1892to1900	1900to1914	1892to1914
2455	29.9984		29.9028			−0.0956
2456	55.9199		55.8702			−0.0497
2457	64.4475		64.3488			−0.0987
2458	82.0072		81.8929			−0.1143
2459	104.8018		104.6832			−0.1186
2460	101.2326		101.1277			−0.1049
2461	143.5216		143.3369			−0.1847
2462	105.5722		105.4131			−0.1591
2463	66.0052		65.8109			−0.1943
2464	26.7402		26.5141			−0.2261
2465	17.8234		17.5973			−0.2261
2466	14.1550		13.9173			−0.2377
2467	7.3848		7.3953			0.0105
2468	4.5339		4.3605			−0.1734
2469	2.6839		2.3401			−0.3438
2470	7.9082		7.5249			−0.3833
2471	10.2713		9.8073			−0.4640
2472	11.6229	11.7775	11.0267	0.1546	−0.7508	−0.5962
2473	5.8876	6.0455	5.1805	0.1579	−0.8650	−0.7071
2474	7.0166	7.1871	6.1985	0.1705	−0.9886	−0.8181
2475	7.3512	6.1147	5.2440	Lost	−0.8707	
2476	11.9902	12.2380	11.4413	Lost	−0.7967	
2477	5.1682	5.2867	4.5855	0.1185	−0.7012	−0.5827
2478	10.2072	10.3117	9.6943	Lost	−0.6174	
2479	10.0464	9.9885	9.3612	Lost	−0.6273	
2480	3.1860	3.2943	2.6441	0.1083	−0.6502	−0.5419
2481	46.8090	46.9252	46.2581	0.1162	−0.6671	−0.5509
2482	16.0733	16.2070	15.4337	0.1337	−0.7733	−0.6396
2483	12.2408	12.3882	11.6105	0.1474	−0.7777	−0.6303
2484	3.5615		2.9389			−0.6226
2485	5.4890		4.8616			−0.6274
2486	3.1822		2.6238			−0.5584
2487	3.4290		3.0016			−0.4274
2488	57.2165		56.8474			−0.3691
2797	88.5345		88.2230			−0.3115

levels observed tentatively at Kagoshima harbor quay close to station 2469. In fact, Omori (1916b) concluded that the tidal level at the quay rose markedly from 1903–1905 to 1914–1916, suggesting the subsidence of the quay. However the change of, for example, monthly mean sea-level fluctuated from 39 to 68 cm between the average in 1903–1905 and the same months in 1914–1916 (Omori, 1916a). Considering that there are various factors to disturb the tidal levels, it seems difficult to discuss the quantity of a reliable pre-eruptive uplift of the quay.

As seen in Fig. 4 and Table 1, the relative height of station 2474 versus 2480 increased 6.22 cm from 1892 through 1900, with an average rate of 0.79 cm/year. Similar uplifts also occurred in 1918–1932 and 1946–1960 with almost the same average rate, i.e., 0.83 and 0.82 cm/year, respectively. This strongly suggests that, in the less active period at Sakurajima volcano, the relative uplift at 2474 occurred nearly continuously at an almost stable rate of about 0.8 cm/year up to at least the 1960s.

As a result, if it is possible to assume that the uplift continued up to the time of the 1914 eruption, the total relative uplift would amount to about 17 cm from 1892 to the beginning of 1914. This is about 0.6 times the value obtained from the difference in the survey between 1892 and 1914, indicating that the co-eruptive deformation in 1914 cannot be obtained by taking only the difference in the observed values in 1892 and 1914. If the location of the source of the pre-eruptive uplift was similar to that of the co-eruptive subsidence, the total co-eruptive subsidence at any station around northern Kagoshima Bay would be roughly about 1.6 times the observed difference between 1892 and 1914.

3–2 The 1946 eruption and a possible deflation

In 1946, a significant eruption occurred again at Sakurajima volcano. In this year, there were repeated explosions with ash ejection at one of the craters at the summit area, i.e., the Showa crater, and lava flowed down to the southeastern mountain foot from March to May.

As seen in Fig. 4, the surveyed data before and after this eruption, i.e., July to August 1932 and August 1946, were similar. However, this does not necessarily suggest that the ground surface was almost fixed during this period. The actual process was probably a progressive gradual uplift and a rapid subsidence in 1946, as discussed before (*e.g.*, Sassa, 1956; Kamo, 1994). The inferred process is indicated by dotted lines in Fig. 4.

A similar process might have occurred on a small scale during December 1960 and February 1963. In these years, explosions occurred intermittently at the summit area. In March 1961, there were intense events in which the window glasses of many houses were broken at the foot of the mountain (*e.g.*, Japan Meteorological Agency, 1961). It is not clear, but one or more of these explosions may have contributed to interrupting the uplift.

Prior to this period, explosions occurred occasionally following a somewhat significant event in 1955. Including the 1955 event, the correlation between the explosions and the height change at 2474 is not known, because the interval of the leveling survey was too long to detect a small temporal difference.

3–3 Retreat of uplift during the 1970s and 1980s

In the 1970s and 1980s, the ground deformation changed entirely. The uplift at 2474 slowed down around the 1970s and gradually reversed a little around the 1980s.

During nearly the last 120 years, the 1970s and 1980s were unusual in that explosions at the summit area of Sakurajima volcano occurred again and again quite frequently, and large amounts of volcanic ash fell down around the volcano every year (*e.g.*, Eto, 1984, 1989a; Nakamura, 2002). Although individual explosions were not large, it is evident that the different progress of the ground deformation during this period was caused by the anomalous repetition of explosive activity.

Adding to this well-known understanding, it seems to be important that, around the early 1970s, the relative height of 2474 compared with 2480 exceeded the level observed in 1900, and approached the inferred level just before the 1914 eruption. This might suggest that the magma reservoir at Aira caldera inflated almost to its upper limit during this period. If the mechanical state of the conduit connecting to Sakurajima volcano was the same as in 1914, a large eruption similar to the 1914 event might have occurred. During this period, however, the actual process was quite different, i.e., there was an anomalous repetition of explosive activities. Considering the occasional repetition of explosions especially since 1955, this might have affected the conduit to allow the gradual transportation of magma to Sakurajima volcano.

3–4 Progress of uplift in the 1990s and 2000s

Ejection of volcanic ash at Sakurajima volcano has decreased since around 1993 (*e.g.*, Nakamura, 2002). This change soon resulted in the uplift at 2474. In the survey of 1997, a slight uplift was obtained. In 2006, the uplift was confirmed once again, exceeding the levels in 1900 and 1975. The average rate of the uplift was 0.35 cm/year from 1997 to 2006. This rate was still smaller than that obtained before the 1970s, but approaching again the inferred level before the 1914 eruption. Assuming the same uplift rate, the subsidence occurred in 1914 has probably been recovered to about 92 % in 2012. This may be a warning of the possibility of the next large-scale eruption in the near future.

4. Altitude of the benchmarks

Leveling surveys observe the relative heights between benchmarks. Therefore, a height change relative to a certain station can be obtained fairly precisely. However, the absolute altitude or the true height change at each location is not obtained directly. It is also problematic that it takes many days to complete a survey of a long leveling route. In the case of the present region, the altitudes of the benchmarks for the first survey in the 1890s was obtained by connecting the leveling route with the tidal station at Hososhima located on the east coast of middle Kyushu, roughly 120 km northeast of station 2797.

The benchmarks along northern Kagoshima Bay were surveyed in 1892 including 2797 located near the northeast corner of Kagoshima Bay. Nearly three years later, the leveling route between 2797 and Hososhima was surveyed from October 1894 to February 1895. Here, the junction point 2797 was surveyed twice in February 1892 and in January 1895. In order to connect the results of the different leveling routes, it was assumed that there was no vertical ground deformation at 2797 during this period (*e. g.*, Land Survey of Japan, 1915; Omori, 1916b). However such an assumption is not necessarily reasonable in the present area, so the true height change is discussed below.

As mentioned in Section 3-1, during the pre-eruptive period from 1892 to 1914, the relative height between stations 2474 and 2480 probably uplifted by 0.6 times the observed subsidence between 1892 and after the 1914 eruption. Based on the surveys in 1892, 1900, and 1914, similar ratios are obtained for the relative heights of 2474-2472, 2474-2477, 2477-2480, and 2482-2480, i.e., 0.4, 0.6, 0.7, and 0.7, respectively.

Using an averaged ratio of 0.6, annual uplifts are tentatively estimated as 2.3, 1.6, and 0.93 cm/year at stations 2474 (−84.32 cm), 2480 (−56.70 cm), and 2797 (−33.66 cm), respectively. Here, the values in parentheses represent the difference in height between the 1890s and 1914, neglecting the problem just discussed. These values, however, differ slightly from those presented by the Land Survey of Japan (1915) and Omori (1916b). This is because the present values were obtained under the assumption that station 2751 in Miyazaki City, located about 60 km ENE of station 2797, was fixed, and that the old values obtained in the 1890s by the Land Survey of Japan were corrected to eliminate the mis-closure of the leveling route, along which the survey took several years to complete the loop. The heights also differ from those by the Geographical Survey Institute of Japan (1975) and Hashimoto and Tada (1992) who assumed the fixed point at 2736 and 2751-1, respectively. In the present paper, the fixed point is tentatively moved to 2751 in order to avoid an apparent discrepancy in the height difference between 2751-1 and 2751, i.e., there is a slight inconsistency of about 1 mm between the data reported by the Land Survey of Japan (1915), the Geographical Survey Institute of Japan (1975), and the database stored in the Geospatial Information Authority of Japan.

According to the value stated above, i.e., 0.93 cm/year, station 2797 is tentatively suggested to have uplifted about 2.7 cm during the three-year interruption of the survey. Considering this, all of the heights of the benchmarks along northern Kagoshima Bay should be lowered by 2.7 cm from the reported values in 1892. However, correcting the heights in 1892 results in changing the correction term itself. After iterations of the same process, the annual uplifts have been revised to 2.3, 1.5, and 0.86 cm/year at stations 2474, 2480, and 2797, respectively. The correction term is now replaced to 2.51 cm, and thus all of the heights of the benchmarks along northern Kagoshima Bay are lowered by 2.51 cm as new inferred values for 1892. Consequently, (i) the differences in the heights between 1892 and 1914 and (ii) the amounts of the actual subsidence are inferred to be −81.8 and −131 cm at 2474, −54.2 and −87 cm at 2480, and −31.2 and −50 cm at 2797, respectively, although errors of several millimeters or more might be included. The inferred heights of stations 2455-2797 in 1892, 1900, and 1914 are listed in Table 1.

Along the leveling route between 2751 and 2797, the inferred heights for 1892 are lowered by 0 at 2751 and 2.51 cm at 2797. For the other stations, the correction term is interpolated in proportion to the distance from 2797.

5. Inflation-deflation models based on the leveling survey data

5-1 Formulation of displacements and volume changes

If a subsurface inflation-deflation source is approximated by a spherical pressure source in a semi-infinite elastic medium, vertical and horizontal ground displacements at an arbitrary place, i.e., u_z and u_r, respectively, are expressed as follows, referring to the formulation by Sezawa (1931) and later by, *e. g.*, Soeda (1944) and Yamakawa (1955).

$$u_z = C_0 D / R^3,$$

$$u_r = C_0 r / R^3.$$

Here,

$$C_0 = \frac{(\lambda + 2\mu) a^3 P_0}{2\mu(\lambda + \mu)},$$

$$R = \sqrt{D^2 + r^2}.$$

D, R, and r are the depth, the three-dimensional distance, and the horizontal distance of the center of the pressure source, respectively; λ and μ are Lame's elastic constant; $a^3 P_0$ is a coefficient to represent the intensity of the pressure source. Incidentally, P_0 is the amount of the expanding or contracting pressure change on a spherical surface with an arbitrary but small radius a.

In the same notation, the volumetric change of the pressure source, ΔV, is approximated as follows (Yamashina, 1986, 1992):

$$\Delta V = \pi a^3 P_0 / \mu.$$

Otherwise, using the estimated vertical displacement u_z

at an arbitrary place,

$$\Delta V = \frac{2\pi(\lambda+\mu)}{\lambda+2\mu}\frac{R^3}{D}u_z.$$

5-2 Total volume of deflation in the 1914 eruption

A plausible source of the deflation is analyzed with an assumption of $\lambda=\mu$, based on the revised values of subsidence obtained in Section 4. The best model fitted at first to the difference between 1892 and 1914 for the stations represented in Fig. 1 is 10.4 km in depth and $590\times10^6\mathrm{m}^3$ in volume contraction. In this calculation, the height of the reference point, i.e., station 2751, is allowed to change freely. As a result, in the best-fit model, 0.4 cm of the subsidence is added at all stations.

The present result is essentially the same as those obtained by Mogi (1958; 10 km in depth and about $660\times10^6\mathrm{m}^3$ in volume contraction) and Hashimoto and Tada (1992; 8.8 km in depth and $510\times10^6\mathrm{m}^3$ in volume contraction). However, the progress of the pre-eruptive inflation during 1892 and 1914 was not included in those models. When this is taken into consideration in the present model, the co-eruptive contraction of the pressure source becomes 1.6 times the value stated above, assuming that the same inflation rate continued up to the time of the 1914 eruption. That is, the volume of the contraction is modified to $940\times10^6\mathrm{m}^3$ in the present model.

In 1914, Sakurajima volcano extruded a huge volume of lava estimated to be $1560\times10^6\mathrm{m}^3$ (Omori, 1914), $1140\times10^6\mathrm{m}^3$ (Koto, 1916), $900\times10^6\mathrm{m}^3$ (Harada, 1948), or more precisely $1340\times10^6\mathrm{m}^3$ (Ishihara *et al.*, 1981). In addition, large amounts of ash and pumice were also ejected (*e.g.*, Omori, 1914; Koto, 1916). Considering the density of the materials, the volume, i.e. $620\times10^6\mathrm{m}^3$ (Omori, 1914), would roughly correspond to $310\times10^6\mathrm{m}^3$ in volume of magma.

In spite of these facts, previous deflation models for the 1914 eruption estimated the subsurface contraction at Aira caldera to be far less than the total volume of magma actually erupted. The present revised model decreases this difference to some extent. However, it is still interesting that the contraction of the pressure source at Aira caldera is not sufficient to explain the erupted materials even in the present model. The lack of magma, if it is actually correct, might suggest the possibilities to be mentioned in Section 6.

5-3 Magma storage and discharge up to the 1960s including the 1946 eruption

Before and after the 1914 eruption of Sakurajima volcano, i.e., 1892-1900, 1918-1932, and 1946-1960, inflation at Aira caldera seems to have continued at nearly a constant rate as seen in Fig. 4. Considering this, the same inflation process at Aira caldera was assumed to continue up to at least the 1960s. Consequently, since the fraction 0.6 out of 1.6 (cf. Section 3-1) is considered to be the contribution of the 22-year accumulation prior to the 1914 eruption, the annual volume of magma accumulation would be roughly $0.6/1.6/22\simeq0.017$ times the 1914 co-eruptive contraction, i.e., $16\times10^6\mathrm{m}^3$/year.

A deflation process similar to the 1914 eruption is likely to have occurred in 1946. Although the deflation associated with the eruption in March-May 1946 was not observed directly, the leveling survey in August 1946 indicated that the difference from the previous survey in July and August 1932 was fairly small. That is, the volume accumulated between 1932 and 1946, i. e., a 14-year period, may thus be considered to have been effectively cancelled by the 1946 eruption. The accumulation during 14 years would be about $230\times10^6\mathrm{m}^3$.

The possible deflation calculated for 1946 is about 1/4 that for 1914. This corresponds to the scale of the 1946 eruption being smaller than the one in 1914. Quantitatively, the volume of lava erupted during March and May 1946 was previously estimated to be about $100\times10^6\mathrm{m}^3$ (Hagiwara *et al.*, 1948) or $92\times10^6\mathrm{m}^3$ (Morimoto, 1948). Subsequently, it was analyzed more precisely as $180\times10^6\mathrm{m}^3$ (Ishihara *et al.*, 1981). In addition, the volume of ash was estimated to be $20\times10^6\mathrm{m}^3$ (Kobayashi and Ishihara, 1988). Alternatively, based on the distribution map of ash-fall deposits by Hagiwara *et al.* (1948), the volume of ash might be inferred to be roughly $130\times10^6\mathrm{m}^3$, if extrapolating the distribution function of ash-falls proposed by Eto (1989a) into the area outside of the map. In either case, including ash which might correspond to about $10-65\times10^6\mathrm{m}^3$ in volume of magma, the total volume of magma that erupted in 1946 would not be so much different from the estimated value of contraction, i. e., about $230\times10^6\mathrm{m}^3$.

Here, the same inflation-deflation source as that in 1892-1914 is assumed because the height change in that period was large at every leveling station around Aira caldera, and thus it would result in the most reliable solution for the magma reservoir. In order to check this assumption, height changes at 2469-2458, 2485-2487, and 2501-2504 located at southwest, northeast, and southeast of Aira caldera, respectively, are presented in Fig. 5. All of their temporal changes were similar to those at 2474-2480 in Fig. 4, although it was, of course, not exactly the same. This suggests that the present assumption is supported at least to some extent.

5-4 Consumption of magma in the 1970s and 1980s

In the 1970s and 1980s, small explosions occurred frequently at Sakurajima volcano. During the same period, Aira caldera almost stopped inflating or began to deflate slightly. Based on the elaborate observation of ash fall, it was pointed out that, roughly speaking, when the quantity of ash-fall deposits exceeded 10×10^6 ton/year, inflation stopped and deflation began at Aira caldera (*e.g.*, Sakurajima Volcanological Observatory, 1995). This weight may be $15-17\times10^6$ ton/year if the fine ash distributed outside the analyzed area is considered using the dis-

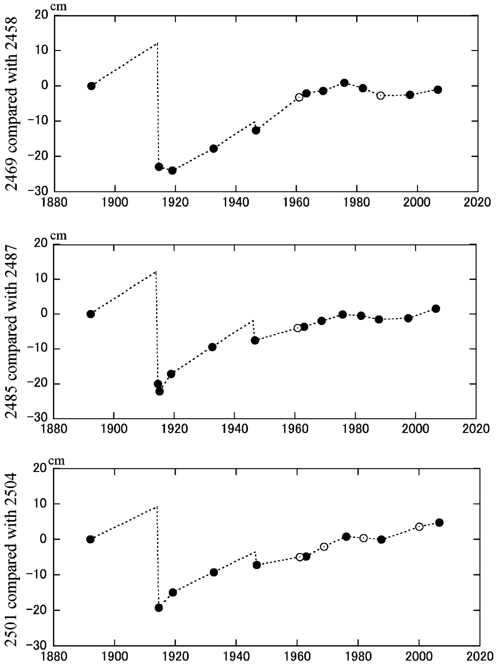

Fig. 5. Height changes at stations 2469, 2485, and 2501 compared with 2458, 2487, and 2504, respectively. Open circles are extrapolated from the data at adjacent stations.

tribution function of ash-falls proposed by Eto (1989a). However, the weight corresponds to only about 5–9x10^6 m^3/year in volume of magma, far less than the probable supply rate of magma between 1892 and the 1960s, i.e., 16x10^6 m^3/year, excepting at least a few years after the 1914 eruption.

6. Discussion on the balance of magma supply and consumption

6–1 Models to explain the volumetric balance in 1914

The volume of extruded lava in 1914 might not necessarily correspond to that of contraction, if vacant spaces existed in the magma reservoir. In addition, if the inflation rate accelerated just before the eruption, the inferred volume of the contraction would be increased. Although these factors could decrease the missing volume mentioned in Section 5–2, the effect would be limited quantitatively.

The possible inconsistency of the volumetric balance could be explained if all of the erupted materials in 1914 were not supplied from the magma reservoir at about 10 km in depth at Aira caldera, but also from another source inside Sakurajima volcano. It is clear that if part of the erupted material was previously stored in Sakurajima volcano itself, the amount of the co-eruptive supply from the reservoir at Aira caldera would be less than the total volume of the eruption. Quantitatively, however, it will not be easy to compensate the large difference because a deflation was not dominant at Sakurajima volcano in 1914 (cf. Fig. 1).

Considering the difficulties discussed above, the following explanations might be possible. (i) First, a supply of magma from a deeper source beneath Aira caldera might explain the missing volume. In the pre-eruptive period, magma must have come up to the reservoir of Aira caldera year by year from the deeper source. In case of the large-scale eruption, once a conduit has opened from the reservoir at Aira caldera to Sakurajima volcano, magma might have been supplied promptly from the deeper source to the reservoir, or directly to the surface craters of the volcano. If so, the volume change of the magma reservoir at Aira caldera does not necessarily coincide with the volume of erupted materials.

(ii) Second, if the reservoir at Aira caldera and the craters at Sakurajima volcano are in fact connected by a conduit, the upward slope should be, roughly speaking, only 45 degrees or less. Considering this, another speculation might also be possible: Materials erupted at Sakurajima volcano might not have been supplied from the reservoir at Aira caldera but from another deeper source located beneath the volcano. If this deeper source also connected with the reservoir at Aira caldera, after the large eruption at Sakurajima volcano, the magmatic pressure must have decreased not only at this deeper source but also at the reservoir of Aira caldera. This would result in a possible withdrawal of magma and the volume contraction at Aira caldera.

All possible explanations have not yet been established, and thus detailed physical and petrological considerations are left for further study, including an evaluation of the present calculation based on a simple inflation-deflation model.

6–2 Balance of magma supply and erupted materials since the 1970s

In the case of the eruptive activity at Sakurajima volcano during the 1970s and 1980s, the volume of erupted materials was reported to be far less than the inferred amount of magma supply at Aira caldera, as mentioned in Section 5–4. In this period, there were no observations for accumulation of considerable volume of magma at Sakurajima volcano or any other shallow place (*e.g.*, Ishihara and Eto, 1978; Eto, 1989b; Eto *et al.*, 1997; Iguchi *et al.*, 2008; Yamamoto *et al.*, 2010). Although it would not be enough in volume, an underestimation of the erupted materials, *e.g.*, fine ash ejected high into the sky might contribute to the deflation of the reservoir during this period. A temporal change in the magma supply rate at Aira caldera might be another possibility. Observations might strongly suggest this (*e.g.*, Eto *et al.*, 1997; Iguchi *et al.*, 2008; Yamamoto *et al.*, 2010), but no particular reason for such a change has been confirmed. Further discussions are desirable in the future.

7. Conclusions

Ground deformation around northern Kagoshima Bay, especially the height change between stations 2474 and 2480 was re-examined for the last 120 years. Here, northern Kagoshima Bay approximately overlaps the collapsed area of Aira caldera. With respect to the present results, the following points have been clarified.

(1) Along the leveling route of special interest, several stations including 2474 and 2480 were surveyed twice before the 1914 large eruption at Sakurajima volcano, revealing a marked pre-eruptive inflation of a plausible magma reservoir at Aira caldera.

(2) Around the early 1970s, the magma storage at Aira caldera might have exceeded the level observed in 1900 and approached the inferred level before the 1914 eruption based on the history of the height change between 2474 and 2480. This could be the reason for the remarkable repetition of explosive activity continuing at Sakurajima volcano in the 1970s and 1980s. If magma was not supplied smoothly to Sakurajima volcano during that period, a large eruption could have occurred.

(3) Explosive activity and ash ejection declined since the 1990s, and the height of 2474 compared with 2480, i.e., the inflation at Aira caldera, is probably again approaching the inferred level before the 1914 eruption. If the inflation continues, it may result in the next large-scale eruption in the near future.

(4) A deflation model for the 1914 eruption was re-analyzed, i.e., the depth of the source and the volume contraction are estimated to be 10.4 km and $940 \times 10^6 \mathrm{m}^3$, respectively. In addition, $16 \times 10^6 \mathrm{m}^3$ of magma is considered to have accumulated annually before and after the period of a large eruption at least up to the early 1970s.

Although several preliminary possibilities have been discussed, a quantitative balance of magma accumulation and erupted materials has not yet been explained well. For a better understanding of the volcanic process, detailed discussion is left for further study, including investigating the plausibility of the values obtained in the present paper.

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(Editorial handling Masato Iguchi)

120年間にわたる姶良カルデラの膨張収縮過程と桜島火山における大きな噴火の可能性

山科健一郎

桜島火山の噴火活動について見通しを得るため，北部鹿児島湾とほぼ位置が重なる姶良カルデラの周りの地殻変動について，特に水準点2474番と2480番の相対的な高さの変化に注目して検討を加えた．この区間では，これまで注目されることがほとんどなかったが，1914年の桜島火山の大きな噴火に先立って明瞭な膨張が生じていたであろうことが確かめられた．これにより，大きな噴火に先立って姶良カルデラ地下に蓄えられたマグマの1914年時点の限界量が推測される．1914年の噴火によって姶良カルデラでは顕著な収縮が生じたが，その後膨張が進んで1900年（大噴火まで14年）の水準を超え，1970年代初め頃には1914年の限界値にかなり近づいたと考えられる．桜島では，1970年代から80年代にかけて爆発的活動が活発に続いた．この期間，姶良カルデラの膨張は停滞およびやや後退していたが，桜島の爆発的な活動が低下すると再び変動が進み始めた．近年，ここで推測された1914年の限界値にさらに近づきつつあり，大きな噴火の可能性があり得ることを示している．一方，姶良カルデラ地下のマグマ量の増減と桜島からの噴出物量の収支については課題があり，今後の検討に委ねられる．