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6. *Relations between the Eruptions of Various Volcanoes and the Deformations of the Ground Surfaces around them.*

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Introduction

It is well known that on the occasions of the great volcanic eruptions the enormous volume of substance which constitutes the earth's crust moves up to the earth's surface as lava flow and fragmental ejecta. Of course, the ejection of lava is always accompanied with the movements of the substances in the earth's crust, and it causes the deformation of the earth's surface. The changes of the state in the earth's crust seem to have a close relation to the mechanism of volcanic eruption. From this point of view, the various types of deformation are investigated in this paper.

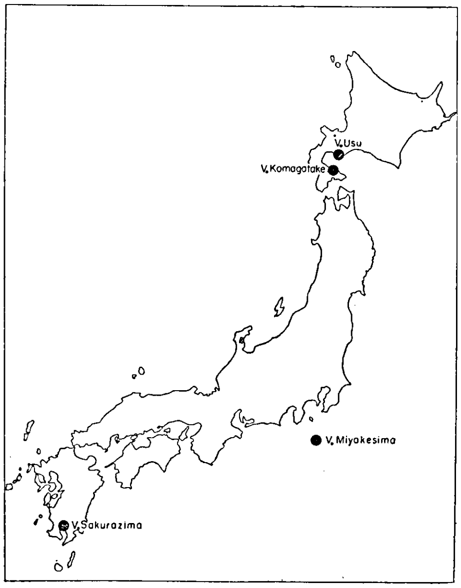


Fig. 1. Locality of the volcanoes concerned with the present discussion, in Japan.

In fact, the remarkable deformation of the earth's crust around the volcanoes has been observed by the precise surveys. F. Ōmori[1] investigated for the first time the vertical displacement of the ground surface around the Usu Volcano before and after the 1910 eruption by precise levellings. And in the 1914 eruption[2] of the

1) F. ŌMORI, *Bull. Imp. Earthq. Inv. Com.*, **5** (1911-13), Nos. (1, 2), **9** (1920), No. 2.
2) F. ŌMORI, *Bull. Imp. Earthq. Inv. Com.*, **8** (1914-19), Nos. (1-6).

Sakurazima Volcano he observed the remarkable depression over the wide surrounding area. Thereafter the precise levellings or triangulations were always executed before and after notable volcanic eruptions in Japan. However, for other districts we have not the data of the survey, except for the Kilauea Volcano, Hawaii.

Thus the feature of the crustal deformation seems to have been obtained nearly sufficiently, but the physical meaning of these notable results has not yet been discussed. The writer investigated the characteristics of the crustal deformation around volcanoes and discussed the mechanism of these phenomena. This paper is composed of the following parts;

Part 1. Relation between the Eruptions of the Sakurazima Volcano, Japan, and the Deformation of the Ground Surface around It
Part 2. The Deformations of the Ground Surface around the Kilauea Volcano, Hawaii, accompanied by the 1924 Eruption
Part 3. Relations between the Deformations of the Ground Surface around the Volcanoes and Other Volcanic Phenomena

Part 1. Relation between the Eruptions of the Sakurazima Volcano, Japan, and the Deformation of the Ground Surface around It.

The 1914 eruption of the Sakurazima Volcano is one of the greatest eruptions in recent years. The volume of ejecta amounted to about 2.2 km^3, and the deformation of the ground surface was very remarkable. The results of precise survey on the deformation were obtained by F. Ōmori and the circular depression of the coast along Kagosima Bay was measured by him. He resurveyed these area in 1915 and 1919,

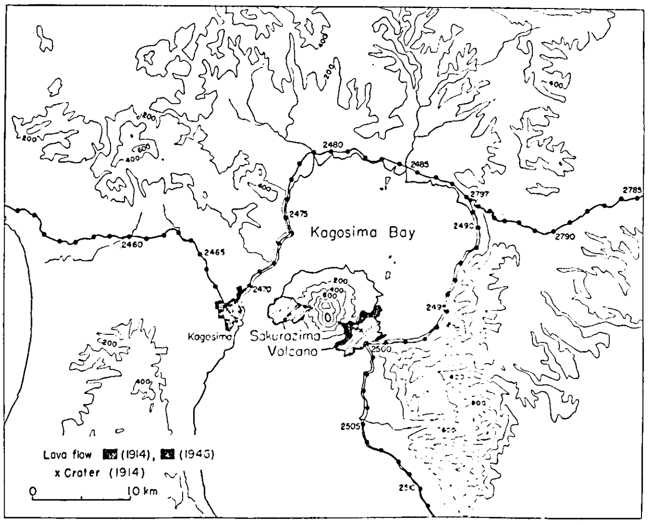


Fig. 2. Topographical map around the Sakurazima Volcano and levelling route in the area.

and found the subsided area recovering. Thereafter, resurveys were carried out in 1932, 1946 and 1957. These results have been discussed by C. Tsuboi[3], N. Miyabe[4] and Y. Harada[5], from the stand point of tilting of land blocks, and T. Minakami and A. Okada[6] recently.

The writer investigated the character of the ground deformation and discussed the mechanism of deformation and its volcanological significance.

§1. The 1914 great eruption[7].

The Sakurazima Volcano is a andesitic volcano situated in Kagoshima Bay, Southern Kyūshū. The volcano consists of three cones ; Kita-Dake, Naka-Dake and Minami-Dake, of which the southern one (Minami-Dake) is active up to the present time.

On the 12th, Jan. 1914, the eruption took place from the two opposite flanks of the Minami-Dake. The numerous newly opened craters are arranged along a line through the centre of the Minami-Dake crater, in an ESE and WNW direction. The outbursts were very vigorous with ejection of lava fragments, pumices and vapour. The two branches of the lava streams flowed to the eastern and the western coasts of Sakurazima Island respectively and covered the area of 24 km^2 and the total volume of the lava of out-flow was estimated about 1.6 km^3. The total volume of lava fragments, pumices and ashes was about 0.6 km^3. Thus, the total sum of the ejecta amounted to 2.2 km^3. Before the eruption, felt earthquakes occured on the early morning of 11th, Jan. 1914 and the number of earthquakes increased to the commencement of the first eruption and thereafter decreased.

§2. The deformation of the ground surface accompanying the 1914 eruption of Sakurazima.

The 1914 eruption of Sakurazima was the largest one (as mentioned above) and the ground deformation of the surrounding area was also

3) C. TSUBOI, *Bull. Earthq. Res. Inst* , **7** (1929), 103. **10** (1932), 570.
C. TSUBOI, *Jap. Jour. Astr. Geophys.* **10** (1932–33), 93.

4) N. MIYABE, *Bull. Earthq. Res. Inst.*, **12** (1934), 471.

5) Y. HARADA, *Bull. Geogr. Surv. Inst.*, **1** (1950), 1.

6) T. MINAKAMI and A. OKADA, *Bull. Volcan. Soc. Jap.*, **1** (1957), 65.
A. OKADA, *Bull. Volcan. Soc. Jap.*, **2** (1957), 53.

7) F. ŌM RI, *loc. cit.* 2)

very remarkable. The subsidence of the coast of Sakurazima Island and the coast of Kagosima Bay were observed and also the tide gage at Kagoshima harbour recorded the changes of sea level. The deformation of the ground surface around the Sakurazima Volcano was surveyed quantitatively by means of the precise levelling and triangulation.

The surveys were executed in 1895 before the eruption and in June 1914 after the eruption, and these results of the precise surveys by F. Ōmori are indicated in Fig. 3 and Table 1. The deformation seems to have occured suddenly at the time of the 1914 eruption, considering the records of tide gage at Kagosima. Within the Sakurazima Island, although several triangulation points close to the craters were destroyed by the violent explosion, the vertical and the horizontal displacements were obtained by triangulation.

From the results of levelling and triangulation, the following characteristics of the deformation of the ground surface were clarified.

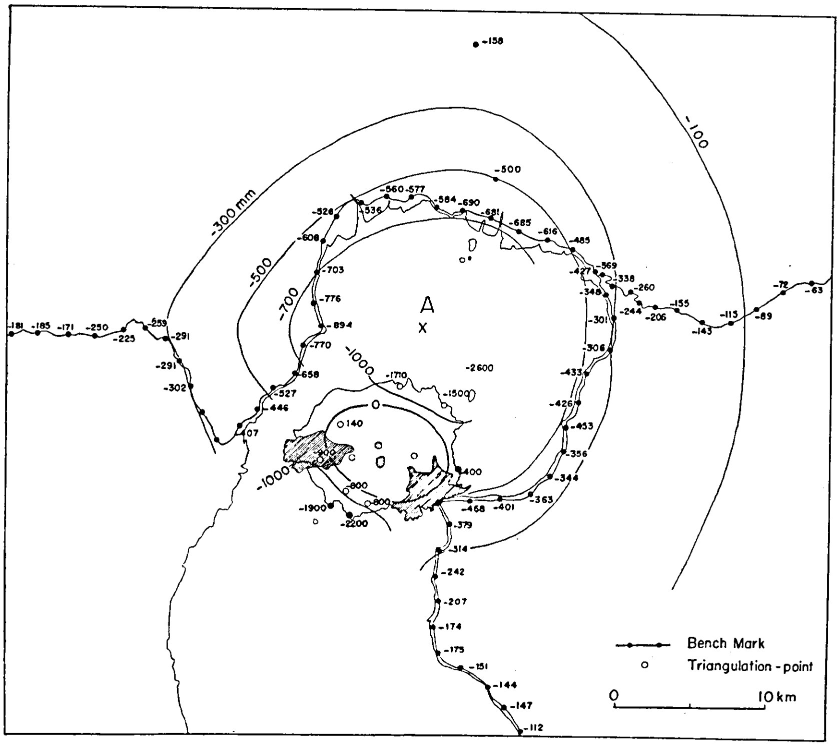


Fig. 3. Vertical displacements of the ground surface around the Sakurazima Volcano before and after the 1914 great eruption. (after F. Ōmori) (A): centre of depression.

Table 1.

B. M.	Vertical displacement Δh (1895—1914)	Distance from the centre of dipression d	B. M.	Vertical displacement Δh (1895—1914)	Distance from the centre of dipression d
2464	−291 *mm*	17.0 *km*	2488	−427 *mm*	11.9 *km*
2465	−291	16.2	(2797)	−369	12.15
2466	−302	15.75	2489	−348	12.1
2467		15.3	2490	−301	12.5
2468		15.3	2491	−306	12.3
2469	−407	13.5	2492	−433	10.95
2470	−446	12·45	2493	−426	11.05
2471	−527	10.4	2494	−453	11.0
2472	−658	8.7	2495	−356	12.0
2473	−770	7.85	2496	−344	12.4
2474	−894	6.7	2497	−363	12.5
2475	−776	7.75	2498	−401	11.6
2476	−703	8.25	2499	−468	11.2
2477	−608	9.15	2501	−379	12.6
2478	−526	9.85	2502	−314	13.95
2479	−536	9.7	2503	−242	15.8
2480	−560	9.55			
2481	−577	9.3	2797	−369	12.15
2482	−684	8.5	2796	−338	12.5
2483	−690	8.55	2795	−260	13.75
2484	−681	8.95	2794	−244	14.15
2485	−685	9.15	2793	−206	15.4
2486	−616	10.05	2792	−155	17.25
2487	−485	11.1	2791	−143	18.8

(1) The limited area close to the crater was upheaved locally and the maximum vertical displacement amounted to several metres. The value of tilting of the ground surface which was calculated from the results of triangulation amounted to $10^{-2} \sim 10^{-3}$.

(2) The circular wide area which subsided at the time of the explosion was not near the active crater of the Sakurazima Volcano, but in the Kagosima Bay 10 km north from the present crater. It is remarkable that the contours of equal depression are typically circular and concentric (Fig. 5). The maximum depression did not exceed 2 m and tilting of the ground surface was less than 10^{-4}.
The two types of deformation of the ground surface are very different as mentioned above.

The deformation of the ground surface accompanied by the volcanic eruption seems to have occured by the movement of the substances or the changes of the pressure in the depth of the earth's crust. The magnitude of the deformed area is affected by the depth of origin causing the deformation of the ground surface. Thus the above mentioned upheavals of the ground surface which extended to the limited area close to the crater were caused by the shallow origin, that is the upward forces near the surface accompanied by the out-flow of lava from a deep source. On the other hand, the origin of the depression extending to the wide surrounding area seems to be deeper. The position of the origin of the deformation is estimated by means of the application of the elasticity theory, in the following section.

§3. The mechanism of the deformation of the ground surface at the time of the eruption.

For the purpose of the estimation of the position of the origin of the depression, the following model of the mechanism of the deformation is assumed; (1) the earth's crust is a ideal semi-infinite elastic body and (2) the deformation of the earth's crust is caused by the sperical source with hydro-static pressure in the earth's crust.

With respect to the assumption (1), the sudden deformation of the earth's crust at the time of the eruption seems to be elastic in the first approximation, although the earth's crust is a visco-elastic body in a long time deformation. It is the writer's opinion that the assumed spherical origin (2) seems to harmonize well with the idea of the magma resevoir under the earth's surface.

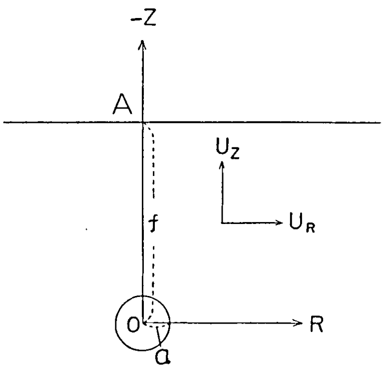


Fig. 4 (a).

According to the elasticity theory, the calculated deformation of the semi-infinite elastic body which is caused by the change of the hydrostatic pressure in a small sphere in the semi-infinite elastic solid is as follows[8]. (Fig. 4.)

8) N. YAMAKAWA, *Zisin* (*Jour. Seis. Soc. Japan*), [ii] **8** (1955), 84.

$$\left.\begin{aligned} U_R &= -\frac{a^3P}{4\mu}\frac{R}{\{(Z+2f)^2+R^2\}^{5/2}}\cdot(5Z^2+14fZ+8f^2-R^2) \\ &\quad +\frac{a^3P}{4\mu}\left[\frac{R}{(Z^2+R^2)^{3/2}}+\frac{R}{\{(Z+2f)^2+R^2\}^{3/2}}\right] \\ U_Z &= \frac{a^3P}{4\mu}\frac{1}{\{(Z+2f)^2+R^2\}^{5/2}}\cdot(7Z^3+38fZ^2+68f^2Z+40f^3+4fR^2+ZR^2) \\ &\quad +\frac{a^3P}{4\mu}\left[\frac{R}{(Z^2+R^2)^{3/2}}+\frac{Z+2f}{\{(Z+2f)^2+R^2\}^{3/2}}\right] \end{aligned}\right\} \tag{1}$$

where

U_R: displacement in the radial direction (R-axis direction)
U_Z: displacement in the direction vertical to the surface
a: radius of the sphere with the hydrostatic pressure
P: change of the hydro-static pressure in the sphere
f: depth of the centre of the sphere from the surface
$\mu(=\lambda)$: Lame's constant

The equations (1) are first aproximation for the case of $a/f \ll 1$. If, take $Z=-f$, the surface deformation is obtained as follows,

$$\left.\begin{aligned} \Delta d &= \frac{3a^3P}{4\mu}\frac{d}{(f^2+d^2)^{3/2}} \\ \Delta h &= \frac{3a^3P}{4\mu}\frac{f}{(f^2+d^2)^{3/2}} \end{aligned}\right\} \tag{2}$$

in which $d\ (\equiv R)$: radial distance on the surface from the point A.
Δd: displacement in the direction of R-axis on the surface
Δh: vertical displacement on the surface.

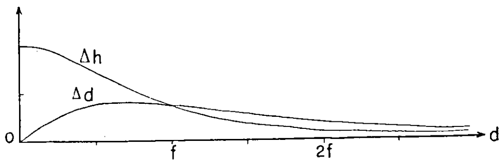


Fig. 4 (b). Calculated curves of the vertical displacement (Δh) and of the horizontal displacement (Δd), versus the radial distance (d).

Thus, if the radius of a sphere is relatively small, the form of the deformation curves is a function of the depth only and the values of displacements depends on P, a and μ.

Comparing the actual deformation by the precise survey with the calculated one, the agreement is surprising when the depth of a sphere is (10±1) km. (Fig. 5) But, we can not obtain uniquely the radius of a sphere and the change of pressure. Fig. 6 is another expression of the relation between the calculation and the observation. The curve

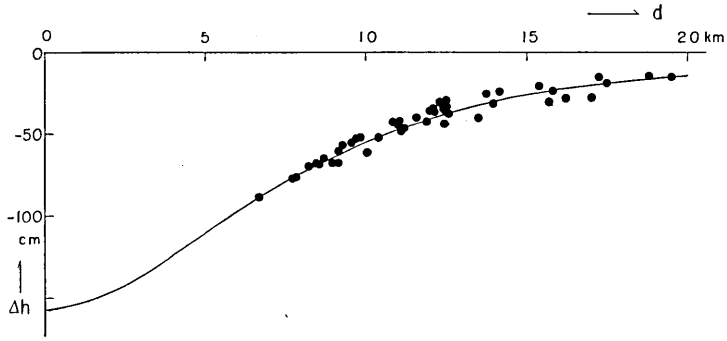


Fig. 5. Relation between the vertical displacements (Δh) of bench marks and the displace distances (d) from the centre of depression (A) to bench marks. The curve is calculated result for the case of the depth 10 km of the spherical origin.

(II) in Fig. 6 shows the vertical displacements of bench marks expected from the calculation along the levelling route and it is completely similar with the variation of the actual displacements of bench marks (III). Therefore, it is possible to explain the deformation of the ground surface by the theoretical results of the deformation of a uniform earth's crust, although the curve (III) has been discussed as a tilting movement of land blocks.

Thus the depression in the wide area around the Sakurazima Volcano seems to have been caused by the decrease of pressure in a spherical origin at the depth of 10 km and the sphere corresponds perhaps to the magma reservoir and the decrease of pressure seems

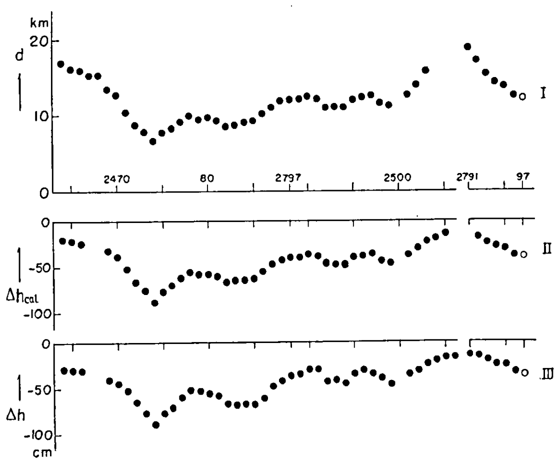


Fig. 6. Relation between the vertical displacement (Δh) and the radial distance (d). (I): radial distance (d) of bench mark from the centre of depression. (II): calculated vertical displacement (Δh cal) at the station of the radial distance (d). (III): observed vertical displacement of bench mark.

to be due to the out-flow or intrusion of lava at the time of the eruption.

On the other hand, the deformation of the limited area close to the crater which seems to have been caused by the upward movement of

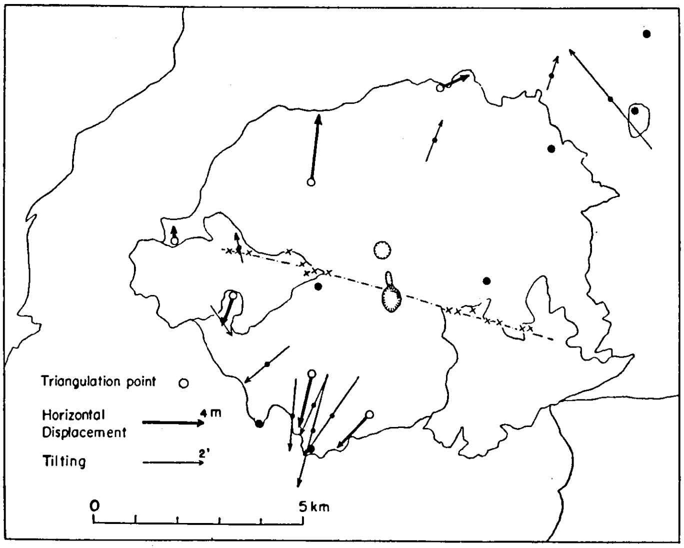


Fig. 7. Horizontal displacements of triangulation points (after F. Ōmori) and tilting of the ground surface calculated from the vertical displacements of triangulation points, in the Sakurazima Island. Chain line is a line of newly opened fissure. (the 1914 eruption)

magma and the out-flow of the lava is conspicuous and complicated, accompanying the fracture of the ground. According to the results of triangulation, the lands of both sides of the fissure lines moved to the out-ward and the upward direction, represented in Fig. 7.

The deformation related directly to the opening of the craters, the occurence of precursory earthquakes, and other volcanic phenomena. Their relations are discussed in Part 3.

§4. The deformations of the ground surface around the Sakurazima Volcano after the 1914 eruption (1914–1946).

Succeeding the precise levelling of 1914, resurveys were carried out in 1915, 1919[9], 1932[10] and 1946[11]. In the period from Aug. 1914 to Feb. 1915, the depression proceeded still. Therefore, the subsided area began

9) F. Ōmori, *loc. cit.* 2)
10) N. Miyabe, *loc. cit.* 4)
11) Y. Harada, *loc. cit.* 5)

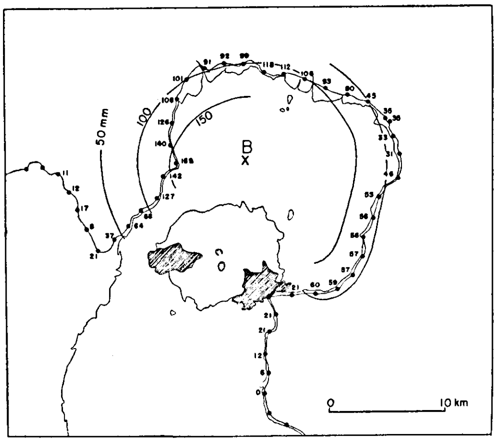


Fig. 8. Vertical displacements of bench marks in the Sakurazima district in the period 1915–1919. (after F. Ōmori) B: centre of upheaval.

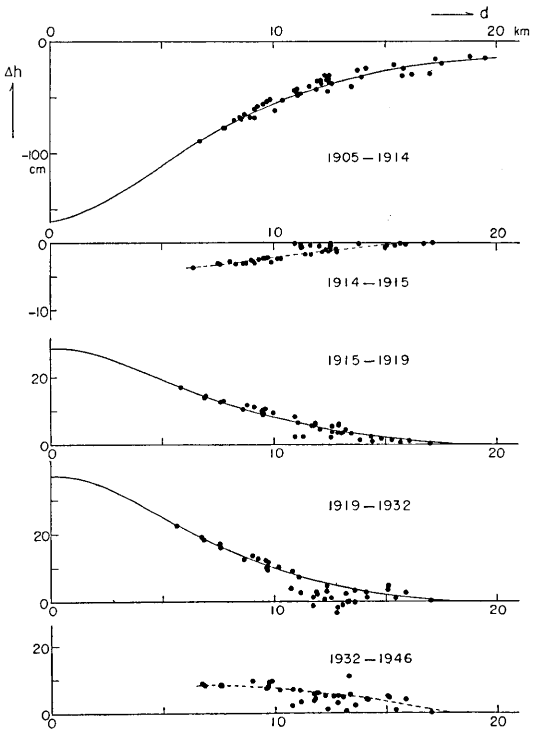


Fig. 9. Relation between the vertical displacements (Δh) of bench marks and the radial distance (d) of bench marks from the centre of depression (or upheaval) in each period.

to rise in the period from 1915 to 1919 and the upheaval continued to 1946. The deformations of the ground surface in each period are of similar type. As in the preceding section, the relation between the distances (d) from the centre of upheaval (or depression) to each bench mark and the vertical displacements (Δh) of each bench mark are shown in Fig. 9. In particular, the upheavals in the periods 1915–1919 and 1919–1932 correspond with the calculated deformation which is obtained by the increase of the pressure of the spherical origin of 10 km depth, like one at the time of the 1914 eruption. And the horizontal position of centres of the deformations agreed nearly with the centre of the depression of the 1914 eruption. The deformation in the period 1932–1946 is of a little different type from the other. It is noticeable that in this period the sudden subsidence corresponding to the 1946 eruption[12] might have occured in addition to the succeeding upheaval.

Thus, the above rising process of the ground surface around the volcano suggests the increase of the pressure in the lava reservoir after the 1914 eruption.

However, the slow movements of the earth's crust seem to be not elastic only, but to include a plastic deformation. Therefore, it is very complicated to investigate quantitatively the state of the pressure origin from the deformation of the ground surface.

§ 5. The relation between the deformation of the ground surface around the volcano and the volcanic activities of the Sakurazima Volcano.

On the basis of the above discussion, the process of the ground movements related to the volcanic activities of the Sakurazima Volcano is explained as follows. In the period preceding the 1914 eruption, high pressure had been stored up in the magma reservoir which is situated at a depth of 10 km in the earth's crust under Kagosima Bay. In 1914, the earth's crust was fractured by the compressed magma under the Sakurazima Volcano and the enormous volume of lavas flowed out suddenly from the craters (the 1914 great eruption). As the result of the out-flow of lava, the pressure in the magma reservoir decreased and the wide area around the volcano subsided remarkably. After the eruption, the rising of the area took place and succeeded to the 1946 eruption. This fact shows that the pressure in the magma reservoir increased gradually and at last the next out-flow of lava occured in 1946.

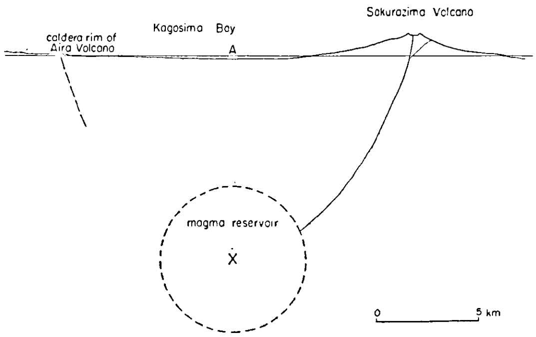


Fig. 10. Profile of the Sakurazima district.

It is quite interesting that the position of the magma reservoir which was obtained from the ground deformation is directly below the centre of the Aira caldera at the rim of which the Sakurazima Volcano stands. This indicates the close relation between the active Sakurazima Volcano and the Aira Volcano[13] which was active in the geological age. (Fig. 11)

12) T. HAGIWARA *et. al.*, *Bull. Earthq. Res. Inst.*, **24** (1946), 143.

13) T. MATSUMOTO, *Jap. Jour. Geol. and Geog.*, **19** (1943), Special No.

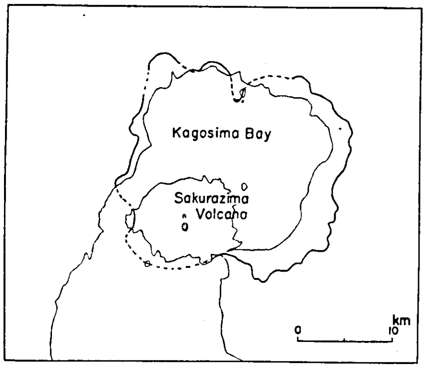


Fig. 11. Aira Caldera (after T. Matsumoto).

How are the surface activities of the volcano related to the ground movements around the volcano? The relation between the volume of the subsidence or upheaval of the wide surrounding area as mentioned above and the eruptive activities at the Sakurazima crater is shown in Fig. 12. It is obvious that the surface volcanic activities are affected greatly by the increase of the pressure in the magma reservior.

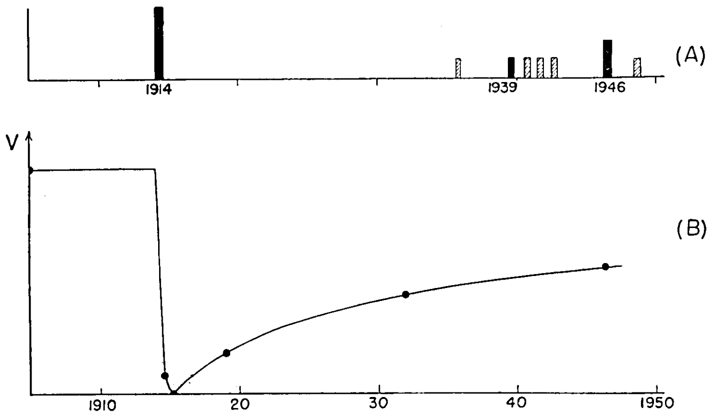


Fig. 12. Relation between the volcanic eruptions of the Sakurazima Volcano and the volume of the depression (or upheaval) in its surrounding area.

Table 2. Volcanic surface activities of the Sakurazima Volcano in the period 1900–1950[14].

Year	Valcanic Activities
1914 (Jan.–June)	Great eruption with outflow of an enormous volume of lavas
1935 (Sept.)	A small explosion (at summit crater)
1939 (Oct.)	A small flank eruption (with nuée ardent)
1940 (April–June)	Small explosions
1941 (April–June)	Small explosions
1942 (July)	Small explosions
1943–1944	Black vapour
1946 (March–June)	Great eruption with outflow of lavas
1948 (July)	Small exploisons
1950 (June–Sept.)	Small explosions

In the above discussion, we investigated mainly the deformation of the ground surface with the wide extent which seems to have been caused by the deep source. On the other hand, the deformation of the limited area near the crater is also remarkable and related to the other volcanic phenomena, but the writer will discuss this subject in the later part.

Part 2. The Deformations of the Ground Surface around the Kilauea Volcano, Hawaii, accompanied by the 1924 Eruption.

The Kilauea Volcano is a shield volcano in Hawaii Island and has erupted frequently at the rift zone on the flanks of the mountain. The 1924 eruption[15] is noticeable for the explosive eruption from the central crater (Halemaumau) and the remarkable deformation of the ground surface accompanying the volcanic activity. In this paper, the remarkable deformations of the ground surface around the crater are investigated on the basis of the precise surveys, in relation to the volcanic activity of 1924.

The 1924 eruption was investigated by various methods, namely the continuous observation of tilting of the ground surface at the volcano observatory, the measurement of the depths of the crater bottom, the seismometric observation, the precise levelling and triangulation of the surrounding area, etc. This study is due to these investigations, especially the interesting results of the precise surveys by R. M. Wilson.

§ 1. Analysis of the results of levelling survey.

The levellings on the surrounding area of the Kilauea crater were executed in 1912, 1921 and 1927. The net of levelling routes covers the area around the crater and is connected to a tide gage at Hilo by a levelling route from the Volcano House to Hilo, in order to obtain the absolute value of vertical displacement. (Fig. 13 (a), (b)).

The vertical displacements of the area in the periods 1912–1921 and 1921–1927 by R. M. Wilson[16] are shown in Fig. 14 and 15 respectively. The depression of the ground surface seems to have taken place suddenly at the time of the 1924 eruption, because the continuous tilt observation

14) H. TSUYA and T. MINAKAMI, *Bull. Earthq. Res. Inst.*, **18** (1940), 318. Geophysical Review, (monthly Journal by the Central Meteorological. Observatory)

15) T. A. JAGGER, Origin and Development of Crater (1947)

16) R. M. WILSON, *Univ. Hawaii Res. Publ.*, No. 10 (1935).

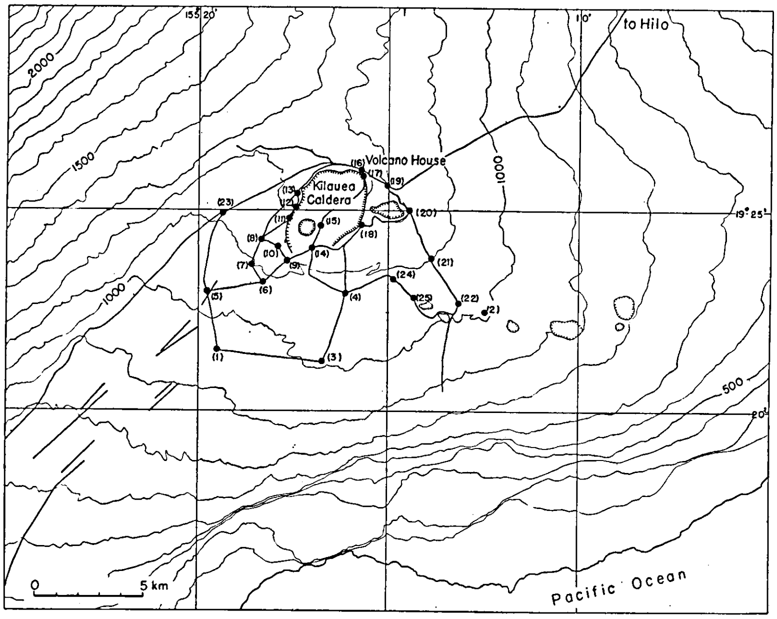


Fig. 13 (a). Topographical map around the Kilauea crater and levelling routes and triangulation points in the district.

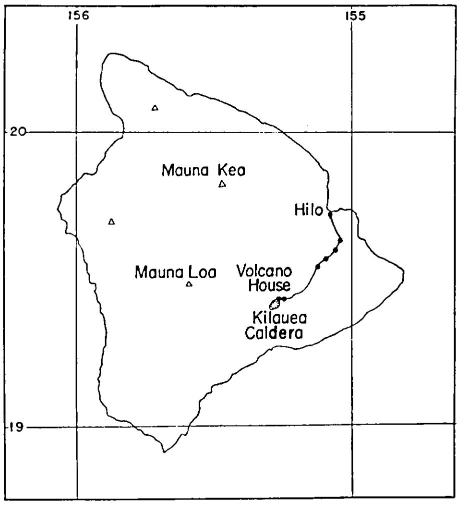


Fig. 13 (b). Levelling route from the Volcano House to Hilo.

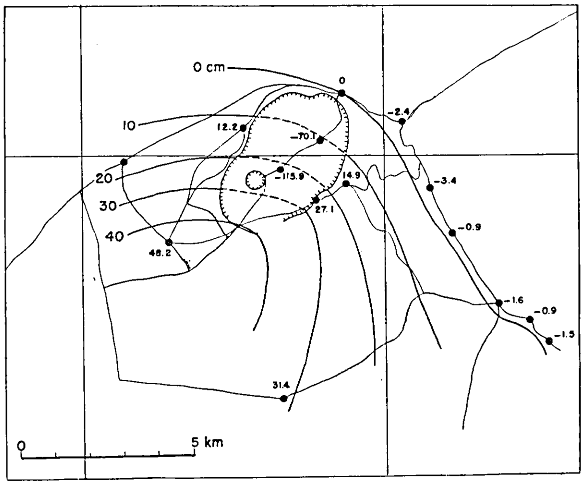


Fig. 14. Vertical displacements of the ground surface around the Kilauea crater in the period 1912–1921. (after R. M. Wilson)

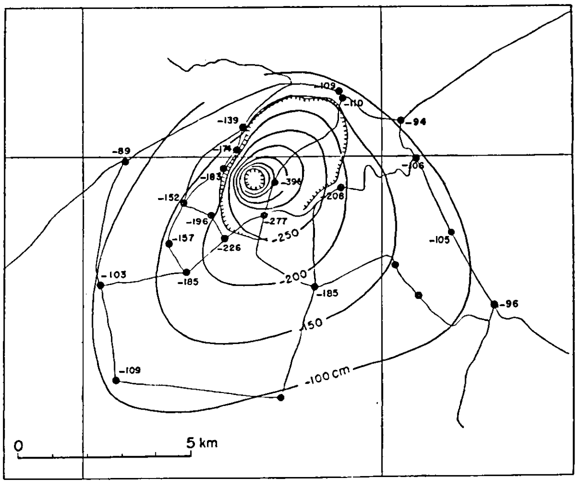


Fig. 15. Vertical displacements of the ground surface around the Kilauea crater in the period 1921–1927. (after R. M. Wilson)

of the ground surface at the volcano observatory at the rim of the Kilauea Caldera recorded the abrupt change of tilting corresponding to the above mentioned depression which was obtained by the levelling survey. At the same time, the bottom of the crater subsided and the change of the depth of the bottom amounted to 1200 feet. These records[17] are reproduced in Fig. 16.

As seen in Fig. 14 and 15, the vertical movements of the ground surface in the caldera region differs from the other area. In the period 1912–1921, the outer region rose uniformly, but the inner region of

Table 3.

No.	Station of Bench Mark and Triangulation Point	Vertical displacement Δh	Distance from the centre (A) d	Location of Station		Horizontal displacement	
				x (W)	y (N)	u (W)	v (N)
		cm	*km*	*m*	*m*	*cm*	*cm*
1	Koae	108.5	6.55	4,069.1	−5,664.7	0	0
2	Puu Huluhulu		8.14	−8,227.5	−3,882.8	0	0
3	Ohale	93.3	5.12	− 766.3	−6,170.4	− 6.1	22.9
4	Ahua Kamokukolau	184.7	2.32	−1,851.7	−3,035.5	16.5	107.3
5	Aa	102.7	5.46	4,531.2	−2,930.3	− 21.0	3.7
6	Nose	184.7	2.90	1,905.3	−2,534.4	− 77.1	32.9
7	Cone Peak	157.0	3.08	2,430.0	−1,666.3	− 78.0	6.1
8	Pali	152.4	2.65	2,000.4	521.8	− 79.3	− 3.7
9	Sand Hill	225.9	1.46	812.0	−1,511.5	− 74.4	52.1
10	Cracks	196.3	1.85	1,278.0	− 854.7	− 98.5	10.7
11	South Rim	182.9	2.01	751.3	407.5	−115.8	− 43.0
12	North Rim	174.3	2.29	445.6	940.3	− 81.4	− 66.1
13	Uwekahuna	139.0	2.83	319.1	1,604.4	− 57.3	− 43.0
14	Spit	277.1	0.40	− 178.9	− 896.1	1.2	96.3
15	Begger	395.9	1.16	662.0	78.6	132.3	31.1
16	Observatory	108.5	4.11	2,635.0	2,468.0	− 4.6	5.8
17		110.3	3.93				
18		207.6	2.38				
19		93.9	4.74				
20		106.1	4.63				
21		104.5	5.23				
22		96.0	6.92				
23		89.6	4.72				
24		150.	3.74				
25		125.	4.75				

17) R. H. FINCH and T. A. JAGGER, *Bull. Seism. Soc. Am.*, **19** (1929), 38.

the caldera subsided remarkably. Thereafter, in the period 1921–1927 the bench marks within the caldera subsided also in an exceptionally large way. The phenomenon that the caldera region subsided always relatively compared with the outer region seems to have some relation to the caldera formation.

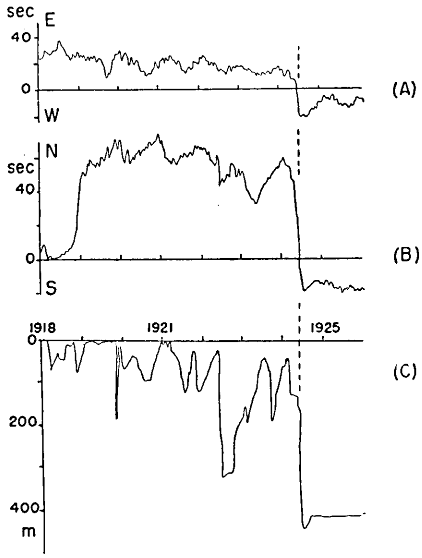


Fig. 16. (A): Tilting records in EW direction at the Observatory. (B): in NS direction. (C): Change of the depth of the crater bottom. (after T. A. Jagger and R. H. Finch)

On the other hand, the wide surrounding area except the caldera region subsided circularly and symmetrically at the time of the 1924 eruption; that is, the contours of equal depression are concentric circles of which the centre is situated at the station (A) near the crater, as shown in Fig. 17. Moreover the distribution of tilting of the ground surface was obtained from the results of levelling (Fig. 18) and the vectors of tilting concentrate also on the above centre of the depression. And the relation between the distanec (d) from the centre of depression to each bench mark and the vertical displacements (Δh) of bench marks is shown in Fig. 19 (a). However, on the wide area which is more distant than 10 km from the centre of depression, there is only one levelling route from the Volcano House to Hilo (north-east direction) and consequently it is insufficient in order to know the areal deformation. Therefore, the circular

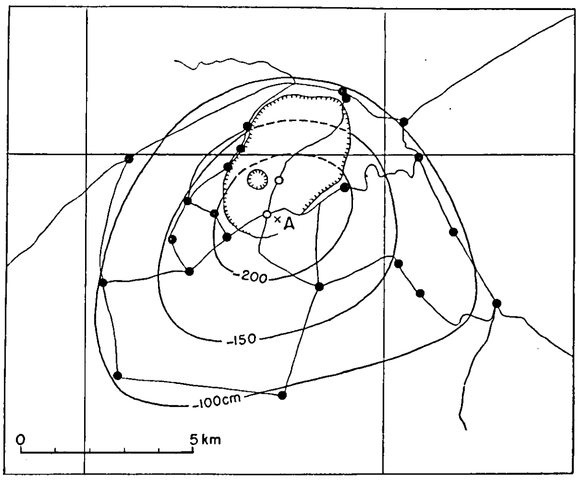


Fig. 17. Contours of equal depression around the crater, excluding the caldera region. (1921–1927) (A): Centre of depression.

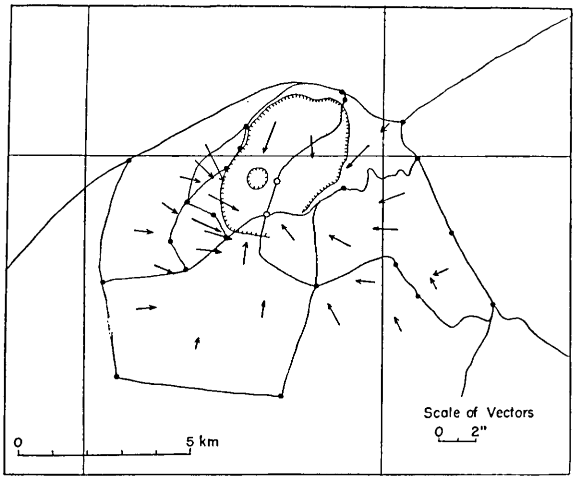


Fig. 18. Tilting of the ground surface calculated from the results of levelling survey (1921–1927).

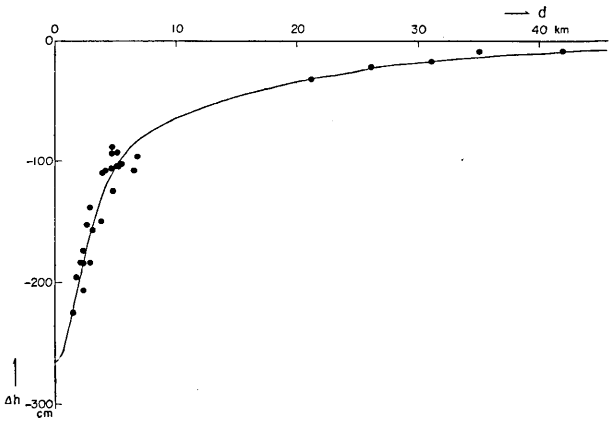


Fig. 19 (a). Relation between the vertical displacement (Δh) of bench marks and radial distances (d) of bench marks from the centre of depression, in the 1924 eruption. Curve is the calculated result of the vertical displacements versus the radial distance (d).

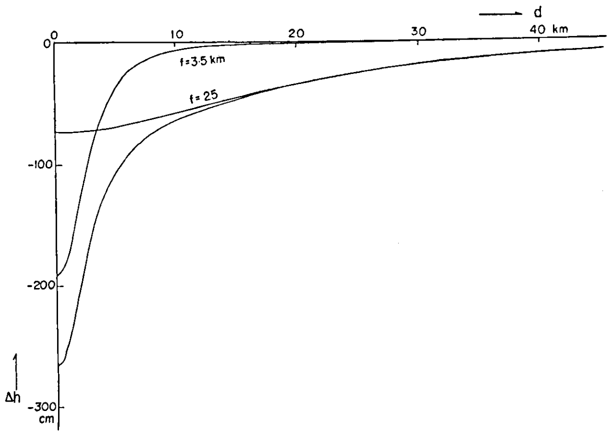


Fig. 19 (b). Calculated vertical deformation curves for the cases of the depth 3.5 km and 25 km, and the superposed deformation curve.

symmetrical deformation with its centre at the station (A) is assumed to be also true in the case of the distant area, in the following discussion.

Considering the depression to have taken place in short time and to be a circular symmetry, the following assumptions are given on the ground deformation, as in Part 1. ; (1) the earth's crust is a semi-infinite elastic solid and (2) the deformation of the earth's surface is caused by a spherical source with hydro-static pressure at a depth in the earth's crust. The calculated result of the above deformation by the elasticity theory has been shown in the preceding Part. [Eq (2)]

The observed depression may consist of two different parts, compared with the theoretical results of the deformation ; the one of the relatively limited area close to the centre of depression which should have been caused by the decrease of the hydro-static pressure of the shallow source and the other of the wide surrounding area by the deep source. By the comparison between the observed and the calculated values, the depths of two sources were determined as follows ; the shallower 3.5 ± 1 km and the deeper 25 ± 5 km, as shown in Fig. 19 (a) (b). The superposition of the above mentioned solutions which are non-linear is impossible mathematically, but the mutual effects of the two boundary conditions seem to be negligible, because the depths of the two sources are very different from each other, and therefore the superposed solution will be applicable in the present case.

Thus, the circular depression of the ground surface around the Kilauea crater before and after the 1924 eruption is explained as the elastic deformation of the ground caused by the decreases of the pressures of the two spherical sources at the depths 3.5 ± 1 km and 25 ± 5 km below the station (A) near the crater (Halemaumau).

§2. Analysis of the result of triangulation.

The triangulation in the Kilauea district was executed in 1922 and 1926 also by R. M. Wilson[18]. The horizontal relative displacements of triangulation points in the period 1922–1926 are shown in Fig. 20, but the triangulation points, Koae (1) and Puu Huluhulu (2), were fixed as the base points. The deformation also seems to have taken place suddenly at the time of the 1924 eruption, like the above mentioned depression. The vectors of the horizontal displacements concentrate on a station near the crater and are larger in the near vicinity of this

18) R. M. WILSON, *loc. cit.* 16)

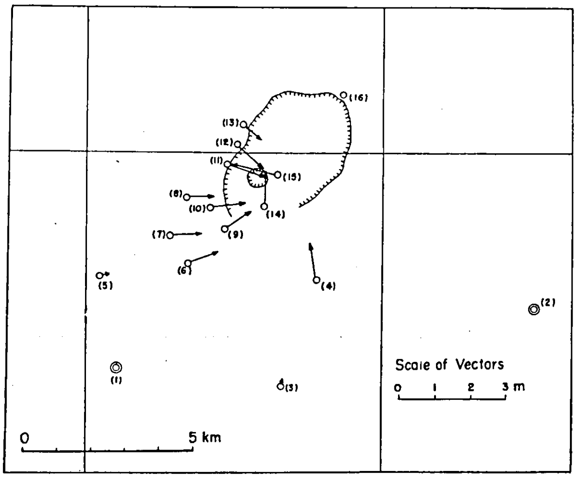


Fig. 20. Relative horizontal displacements of triangulation points around the Kilauea crater in the period 1922–1926, fixed station (1) and (2). (after R. M. Wilson)

station, like the vectors of tilting. As will be discussed in the next section, it seems that the horizontal deformations correspond to the above mentioned vertical one.

In order to the make clear the characteristics of the deformation, the two-dimensional strain on the ground surface caused by the horizontal deformation is calculated by means of C. Tsuboi's method[19]. If we take X and Y axes in the directions of west and north respectively and represent by u and v the westward and northward conponent of displacement of a triangulation point, then the dilatation, the rotation and the maximum shear are given as follows.

$$\begin{aligned} &\text{Dilatation} && \Delta=\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right) \\ &\text{Rotation} && \varpi=\frac{1}{2}\left(\frac{\partial v}{\partial x}-\frac{\partial u}{\partial x}\right) \qquad (3) \\ &\text{Maximum Shear} && \Sigma=\sqrt{\left(\frac{\partial u}{\partial x}-\frac{\partial v}{\partial y}\right)^2+\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)^2} \end{aligned}$$

The distributions of Δ, ϖ and Σ are shown in Fig. 21 (a), (b) and (c) respectively. From the results, the following characteristics are noticeable.

(1) The contours of the equal dilatation and maximum shear are

19) C. TSUBOI, *Jap. Jour. Astr. Geophs.*, **10** (1932–33), 93.

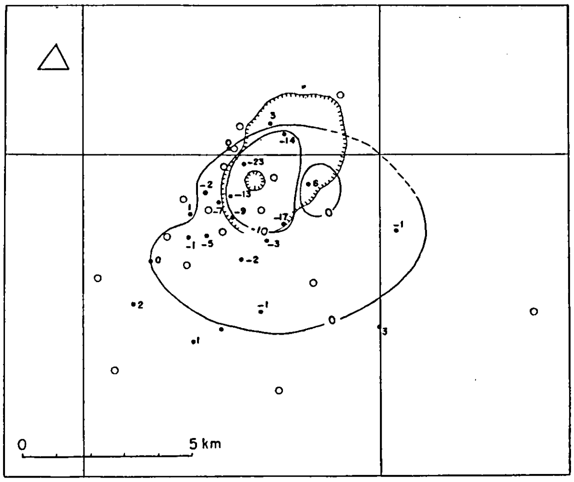


Fig. 21 (a).

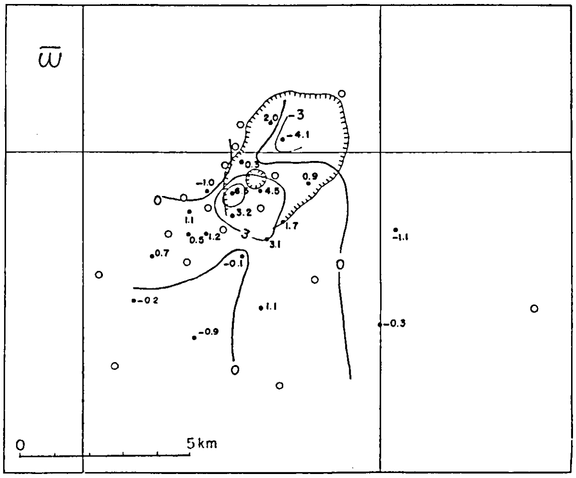


Fig. 21 (b).

Fig. 21 (a) (b). Two dimensional strain of the ground surface around the Kilauea crater;

(a): Dilatation in 10^{-4}

(b): Rotation in 10^{-4}

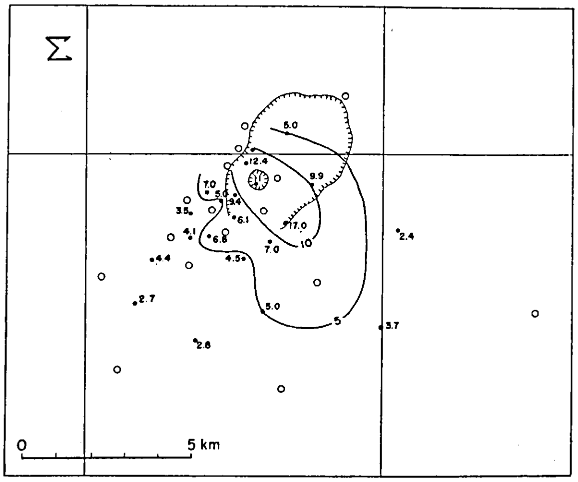


Fig. 21 (c).

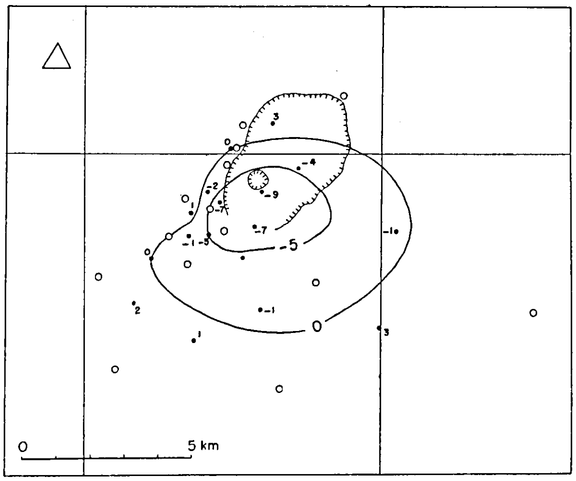


Fig. 21 (d).

Fig. 21 (c)(d). Two dimensional strain of the ground surface around the Kilauea crater;

(c): Maximum shear in 10^{-4}

(d): Dilatation, excluding the caldera region, in 10^{-4}

nearly concentric.

(2) The distribution of rotation is irregular, namely the area did not rotate systematically.

(3) Within the caldera, the strain amounted to 10^{-3}, against 10^{-4} on the outer region. This indicates that the horizontal movements of triangulation points in the caldera are exceptionally large.

Thus, excluding triangulation points within the caldera, the area around the crater is assumed as a uniform earth's crust, as in the preceding section, and then the distribution of dilatation on the area calculated again. (Fig. 21 (d)) The contours of equal dilatation are also concentric circles and their centre almost agrees with the centre of depression. (A).

§3. The relation between the horizontal and the vertical displacements.

As the stations of triangulation points coincide completely with a large part of bench marks of levellings, we can discuss sufficiently the relation between the horizontal displacements and the vertical displacements in the deformation accompanying the eruption. The result obtained from the measured values is shown in Fig. 22.

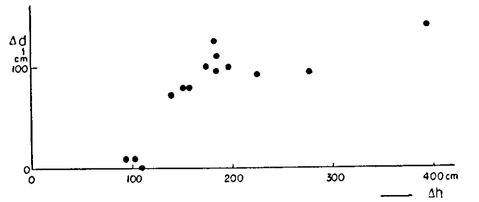


Fig. 22. Relation between the vertical displacements (Δh) and the relative horizontal displacements (Δd).

However, in the preceding discussion the stations of two triangulation points (Koae and Puu Huluhulu) were assumed to be immovable in the period, although they should have been displaced actually, more or less. Here, the horizontal displacements which are presumed from the theoretical result of the model of deformation obtained by levelling survey are assumed as displacements of the two stations. By this assumption, the absolute displacement of

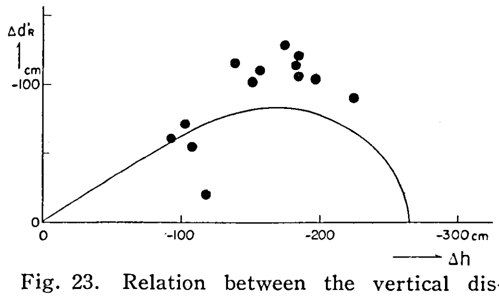


Fig. 23. Relation between the vertical displacements (Δh) and the radial components ($\Delta d_R'$) of horizontal displacements.

Curves show a theoretical result for the elastic model obtained from the result of levelling survey.

other triangulation points are estimated. The difference between the relative deformation and the absolute one obtained by the above procedure is not much qualitatively. Next, the relation between the radial component and the vertical displacement is shown in Fig. 23, and the relation between the radial component ($\Delta d_R'$) of the horizontal displacement and the radial distance (d) of the triangulation point from the centre of depression (A) is shown in Fig. 24. At the same time the calculated curve for the horizontal displacement of the model of deformation determined from the result of levelling are shown in Fig. 23 and 24, respectively.

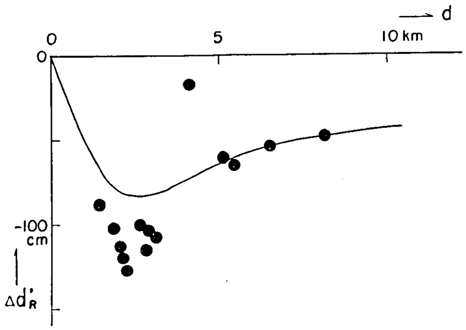


Fig. 24. Relation between the radial components of horizontal displacements ($\Delta d_R'$) and the radial distances (d) of the triangulation points from the centre (A). Curve is a theoretical result for the model.

Thus, it may be said that the elastic model obtained from the result of levelling survey is also consistent with the result of triangulation.

§4. Conclusion.

The results of the precise surveys by R. M. Wilson on the deformation of the ground surface at the time of the 1924 eruption are very interesting because of the large scale of the deformation itself and also for the reason that triangulation and levelling were executed simultaneously and independently.

According to the above discussion, the remarkable depression of the ground surface seems to have been caused by the decrease of the pressure of two spherical sources situated at depths of 3.5 km and 25 km. The changes of the pressure of the spherical sources may correspond perhaps to the decrease of the hydro-static pressure of magma reservoirs below the area and may have been caused by the intrusion or the extrusion of magma from the reservoirs. The sudden subsidence of the crater bottom before and after the 1924 eruption (Fig. 16) also suggests the above conclusion.

On the other hand, the volume of extruding lavas from the crater (Halemaumau) is relatively little. Therefore, the depression seems to be caused not by the out-flow of lavas from the crater, but by the intrusion of magma or the invisible out-flow of lavas from the rift zone under the sea. Thus, it may be concluded that the volcanic activity in 1924 took place on a large scale under the earth's surface rather than on the surface.

Part 3. Relations between the Deformations of the Ground Surface around the Volcanoes and Other Volcanic Phenomena.

As mentioned in the preceding Parts, both the eruptions of the Sakurazima Volcano (1914) and of the Kilauea Volcano (1924) were accompanied by typical enormous depression. However, there are various types of the ground surface deformation. For example, at the time of the eruption of the Usu Volcano, a remarkable upheaval of the ground surface took place, in particular more than 100 m at the limited area close to the crater and on the other hand, the depression around it was of no account.

Thus the study of the physical meaning of such various types of ground deformation will give a clue to make clear the mechanism of the volcanic eruption. From the above-mentioned point of view, various eruptions are investigated in the present Part; namely, the Usu Volcano (1910 and 1943–1945), the Komagatake Volcano (1929), the Miyake-sima Volcano (1940), the Sakurazima Volcano (1914 and 1946) and the Kilauea Volcano (1924).

§1. The 1910 and the 1943–1945 eruptions of the Usu Volcano.

The Usu Volcano stands at the rim of the Tōya caldera (Tōya Lake) and erupted frequently forming the lava domes or the cript domes of dacite. In recent times, the new mountains of the Yosomi-yama and the Shōwa-sinzan were formed in the 1910 eruption and the 1943–1945 eruption respectively. The upheavals of the ground surface around the volcano were very remarkable in each case.

The 1910 eruption[20] The eruption commenced from the newly opened fissure on the north flank of the mountain on July 25, 1910 and the abundant volcanic detritus of various sizes which were not dedived from fresh lavas were ejected, but the out-flow of lava did not occur. Thereafter the limited area of the ground surface near the craters was upheaved largely and the rising amounted to about 100 m.

20) F. Ōmori, *loc. cit.* 1)

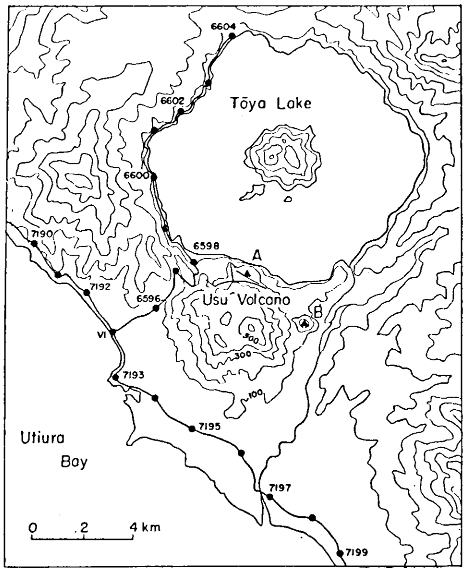


Fig. 25. Topographical map around the Volcano Usu and the levelling route in the district. A: new mountain (1910) B: new mountain (1943–45).

The phenomenon seems to have been caused by the uplift of the cript dome of very viscous lava. Preceding the eruption, a large number of earthquakes was felt in a wide area around the volcano and the radius of area of sensible motion of the strongest earthquake on July 24 amounted to about 60 km in NE direction and 140 km in SW direction.

The levelling surveys were executed repeatedly in 1905, 1911, 1912 and 1919[21]. The changes of level of bench marks before and after the 1910 eruption are shown in Fig. 26. The area around the craters was upheaved remarkably,

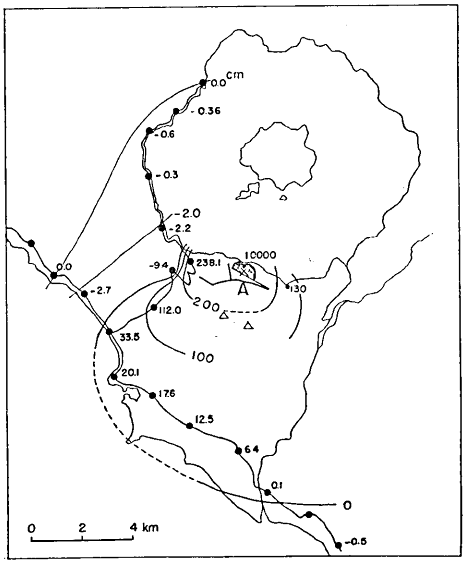


Fig. 26. Vertical displacements of bench marks and contours of equal vertical displacement around the Volcano Usu, before and after the 1910 eruption (1905–1919). (after F. Ōmori) A: new mountain.

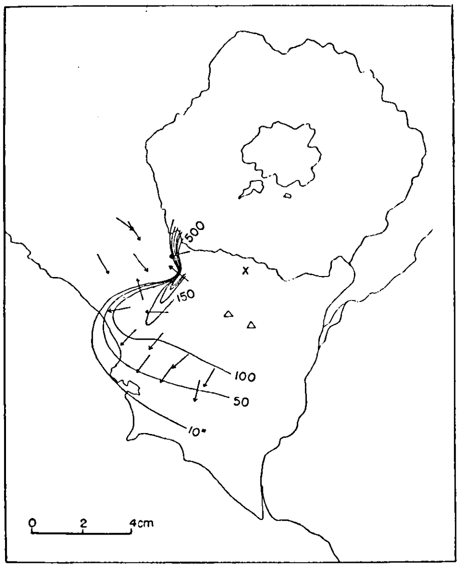
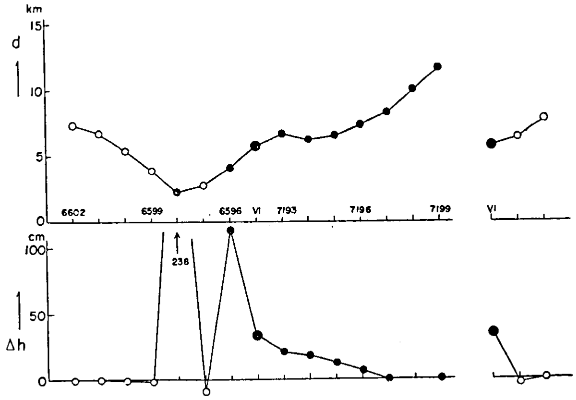


Fig. 27. Tilting of the ground surface calculated from the results of levelling survey (1910 eruption).

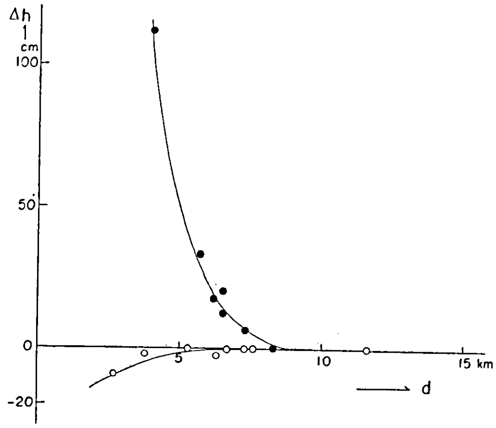
21) F. ŌMORI, *loc. cit.* 1)

with the exception of a small amount of depression of the western region. Fig. 27 is the distribution of tilting of the ground surface around the volcano which was calculated from the results of the levelling survey. The discontinuous boundary between the depression and the upheaval is conspicuous and it suggests the formation of a fault under the ground surface. The relation between the distances (*d*) from the centre of craters to bench marks and the vertical displacement (Δh) is shown in Fig. 28 (a) (b). It is remarkable that the branches of upheaval and of depression in Fig. 28 (b) are symmetrical.

The 1943–1945 eruption[22] The eruption forming the new mountain of the Shōwa-sinzan was a most famous one in recent years. The precursory earthquakes began to occure from Dec. 28, 1943. The strongest earthquake of Jan. 5, 1944 was felt as far as over 20 km from the volcano. After that, eruptions took place at the area of the east flank of the mountain in June, 1944. Successively, the area was upheaved remarkably by the intrusion of lava and lastly the lava dome extruded to a height of 300 m from the ground surface. The process of development of lava dome was investigated



(a)



(b)

Fig. 28. (a)(b) Relation between the vertical displacements (Δh) of bench marks and the radial distances (*d*) of bench marks from the centre of craters, in the 1910 eruption. open circle: depression, closed circle: upheaval.

22) T. MINAKAMI, T. ISHIKAWA, and K. YAGI, *Bull. Volcanologique*, [ii], **11**, (1951), 45.

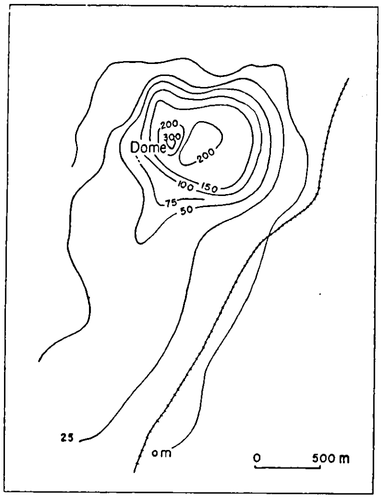


Fig. 29 (a). Upheavals of the ground surface in the vicinity of the new-mountain (the Shōwa-sinzan), at the time of the 1943-1945 eruption (after M. Kaneko).

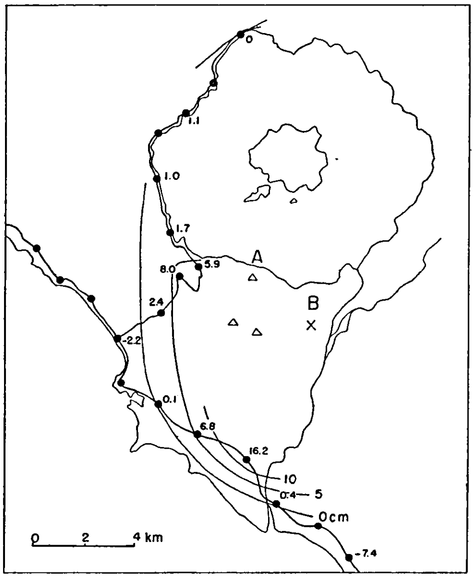


Fig. 29 (b). Vertical displacements of bench marks and contours of equal vertical displacements around the Volcano Usu before and after the 1943-1945 eruption. B: new mountain (after T. Minakami and A. Okada)

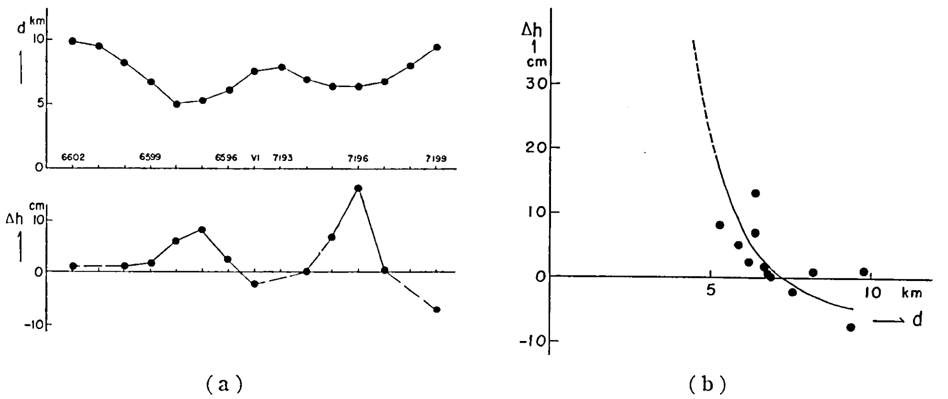


Fig. 30 (a) (b). Relation between the vertical displacements (Δh) of bench marks and the distances (d) from the crater to bench marks, in the 1943-1945 eruption.

particularly by many geophysists and geologists. The topographical change[23] in the vicinity of the new mountain concerning the 1943-1945 eruption are shown in Fig. 29 (a). The wide area around the volcano was upheaved also, according to the results of the levelling survey[24] in Fig. 29 (b). The relation between the distance (d) from the crater to the bench marks and the vertical displacements (Δh) at each bench mark are shown in Fig. 30 (a) (b),

These upheavals of the area near the crater as mentioned above seem to have been caused by the upward force accompanied by the uplift of the viscous lava, and the occurrence of the precursory earthquakes have reference to the magnitude of the ground deformation of this type.

§ 2. The 1929 eruption of the Komagatake Volcano[25].

The Komagatake Volcano is a andesitic strato volcano, in Hokkaido. In June 1929, it erupted at the central crater and ejected abundant

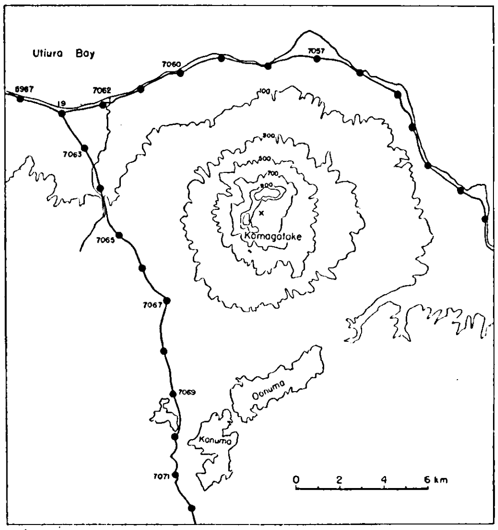


Fig. 31. Topographical map around the Komagatake Volcano and levelling route in the district.

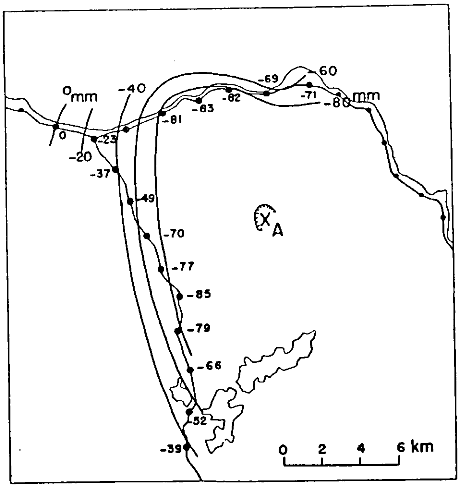


Fig. 32. Vertical displacements of bench marks and contours of equal depression around the Komagatake Volcano, before and after the 1929 eruption (after C. Tsuboi and the Land Surv. Depart.)

23) M. KANEKO, *Report Geol. Survey. Jap.*, 136 (1950).

24) T. MINAKAMI, *et. al.*, *loc. cit.* 22).

25) H. TSUYA, *et. al.*, *Bull. Earthq. Res. Inst.*, **8** (1930), 239.

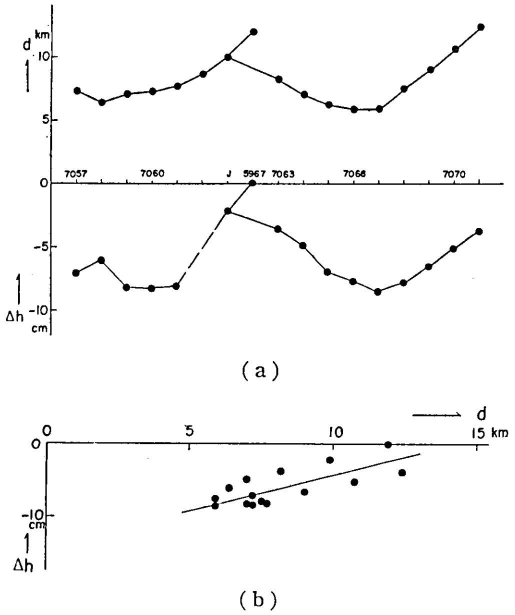


Fig. 33 (a) (b). Relation between the vertical displacements (Δh) of bench marks and the distance (d) from the centre of crater to bench marks, in the 1929 eruption.

pumices and ashes, but did not send out lavas. Precursory earthquakes were not felt at all by habitants near the volcano.

According to the results of the levelling survey[26] before and after the eruption, the area at the foot of the mountain subsided circular-symmetrically (Fig. 32). The relation between the distances (d) from the crater to bench marks and vertical displacements of bench marks (Δh) are shown in Fig. 33 (a) (b). The depression is the same type as in the case of the Sakurazima eruption (1914) and suggests the existence of a magma reservoir directly under the crater.

§3. The 1940 eruption of the Miyake-sima Volcano[27].

The Miyake-sima Volcano, one of the Seven Izu Islands, sent out fluidal basaltic lavas from the fissure on the north-east flank of the mountain, in July 1940. The occurence of felt earthquakes preceding the eruption was of no account, even if they took place.

The deformation of the ground surface before and after the eruption was obtained by triangulation [28] (Fig. 35). According to the results, the ground on both sides of the newly-opened fissure displaced outwardly as if the fissure had opened wider. (Similar deformation also took place at the time of the fissure eruption of the Sakurazima Volcano in 1914). The area around the caldera subsided and this seems to suggest that the magma reservoir is situated below the caldera. But, the accuracy

26) C. TSUBOI, *Bull. Earthq. Res. Inst.*, **8** (1930), 298.
27) H. TSUYA, *et. al.*, *Bull. Earthq. Res. Inst.*, **19** (1941), 260.
28) *Bull. Earthq. Res. Inst.*, **19** (1941), 544.
S. OMOTE, *ibid.* **20** (1942), 127.

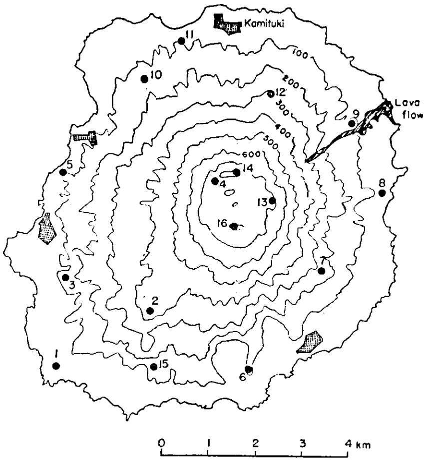


Fig. 34. Topographical map of the Miyakesima Volcano.

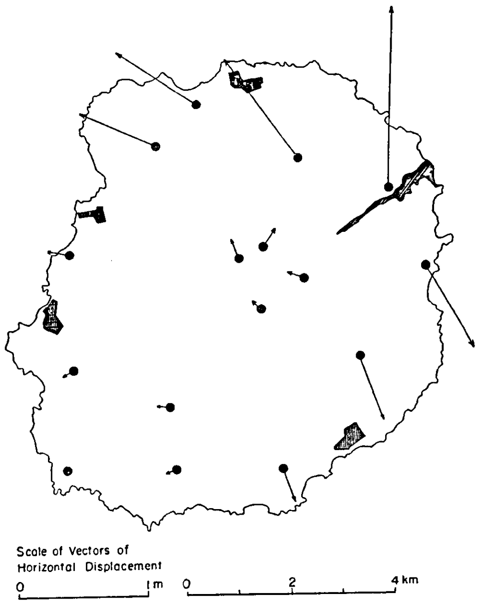


Fig. 35 (a). Horizontal displacements of the triangulation points[28].

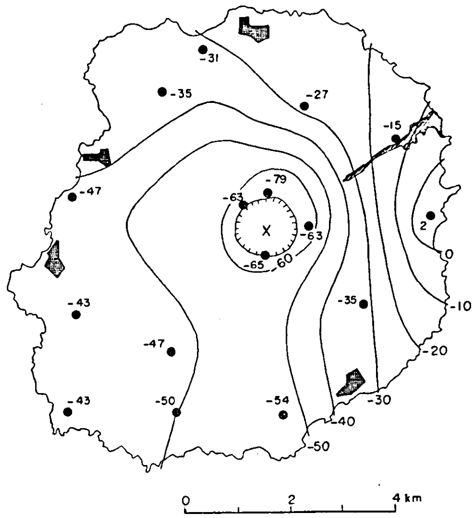


Fig. 35 (b). Vertical displacements before and after the 1940 eruption[28]. (in cm)

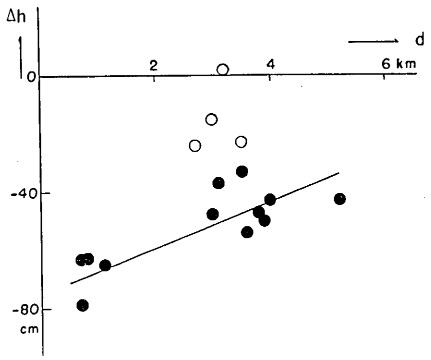


Fig. 36. Relation between the vertical displacements of the triangulation points and the distances (d) of triangulation points from the centre of caldera. (open circle: triangulation points close to the fissure).

of vertical displacements by triangulation is insufficient to discuss quantitatively. The relation between the distances (d) from the centre of the caldera to each triangulation point and the vertical displacements (Δh) of the triangulation points is shown in Fig. 36. The depression decreases with (d), except the limited area close to the fissure. The horizontal deformation (dilatation, rotation and others) have already been investigated by S. Omote.

Note The precise surveys of the ground deformations around the Asama-yama Volcano[29] and the Aso-san Volcano[30] have been executed repeatedly and interesting results have been obtained. However, as they continue to erupt on a small scale, the relation between the volcanic eruption and the ground deformation seems to be different from the above mentioned cases. Therefore, the present discussion was limited to the ground movements at the times of solitary great eruptions.

§4. The depression and its volcanological meaning.

As the eruptions are essentially the phenomena of out-flow of lavas from a depth in the earth's crust, the depression of the ground surface related to the deep sources seems to be clue to make clear the mechanical changes of the inner state of the earth's crust before and after the eruption.

As mentioned in the preceding discussion, the depression of the ground surface seems to be caused by the decrease of the volume of the magma reservoir (or the pressure decrease) resulted from the out-flow of lavas and therefore some information on the following subjects will be obtained from the analysis of the depression.

(1) The horizontal position of the magma reservoir
(2) The depth of the magma reservoir
(3) The change of the inner pressure (or change of the volume) of the magma reservoir

But the actual deformation of the ground surface is affected also by the geological structure and the upheaval deformation near the crater.

Fig. 37 represents the relation between the subsidence and the radial distance from the centre of depression, in the cases of the various eruptions. The volume of subsidence which is obtained from the curves corresponds to the magnitude of volcanic activities under the ground

29) T. MINAKAMI, *Bull. Volcanologique*, [ii], **18** (1956), 65.
30) K. YOSHIKAWA, *Zisin* (*Jour. Seis. Soc. Japan*) [ii], **7** (1954), 151.

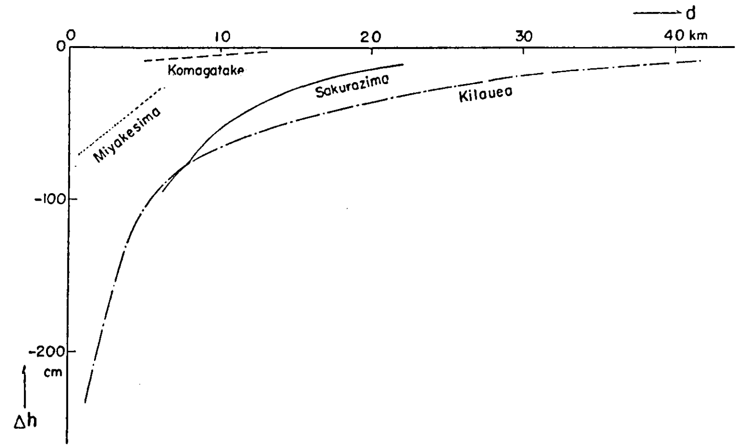


Fig. 37. Curves of depression versus the radial distance (*d*) in the eruptions of various volcanoes.

surface. For example, although the volcanic ejection in the 1924 Kilauea eruption was relatively small, the magnitude of the volcanic activity under the ground surface might have been as large as the 1914 great eruption of the Sakurazima Volcano. It has been supposed that the enormous volume of magma extruded perhaps from the east zone in the sea bottom[31)], but we could not observe it.

§5. The upheaval around the crater and the other volcanic phenomena.

The upheaval of a limited area close to the crater seems to have been caused by the upward forces near the surface at the time of the out-flow of lavas, and therefore the magnitude of upheaval may be determined by the following various factors; crater opening newly or not, volume of extruding lavas, velocity of the upward motion of the over head of magma, viscosity of lavas, etc.

On the other hand, the fracture of the earth's crust will be caused by the intrusion and the extrusion of magma and consequently earthquakes will occure. Actually, preceding to the out-flow of lavas, a number of earthquakes have taken place frequently, and the seismic activity[32)] is related to the similar various factors, as the case of the upheaval of the earth's surface near the crater (volume of extruding

31) G. A. MACDONALD, *Catalogue. Active Volc. World, Part* 3 (1955), 27.
32) T. MINAKAMI, *et. al., loc. cit.* 22)

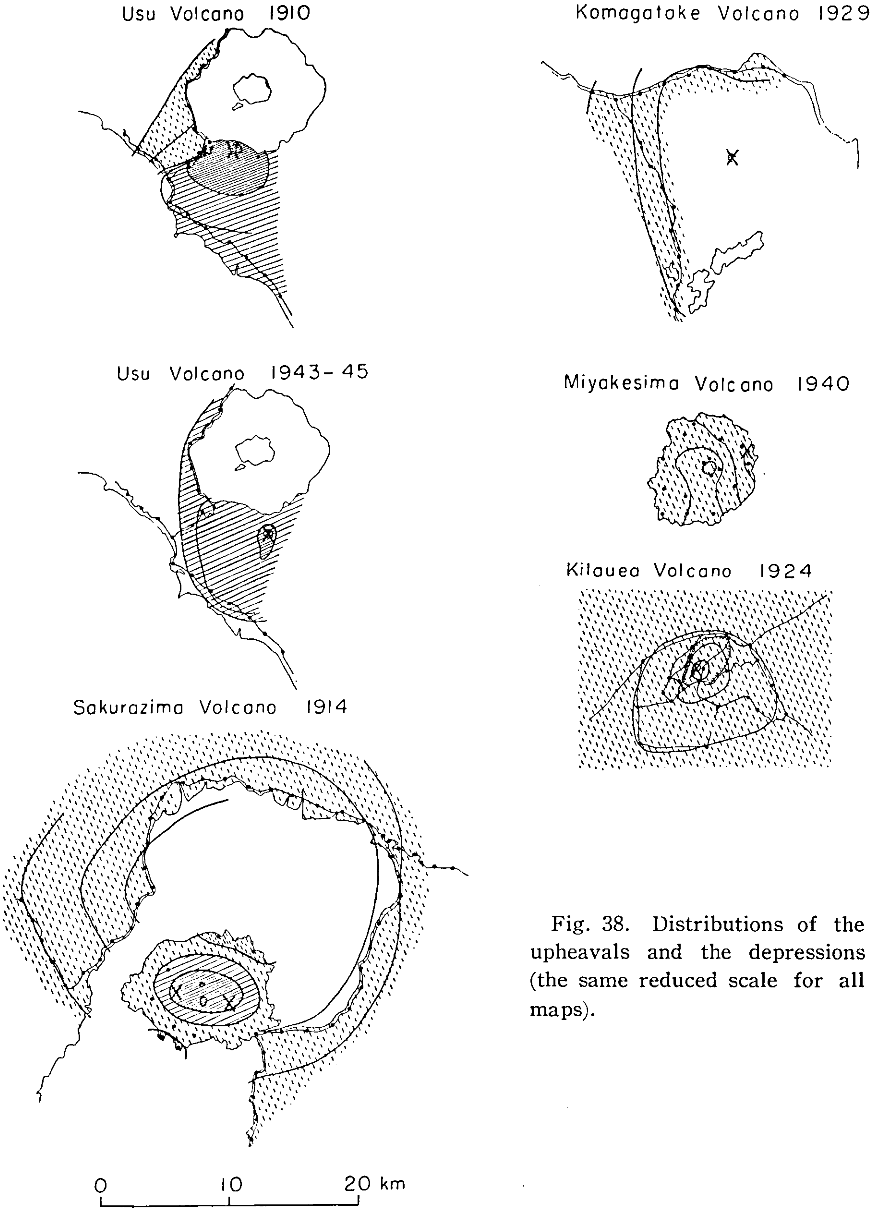


Fig. 38. Distributions of the upheavals and the depressions (the same reduced scale for all maps).

lavas, viscosity of lavas, etc.). Therefore, it is supposed that there will be a close relation among them. Regarding the above mentioned eruptions, the marked relations between the deformation of the earth's crust and the other volcanic phenomena are listed in Table 4.

Table 4.

Volcano	Year	Ground surface deformation: Volume of depression	Ground surface deformation: Volume of upheaval	Ground surface deformation: Maximum upheaval	Volume of ejecta	Crater opening	Precursory earthquakes	Type of lava	Viscosity of lava
		km^3	*km*^{3}	*m*	*km*^{3}				
Usu	1910	0.0	—	~100	—	newly (flank E.)	strong	dacite	10^{11}—10^{12} (1000°C) [33]
	1943 -45	—	0.18	~300 (200)*	—	newly (flank E.)	strong		
Sakurazima	1914	0.7	~0.1	~ 10	2.2	newly (fissure E.)	strong	andecite	$3\sim6\times10^5$ (1000°C) [31]
	1946	—	—	—	0.08	old fissure	unfelt		
Komagatake	1929	0.03	—	—	0.05 [35]	old crater	unfelt, but not observed.	andecite	—
Miyakesima	1940	0.08?	0.00	0.02	0.02 [36]	newly (fissure E.)	unfelt, but not observed.	basalt	7×10^5 (1000°C) [37]
Kilauea	1924	1.5 (0.3)**	0.00	0.00	0.0002 [38]	active crater (Hale-maumau)	felt	basalt	$2\sim4\times10^4$ (1100-1050°C) (1952) [39]

* Upheaval of the old layer (the roof mountain).
** Volume of depression in the circular region of radius of 5 km of which the central is the crater.

33) T. MINAKAMI, *et. al.*, *loc. cit.* 22)
34) T. HAGIWARA, *et. al.*, *loc. cit.* 12)
35) H. TSUYA, *et. al.*, *loc. cit.* 25)
36) H. TSUYA, *et. al.*, *loc. cit.* 27)
37) T. HAGIWARA, *Bull. Earthq. Res. Inst.*, **19** (1941), 299.
38) G. A. MACDONALD, *loc. cit.* 31)
39) G. A. MACDONALD, *U. S. Geol. Survey Bull.*, 1021-B (1955), 15.

Summary and Acknowledgment

The various deformations of the ground surface around the volcano before and after the eruptions were investigated, on the basis of the results of the precise levellings and triangulations. According to the above investigation, there are two types of ground deformation; one is the circular depression of the wide area which is concerned with the change of the state of the magma reservoir and the other is the upheaval of the limited area near the crater which is caused by the extrusion of lavas. The two types of ground deformation will take place more or less in all cases of eruptions, but their magnitudes seem to depend on the characters of the eruption. The remarkable relation between the ground deformation and the other volcanic phenomena was obtained in this paper. Moreover the writer discussed the mechanism of the eruption owing to the investigation of the ground deformation, particularly in the Sakurazima eruption (1914) and the Kilauera eruption (1924).

In conclusion, the writer wishes to express his sincere thanks to Prof. T. Minakami who gave him much advice and encouragement.

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6. 火山の噴火とその周辺の地殻変動との関係

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噴火の際に火山周辺の地殻が著しく変動することは，古く1910年の有珠山の噴火の場合に大森博士によつて精密水準測量が行われて以来，主な噴火について同様の測量が実施されて，次第に明らかになつて来た．これらの火山周辺の地殻変動に関する研究は必ずしも少なくないけれども，火山の噴火の機構との関係としてその火山学的意味を吟味したものはほとんど見られない．本論文ではこれまでに得られた測量の結果を調べて地殻変動の特性及び，噴火現象との関係を明らかにすることを試みた．

第1部では桜島の大正3年の大噴火及びその後の火山活動に関係した地殻変動を論じ，第2部でKilauea 火山の1924年噴火の際の大規模な沈降を解析してその機構を考察した．第3部に於いて，その他の諸火山の噴火を加えて，地殻変動の一般的な特性を論じ，噴火に関係する他の諸現象，例えば火山性地震の発生などとの密接な関係を明らかにした．これらの結論を要約すると次の様になる．噴火に関係した地殻変動には2つの type があつて，その発生機構を異にし，この両者が重なつて現れるのが一般である．その一つは火口の近傍の比較的狭い地域に起る隆起であつて，有珠山の場合の様に極めて著しい場合がある．これは溶岩が地下から流出する過程に於いて地殻上層を押し上げることによつて起つたものと考えられ，その大きさは溶岩の粘性や火口形成の状況等に関係するものである．もう一つの変動は一般に更に広い地域に一様に起る沈降で，これは地下に存在すると考えられる溶岩溜の容積が，噴火の際の溶岩の流出の結果急激に減少するために起つたものと推定される．例えば大正3年の桜島の噴火の際に起つた鹿児島湾岸一帯の沈降は火口の北方 10 km 深さ 10 km の溶岩溜の状態の変化によつて起つたと考えられ，この溶岩溜の位置が古いアイラ火山の直下に存在することは興味ある事である．またこの様な沈降の規模は地下に於ける活動の規模を推定するのに役立つと考えられる．例えば1924年の Kilauea 火山の噴火では火口からの溶岩の噴出は微々たるものであつたが，地下活動は桜島の大噴火に匹敵する規模のものであつたと推定される．