12. *Recent Activities of Volcano Usu (V). Topographical Deformations During the 1943-1945 Eruption.*

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1. Introduction.

The marked topographical deformations which appeared in connection with explosive activities were brought to light in a number of volcanoes on the basis of resurveys made by means of precise levellings and triangulations. For example, in the cases of the volcanic activities of Usu[1] in 1910, Sakura-zima[2] in 1914 and 1946, Komagadake[3] in 1929, Miyake-sima[4] in 1940, and Asama[5] in 1935-1937, upheavals and subsidences or horizontal displacements were made clear on and around those volcanoes, though the scales of deformation and the affected area varied according to the natures and magnitudes of eruptions.

However, these topographical deformations were usually elucidated by two series of surveys, of which the first was mostly carried out several years before, and the second just after the eruption. Therefore, we can not distinguish clearly whether they occurred prior to or in the midst of the eruption.

Since the recent outstanding eruption of Usu was preceded by about half a year of the pre-volcanic stage, in which the topographical deformations accompanying numerous perceptible earthquakes were in fact remarkable, levelling surveys[6] together with seismic observations[7] were carried out not only in the course of the paroxysmal eruption but also in the pre-volcanic stage. As the

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1) F. ŌMORI, *Bull. Imp. Earthq. Inv. Comm.*, 5 (1911), 1 and 9 (1920), 41.

2) N. MIYABE, *Bull. Earthq. Res. Inst.*, 12 (1934), 471, C. TSUBOI, *Jap. Jour. Astr. Geophy.*, 10 (1933), 93. Y. HARADA, *Bull. Geogr. Surv. Bur.*, 1 (1948) 9.

3) C. TSUBOI, *Bull. Earthq. Res. Inst.*, 8 (1930), 298.

4) S. OMOTE, *Bull. Earthq. Res. Inst.*, 19 (1941), 389.

5) E.R.I., *Bull. Earthq. Res. Inst.*, 18 (1940), 463.

6) T. MINAKAMI, *Spec. Bull. Earthq. Res. Inst.*, 3 (1944), 1. *Bull. Earthq. Res. Inst.*, 25 (1947), 65, 71, S. OMOTE, *Spec. Bull. Earthq. Res. Inst.*, 3 (1944), 22.

7) T. MINAKAMI, *Bull. Earthq. Res. Inst.*, 27 (1949), 123, 129.

result of that, we could throw light on the modes of the crustal deformations and their developments in the various stages of the recent activity.

Judging from natures of volcanic phenomena, the recent activity of Volcano Usu during the period from December 28, 1943 to October 1945, are divided into the following three stages which accord essentially with the classification made by T. Ishikawa,[8] though he subdivided them into finer details.

1) Pre-volcanic stage:

This stage including the period from occurrence of the first earthquake to the day preceding the first explosion, is characterized by numerous perceptible earthquakes on and around Usu and remarkable rise of the ground at the eastern foot of the mountain forming cracks and fissures of various scales. The stage lasted six months from December 28, 1943 to June 22, 1944.

2) Stage of paroxysmal eruption:

The second stage includes the four months during paroxysmal explosions, forming seven craterlets newly opened at the central area of rise, namely the period from June 23 to October 31, 1944.

3) Stage during birth and development of lava-dome:

The third stage falls on the period in which a lava-dome appeared at the centre of the craterlets which opened in the second stage. Toward September 1945, the lava-dome being completly formed, the recent remarkable eruption came to an end. Accordingly, this stage includes the period from directly after the last paroxysmal eruption on October 31 to the end of the recent activity.

Although the division into these three stages just mentioned was made mainly from the view-point of volcanic phenomena, they harmonize well with the characteristics of earthquakes and topographical deformations.

2. Developments of the Rising Movements at the Eastern Base of Mt. Usu.

The cracks and fissures newly formed on the roads, canals, banks and corn fields between villages Kami-Osaru and Yanagihara, seem to indicate that the rising movements of the land at the eastern skirt of the volcano began to develop already towards the end of January, 1944. However, after the upheaval of the mentioned area lasted for about a month, the movement shifted immediately 1 km north to village Yanagihara.

On March 25, 1944, the writer in co-operation with the Civil Engineering Section of the Hokkaido Prefecture planned the levellings along the civil road

8) T. ISHIKAWA, Read at the Pacific Sci. Cong. of 1948.

passing through the rising area including villages Kami-Osaru, Yanagihara, Hukaba and Sōbetu. During March 28-April 4, 1944, the levellings along the route from Kami-Osaru to Hukaba were carried out daily or semi-daily to determine the mode of the uplifting movement. Thereafter, levellings were carried out twenty four times on the same route in order to elucidate the topographical deformations throughout the whole period of the eruption described above.

Although the topographical deformations based on those levellings were partly reported in the previous paper, the phenomena are here reviewed with respect to another particular.

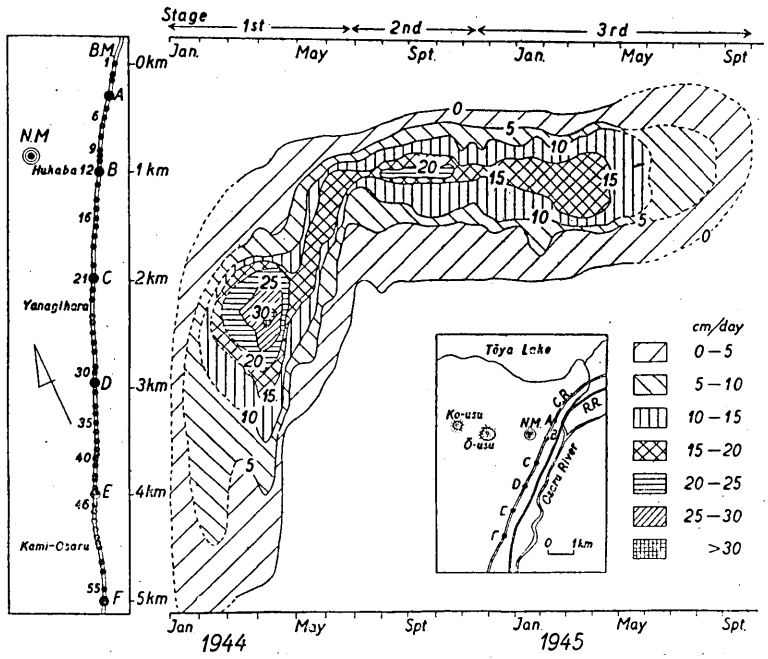

Fig. 1. Development of rising velocities at the eastern foot of Mt. Usu, during the period from March 1944 to September 1945.

As mentioned already, along the route of 5 km in length from Kami-Osaru to the southern part of Sōbetu, including 55 bench marks which were established at 100 m intervals, our levellings were made 30 times in the total or at intervals of two weeks on the average of surveys during the period from March 29, 1944, to May 22, 1945. From the results of those levellings, it was made clear that the vertical deformations developed in the form of dome throughout the three stages, amounting to 30-20 cm per day in the maximum

rising velocity on this route. In order to examine the variations of the rising movements through the three stages mentioned, daily rising velocities of those bench marks are illustrated on the diagram of Fig. 1, on the basis of these levellings. Since our levellings did not cover the period before March 23, 1944 and after July 1945, approximate estimations concerning the rising velocities on this route before and after our surveys were made by means of available results of other surveys such as levellings on the railroad at the initial stage and tilt measurments of land by making use of the dammed water at the final stage, which was temporarily formed by marked upheaval at the bed of River Sōbetu. Aided by this figure, it will be clearly recognized that the centre of rising movements at Yanagihara shifted again nearly 1 km to Hukaba during the period from the middle of April to the later part of May, 1944, and after that, the upheaval at Hukaba lasting without break till the end of the recent eruption, did not remove much, though to some extent to the north, which resulted in the new formation of the roof mountain more than 200 m high. Taking into consideration, in addition to the result shown in Fig. 1, the results of other surveys such as tilt measurments on and around the rising area and levellings covered on the railroad and at the river side of Osaru, we may conclude that the disturbed area including the uplifting ground became more and more concentrated to a limited area in accordance with the developments of the eruption.

It must be added also that our levelling route on the civil road traversed about 300–400 metres east of the centre of upheaval. On this account, the upheaved amounts and their rising velocities both given by our levellings do not show the maximum values of the present topographical deformations, which are estimated at nearly three times the former.

Concerning the correlations of the topographical deformations with the developments of the recent eruption, we can remark that in the course of the pre-volcanic stage, the rising movements shifted 2 km north from Kami-Osaru to Hukaba and simultaneously converged in the limited area less than 1 km in its diametre toward the middle of June, 1944, when the paroxysmal stage began to start. During the birth of the lava dome and its rapid development, the rising area with velocities over 15 cm per day was enlarged conspicuously and subsequently the ground deformations were decreasing in their velocity as well as in their affected area up to September 1945 when those new formations were completely built.

To make everything precise, the phenomena are examined by movements of several bench marks which seem to represent their general modes. For the purpose, the movements and their daily velocitses with respect to the bench marks Nos. 6, 9, 12, 16 and 21 of which the locations are shown on the

map in Fig. 1, are illustrated in Fig. 2 by taking time in abscissa. As will be seen in this figure, each bench mark rose with variable velocities according to the developments of the recent activity, though displacement curves in the

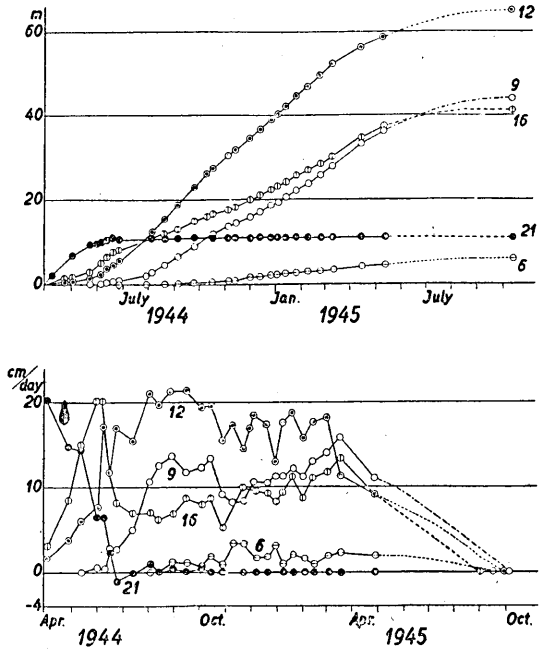

Fig. 2. Modes of upheaval and rising velocity of the representative bench marks (Nos. 6, 9, 12, 16 and 21) situated at the eastern foot of Volcano Usu during the recent eruption.

figure show only simple increase in their heights. It may be also interesting to make clear the topographical deformations within shorter period than those just mentioned. From this view-point, the results of the levellings which were carried out semi-daily at the initial stage from March 29 to April 4, 1944, are shown on the map in Fig. 3, in the form of daily velocity. By a glance at this diagram, we can conclude that the daily movements of the area during the seven days presented a considerable similarity as if those bench marks uplifted with constant velocities respectively.

It is, however, worthy of note that tilts on a small area changed their directions frequently, notwithstanding the fact that the area on which tilt measurements were continuously made, was rising with nearly constant velocity during the period. Therefore, it will be reasonable to infer that the tilts at an extremely limited area, such as several square metres, are not simple

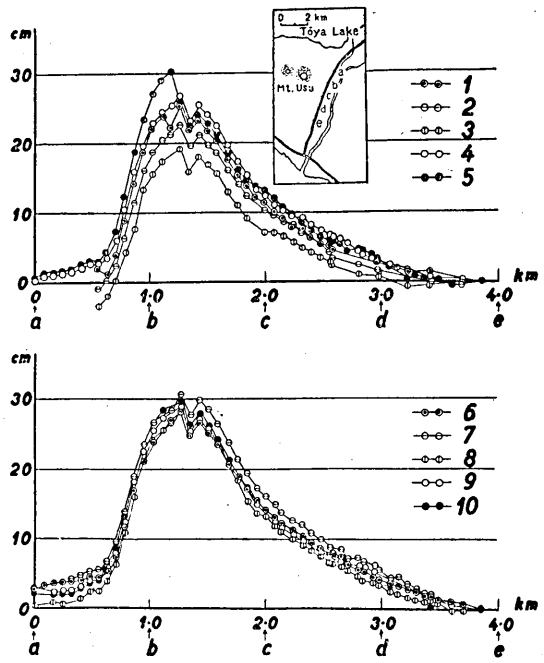

Fig. 3. Daily rising velocities at the Yanagihara area during March 29-April 4, 1944.

1……Mar. 29, 1944. 2……Mar. 30 (a. m.). 3……Mar. 30 (p. m.).
4 ……Mar. 31. 5……Apr. 1 (a. m.). 6 ……Apr. 1 (p. m.).
7……Apr. 2 (a. m.). 8……Apr. 2 (a. m.). 9……Apr. 4 (a. m.).
10 ……Apr. 4 (p. m.).

with respect to either their areal distribution or their time variations, even when the vertical movement of that area takes place in a simple manner. The foregoing relations between the topographical deformations and their differential quantities concerning time and space hold true with the results of tilt observations at Volcano Asama[9] which have been carried out continuously since 1934.

3. Horizontal Displacements on the Rising Area.

Measurements[10] for determining the horizontal displacements of the rising ground had been occasionally made during the recent eruption, though these

9) T. MINAKAMI, *Bull. Earthq. Res. Inst.*, 20 (1942), 431.

10) A. ZITSUKAWA and T. NAGATA, *Zisin*, 14 (1944), 1, S. MIYAMURA, *Spec. Bull. Earthq. Res. Inst.*, 3 (1944), 37.

surveys were not carried out so systematically as in the case of the vertical movements mentioned above. Generally speaking, however, the horizontal deformations throughout the eruption developed always in the outward or radial direction from the active craterlets which were all located on the central part of the uplifted area. As the result of that, the civil road and the railroad running 500 m and 650 m east respectively of those craters, both shifted exceedingly toward the eastern direction during development of the new mountain.

To determine the mechanism of the new formations, namely, the roof mountain and the lava dome, it is, in fact, important to make clear not only the vertical deformations of ground, but also its horizontal displacements. For this purpose, surveys concerning the horizontal displacements were made in the summer of 1949, at those two roads on the basis of the topographical map which had been drawn prior to the recent eruption. In other words, the total displacements at the eastern flank and base of the new mountain were given by comparing the positions of these roads before and after the ground deformations. As the result of this investigation, it was made clear that the civil road and the railroad shifted about 60 m and 20 m respectively in their most affected points toward east or radial direction from the centre of the

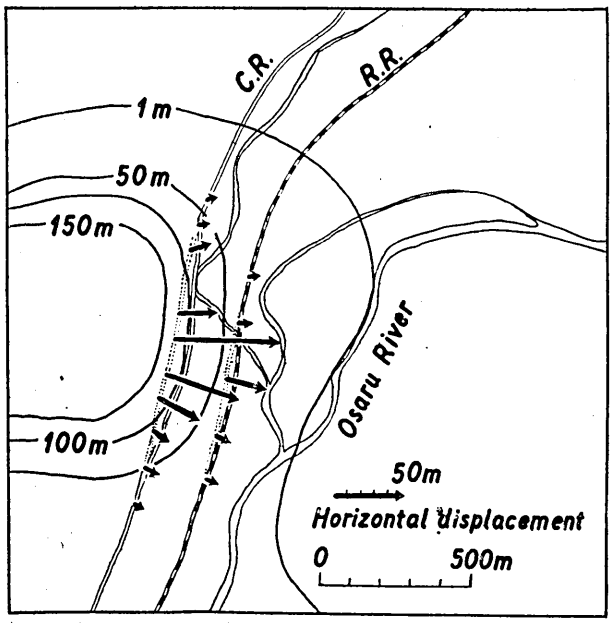

Fig. 4. Horizontal displacements at the eastern base of the newly formed mountain.

new mountain. Since these two points just mentioned were uplifted simultaneously nearly 70·m and 20 m respectively, the topographical deformations of this area were of quite the same amount in both vertical and horizontal directions. Fig. 4 shows the horizontal displacements of the civil road and the railroad together with the total upheaval of the area.

It must be remarked that, so far as the horizontal displacement is concerned, it underwent its greatest development at the final stage of the eruption. It is, however, quite natural that at the initial stage when lava had been intruding in the deep-seated vent, the vertical movements were decidedly superior to the horizontal deformations, and in converse the latter phenomena became exceedingly predominant according as viscous lava approached or came up to the earth's surface.

4. Mechanism of Development of Front Mountain.

Towards the middle of July, 1944, when the paroxysmal eruption was at its height, it was noticeable that the ground around the base of the new mountain began to rise abnormally and developed rapidly according as the lava dome grew and the horizontal displacements in the radial direction accelerated. In May 1945, a hill in the form of a ring or a half-ring, which is called the front mountain, was formed at the margin of the roof mountain (Fig. 6). Judging from morphological investigation, the front mountain is built up more completely at its eastern part which includes the former rice-field of soft soil than at the other part, which is formed by firm materials such as the Usu lava-flows and the Takinoue lava.

As will be seen in Fig. 4, the ground corresponding to the inner and outer sides of the ring-shaped hill shifted about 55 m and 15 m respectively outwards from the original positions.

In a small part of the ring formation in Fig. 5, A_1, A_2 and B_1, B_2 represent the original positions of the inner and outer sides, A_1', A_2' and B_1', B_2' the shifted positions corresponding to the former, O the centre of the lava-dome newly formed, θ, angle of the sector and r_1, r_2, r_1', r_2', distances between the original and shifted positions at the inner and outer sides of the front mountain. To compare lengths of the segments A_1A_2 etc. and the arcs A_1B_1 etc. and the area $(A_1A_2B_1B_2)$ with those after the deformations, the following ratios are made:

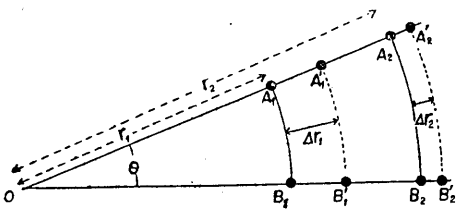

Fig. 5. Schematic illustration of horizontal displacement around the roof mountain.

$$\frac{A_1'A_2'}{A_1A_2} \text{ or } \frac{B_1'B_2'}{B_1B_2} = \frac{r_2+\Delta r_2-r_1-\Delta r_1}{r_2-r_1} = 0.733,$$

$$\frac{\Delta r_2-\Delta r_1}{r_2-r_1} = -2.7\times10^{-1} \text{ .....contraction},$$

$$\frac{\widehat{A_1'B_1'}}{\widehat{A_1B_1}} = \frac{\theta\,.\,(r_1+\Delta r_1)}{\theta\,.\,r_1} = 1.11,$$

$$\frac{\Delta r_1}{r_1} = 1.1\times10^{-1} \text{ .....elongation},$$

$$\frac{\widehat{A_2'B_2'}}{\widehat{A_2B_2}} = \frac{\theta\,.\,(r_2+\Delta r_2)}{\theta\,.\,r_2} = 1.02,$$

$$\frac{\Delta r_2}{r_2} = 2.3\times10^{-2} \text{ .....elongation},$$

$$\frac{\text{area } \widehat{A_1'B_1'}\,\widehat{A_2'B_2'}}{\text{area } \widehat{A_1B_1}\,\widehat{A_2B_2}} = \frac{1/2\,.\,\theta.\,\{(r_2+\Delta r_2)^2-(r_1+\Delta r_1)^2\}}{1/2\,.\,\theta.(r_2^2-r_1^2)} = 0.778,$$

$$\frac{2r_2\Delta r_2+\Delta r_2^2-2r_1\Delta r_1-\Delta r_1^2}{r_2^2-r_1^2} = -2.2\times10^{-1} \text{ .....contraction},$$

where r_1=500 m, r_2=650 m, Δr_1=55 m, Δr_2=15 m.

As the above results show manifestly, the line sides in the radial direction were considerably contracted, and on the other hand the arc sides were elongated along the co-radial direction. As the result of that, the area in question shows remarkable contraction amounting to 2.2×10^{-1}. It is thus obvious that the hill of ring form was built by considerable pressure acting laterally from the centre of disturbance owing to intrusion and extrusion of viscous lava and resulted in abnormal upheaval nearly 20 m high, retaining the original surface of ground. At gullies formed in the front mountain, we can observe remarkable warpings, foldings and thrusts of rather small sizes caused in the manner just mentioned. (Fig. 7).

Although the front mountain is a swelling of ground formed by mainly lateral pressure, tensional forces might act upon this area in the co-radial direction in the course of rapid development of the new formations.

On the other hand, cracks and fissures newly formed on the rising area were varing in their sizes as well as in their running directions. However, the fact that those of a comparatively larger scale were mainly running in the radial direction, suggests close relations with the tensional forces due to

the outward movements of ground. At all events, the mechanism concerning the formation of the front mountain are to be explained satisfactorily only by introducing the horizontal movements of the area and enormous lateral pressure which were both produced by invasion of viscous lava of large volume more or less solidified.

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12. 最近の有珠山の活動 (其の5) 噴火中 (1944–1945) に現はれた地形變動

地震研究所 水上 武

既に報告した第1, 第2報に於て, 1943年12月28日にはじまる今回の有珠山の噴火に伴つた地震活動及びその後間もなく明かになつた東山麓の隆起について述べ, 更に昭和新山に成長するまでの經過の概略を報告した. また第3, 第4報に爆發的噴火及び熔岩丘の成長に伴つた地震の2, 3 の性質について述べた.

本文には同火山東麓の隆起の進行について水準測量の結果を綜合し, 地形變動の進展と噴火現象との關聯について報告してある. 特に1944年3月下旬より4月上旬に柳原部落を中心とする隆起を7日間に亘る毎日2回の測量結果を示し, この短い期間に於ける地形變動の模樣を明かにし, この期間の隆起の速度, 隆起の地域が互に極めて類似する事を示した.

今回の活動によつて生じた所謂"昭和新山"の周邊の水平移動を調査した. その結果新山の中心より外方え向つて土地が放射狀に著しく移動している事が明かになつた. 粘性の大きい熔岩の噴出による横壓に原因するものと考えられる. この測定結果を用いて, 新山の周邊に環狀に形成された前山 (Front mountain) の生成機構を考究した.

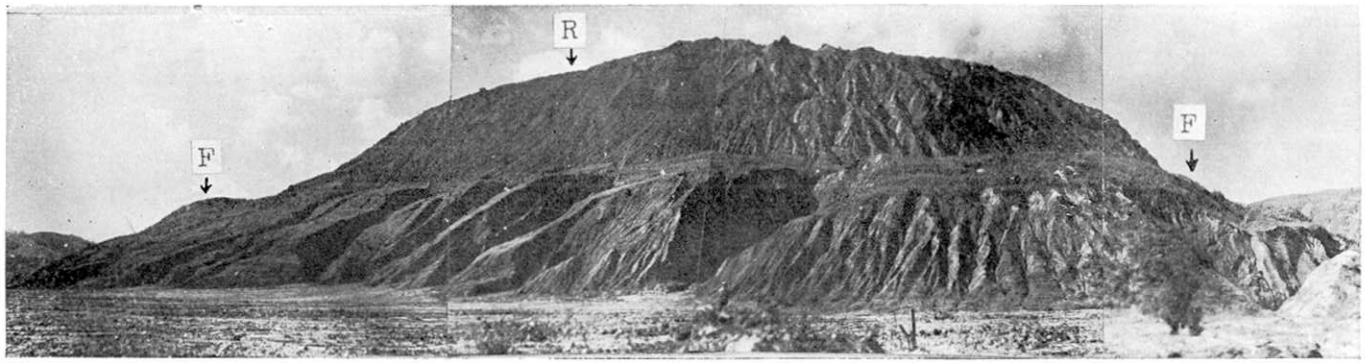

Fig. 6. The roof mountain and front mountain formed in the course of the recent eruption.
R; Roof mountain. F; Front mountain.

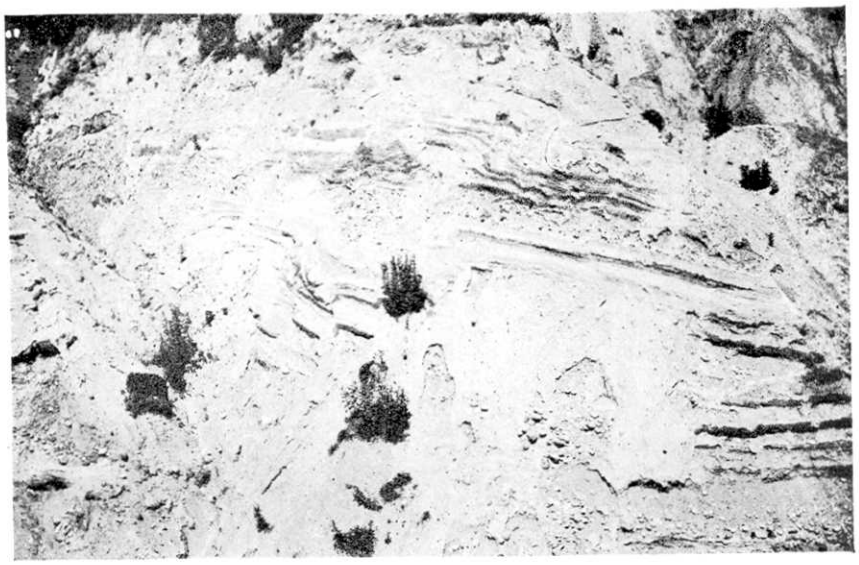

Fig. 7. Warpings and foldings of small size seen in gullies on the front mountain.