Gigantic Directed Blast at Shiveluch Volcano (Kamchatka)

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Abstract

On November 12, 1964, after a long swarm of preliminary earthquakes a gigantic directed blast took place at Shiveluch Volcano. The Crater top of the volcano with five large domes was completely destroyed. The deposits of the directed blast fell on an area of 98 sq. km, at a distance up to 10 km from the crater. The volume of the deposits is 1,5 km^3 at least.

A new crater was formed, its size is 1,5 × 3 km. Numerous pyroclastic flows were poured out the new crater.

The eruption lasted only one hour, its thermal energy is $1{,}3 \times 10^{25}$ ergs, kinetic energy of the blast - 1×10^{24} ergs, air wave energy - $1{,}8 \times 10^{21}$ ergs. Initial velocity of the explosion: 280-310m/sec, pressure: 800-1000atm.

The eruption of Shiveluch volcano belongs to the « Bezymianny type » eruption.

Introduction

On November 12, 1964 a short and a very powerful and interesting eruption of Shiveluch volcano took place. Shiveluch volcano is the northernmost among the active volcanoes of Kamchatka. It is located on the left shore of Kamchatka river approximately 50 km N-NW of Kliuchi village, where the Volcano-station is situated.

First Shiveluch volcano was mentioned by S.P. Krasheninnikov in 1755. In 1829 it was briefly studied by A. Erman (ERMAN, 1848). In 1897 Shiveluch volcano was visited by K. I. Bogdanovitsch. The geological (KONRADY and KELL, 1925) and zoological (SCHMIDT, 1916; DERZHAVIN, 1916) parties of the Kamchatka expedition of the Geographical Society 1909-1911 studied the volcano more in detail. Unfortunately the detailed description of the geological party materials was not published.

Bogdanovitsch's and Konrady's collections were worked up by A. N. ZAVARITSKY (1935). It was the first petrographic description of the Shiveluch lavas.

In 1944 the volcano was visited by B.I. Piip. In 1937-38 and 1946-1948 Shiveluch was especially studied by A. A. Menailov, who considered the Main Top of Shiveluch as a poligenic stratovolcano (MENAILOV, 1955). In 1948-51 this volcano was studied by G. S. Gorshkov, who irrespective of A.A. Menailov came on the whole to the same conclusion (GORSHKOV, 1953).

G. S. Gorshkov went on studying Shiveluch volcano in 1954-57. The preliminary information of the eruption in 1964 was published by B. I. PIIP and E. K. MARKHININ (1965). The results of the eruption were studied in detail by the authors of this article.

Structure of the Volcanic Massif

Shiveluch volcano rises in the form of an isolated massif among the swamps and lakes of the Central Kamchatka depression (Fig. 1). The diameter of the volcano base is at least 40 km, and its area is more than 1200 sq. km.

The Shiveluch massif is rather greatly destroyed and it has no usual form of cone. Two tops can be observed from the south-east which are divided by a saddle. The northern top, so called « Main top », has a height of 3335 m, and the southern top, so called « Crater top », has a height of 2700 m; the last one is the place of the recent activity (Fig. 2).

Main top and the western section of the massif on the right shore of the Baidarnaya river are the parts of the ancient cone.

The remained parts of the ancient cone outline a big caldera with a diameter up to 7 km widely open southwards. The caldera ridge has also an opening to the north-west. Both pure volcanic and perhaps volcanotectonic processes took part in the caldera formation.

The postcaldera activity was concentrated in the north-western part of the depression, where the so called Crater top is situated. The eastern and south-eastern slopes of Crater top are composed by rather thick monolithic lava mass, the nature of the surface and internal structure of which allow us to consider this lava formation to be a residue of the effusive (exogenous) dome. The formation of the effusive dome was completed by a powerful, directed to the south

explosion, and there are only two isolated parts which are remained from the dome. After this explosion an elongated, open to the south, crater was left with the dimensions of approximately 3 × 4 km. All the subsequent activity (not taking into consideration the chain of the domes on the outer western slope of the old cone) was concentrated in this crater, in which some extrusive (endogenic) domes grew up. All the domes (both extrusive and effusive) are composed of hornblende andesites.

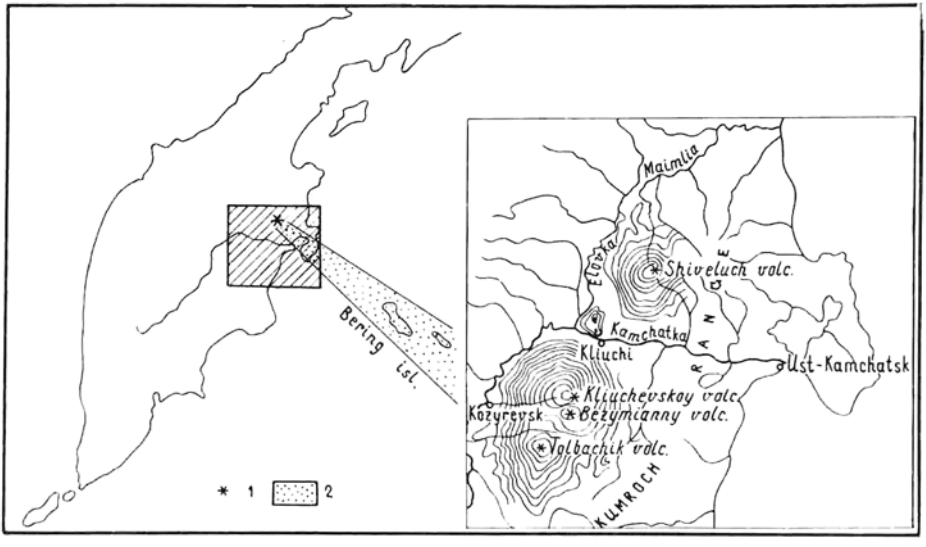

FIG. 1 - Location of Shiveluch volcano. 1 - Volcano, 2 - Area of ashfall.

Now, after the eruption in 1964 the remnants of the greatest and highest dome « Fourth top » are preserved, the whole eastern half of which was destroyed in former times by very powerful explosions.

Till November 1964 there were two extrusive domes south of the « Fourth top ». East of the « Fourth top » there were two more domes: « Central dome » and the easternmost « Suelich », which was formed during the eruptions of 1944-50.

Now in the place of the these four domes a big, open to the south, explosive crater was formed, the width of which is 2 km (Fig. 3).

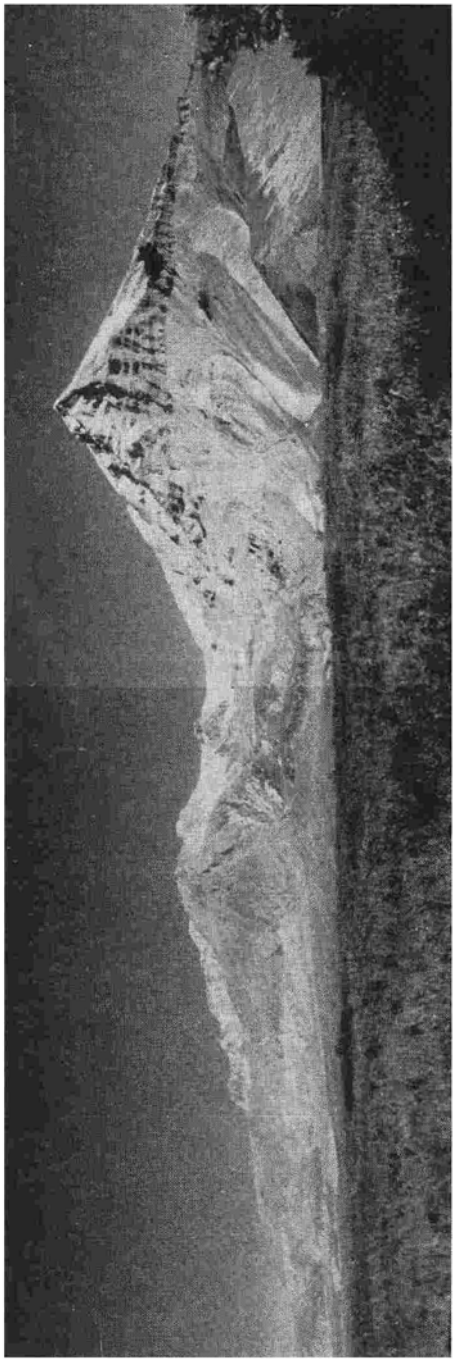

FIG. 2 - Main top (on the right) and Crater top (on the left) of Shiveluch volcano. View from South-East, 1949. *(Photo by G. S. Gorshkov).*

The southern part of the volcanic massif is a rather plane surface, gently sloping to the valley of the Kamchatka river. In the slopes of deep, steep valleys, cut through this part of the massif, the layers

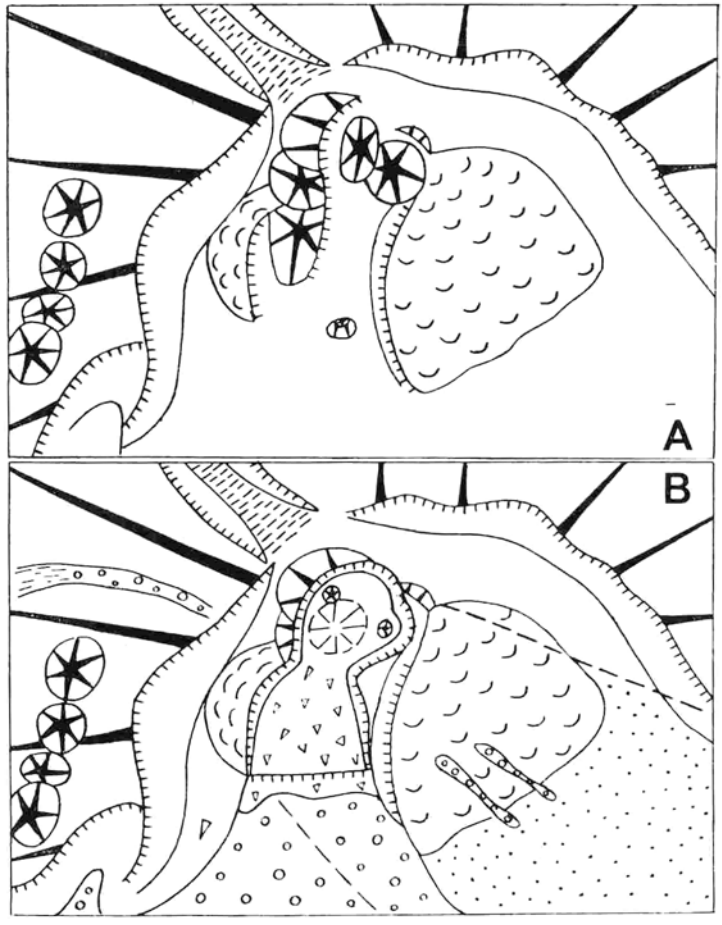

FIG. 3 - Sketch of Crater top before (A) and after (B) the eruption of 1964. Legend as in Fig. 5.

of loose volcanogenic rocks were revealed, among which explosive deposits, pyroclastic and mud flows of the former eruptions, sometimes together with the remnants of the arboreal vegetation are exposed.

Seismic Activity

The eruption of 1964 was not unexpected and it was preceded by a prolonged and specific seismic preparation. The first very weak earthquakes were registered yet in January; till April it was recorded 10 shocks with K = 6-9. For the first ten-day period of May a distinct earthquake swarm took place and a supposition was said about a possible eruption (TOKAREV, 1964).

In the middle of October a new increase of seismic activity began which directly preceded the eruption. Since October 24, the earthquakes took place daily and their number and energy increased continuously. For the last twenty-four hours before the eruption 73 earthquakes with K = 8-13 were recorded; for 7 hours before the eruption the earthquakes were taking place practically continuously, and the records of them on the seismograms of the nearest stations gave continuous oscillations. Some earthquakes were felt in Kliuchi and Kozyrevsk (at a distance of 50 and 80 km respectively) their intensity was III-IV and they were accompanied by the underground roar.

The strongest earthquakes took place at 7.07 and at 7.13 a.m. on November 12. The first earthquake was in close connection with a gigantic explosion, which destroyed the domes of Crater top and formed a new crater of more than 2 km in diameter. This explosion gave rise to a powerful airwave; intensive volcanic tremor was recorded during the eruption.

After the beginning of the eruption the earthquakes have almost stopped, and only in the very end of the eruption some shocks with K = 10-11 were recorded; the last earthquake took place at 8.15 a.m. Then a number of earthquakes and their force abruptly reduced, but yet on November 12 and 13, some tens of shocks with K = 5 (for the first twenty-four hours: 64 shocks) were recorded. On November 16, the shocks stopped completely.

In the whole it was recorded 479 earthquakes with total energy of 2×10^{20} ergs (Fig. 4). Thus according to the seismic data it is possible to mark out the following four stages:

1. The preliminary seismic stage, beginning since January 1964 up to the middle of October.

2. Stage of the direct seismic preparation, beginning with October 17-21 up to November, 12.

3. Paroxysmal eruption on November 12th, 1964.

4. Post-eruptive stage of seismic activity release from November 12 up to November 16, 1964.

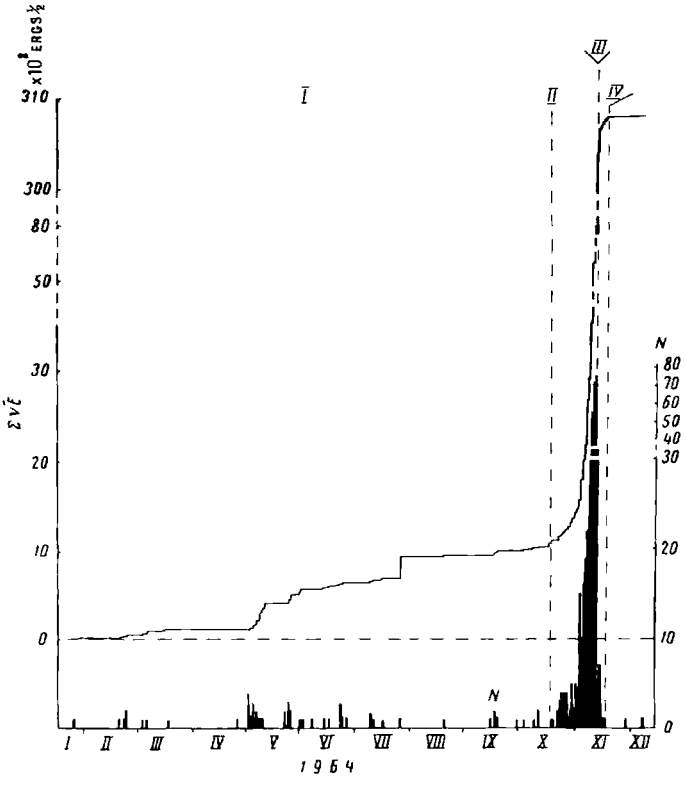

FIG. 4 - Characteristics of seismic activity at Shiveluch volcano in 1964. $\Sigma \sqrt{E}$ = strain - release characteristic sequence of earthquakes; N = number of earthquakes for every 24 hours with $K \geq 6$ (after TOKAREV, 1967).

Eruption

There were no changes in the activity of Shiveluch volcano before the eruption. The eruption was of very short duration, and as it was still dark the eye-witness observations gave only a very general idea of its character.

Undoubtedly a paroxysmal explosion took place at 7.07 a.m., but it is quite possible that preliminary, more weak explosions began still at night.

Eye-witness accounts paint the eruption in bright, exciting colours. In semidarkness the ashcloud of 10-15 km in height was seen above the valley of Kamchatka river. Bright and wide lightnings were dispersing from the centre of the cloud to its edges. Prolonged roaring and powerful peals of thunder were heard in all neighbouring villages: Kliuchi, Kozyrevsk, Lazo, Krakhtcha. In the western part of the massif, below its top, « a narrow tongue of flame was breaking through ». By this time the eruptive cloud closed the 5th part of the sky and, quickly expanding and curling under the influence of the wind, moved to the Pacific Ocean coast. By 8 a.m. the eruption went down, and only some occasional avalanches were marked at the volcano foot. For some hours more the top was still closed by dense vapour cloud. In the middle of the day some scientific workers of the Volcanological Institute (among them was one of the authors, Yu. M. Dubik) flew round the volcano at the plane « An-2 » and saw an enormous explosive crater in the place of Crater top and a wide tongue of pyroclastic deposits south of it. The whole district completely changed; a basic camp of Volcano-station, which was at a distance of 7 km from the crater, was destroyed.

In fact the eruption was over with that, but the eruptive cloud being loaded with volcanic sand and ash went on moving to the south-east.

At 8.30 a.m. being cut through by lightnings the ashcloud hang over the village Ust-Kamchatsk. Ash fall began, and a noticeable smell of sulphur was felt in the air. Crash and roaring of the thunderstorm discharges did not stop for two hours.

Visibility dropped to zero; the districts were lighted up only with red gleams of lightnings. Atmosphere was so loaded with electricity that the telephone and radio connection with other villages was broken.

Many inhabitants of Ust-Kamchatsk observed phenomena of calm electric discharges - « St. Elmo's fire ». The ashfall continued for three hours; the ash layer was 3 cm thick, ash quantity reached 28 kg/m^2.

By 1 p.m. of the same day the eruptive cloud advanced towards Komandor Islands, where the ashfall continued till 5.30 p.m. The thickness of the ash cover was equal to 2.5 mm here that corresponds

to 2 kg/m^2. There are not any data about subsequent way of the ashcloud. The information about the immediate observations during the eruption period was over this time.

Only in the course of special investigations which were done directly at the volcano it succeeded to establish a real picture of the eruption, its nature and scales. The first expedition at the head of Yu. M. Dubik reached the volcano on November 22, in 10 days after the eruption. In March, 1965 the eruption district was observed from a plane and helicopter by G. S. Gorshkov. The main volume of investigations was done by both authors in the summer 1965.

Directed blast.

It was ascertained that at the volcano a very powerful, southward directed blast took place, which almost completely blew off the domes of Crater top. Just after the directed blast it was ejected pumiceous juvenile material, which formed an enormous ashcloud from a thick layer of pumice fell out in the neighbourhood. The main mass of juvenile material was erupted in the form of pyroclastic flows, which, having come through the snow-covered slopes and valleys, formed mudflows (Fig. 5).

The eruption sharply changed the volcano appearance. A new large crater with dimensions of 1.5 × 3 km was formed in the place of Crater top domes (Fig. 6 and 7).

In the plan the crater has a compound form and consists of two parts. The northern one is cut into the masses of Fourth top and Suelich dome and it has an oval form measuring 1.5 × 1 km. The height of the northern wall is about 700 m; southward it decreases to 300-400 m. Extrusion roots are exposed in the walls. The upper part of the profile, east of the Fourth top, is composed of a powerful glacier.

The southern part of the crater has a form of a trapezium and its area is about 4 km^2. In the western scarp feeding chimneys of several effusive domes are exposed. The upper part of the section is represented by massive andesites. The eastern wall is composed of a coarse pyrocrastic material which represents agglomerate mantles of several old extrusive domes. In a fortnight after the eruption the crater floor emitted vapour almost everywhere and was filled up with large-size blocks of pink andesite.

The outlines of the new crater wonderfully precisely coincided with the outlines of the old crater, which had been here before the domes were squeezed out.

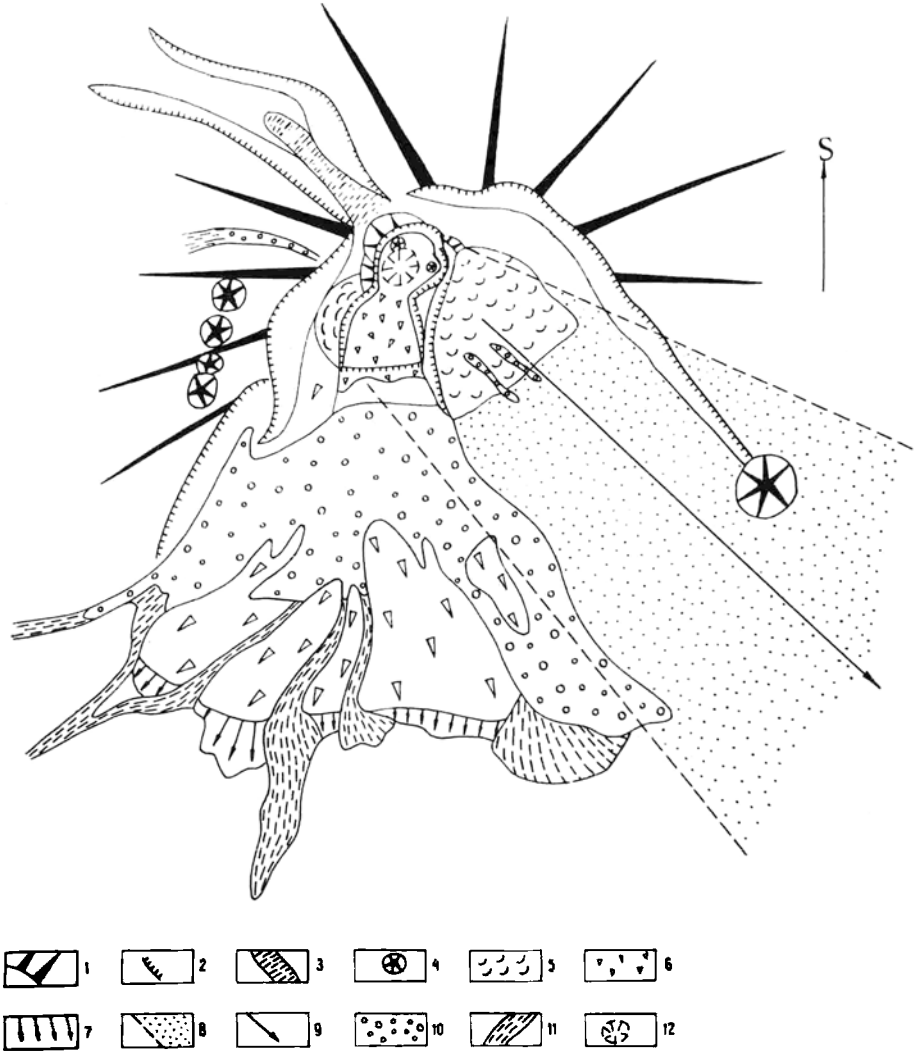

FIG. 5 - Areal expansion of the eruptive deposits. 1 - slopes of the volcanic edifice, 2 - scarps, 3 - Tushev's glacier, 4 - extrusive domes, 5 - effusive domes, 6 - deposits of the directed blast, 7 - slided parts of explosive deposits, 8 - The area of pumice and ashfall, 9 - axis of the ashfall, 10 - pyroclastic flows, 11 - mud flows, 12 - a dome-shaped upheaval on the floor of the crater.

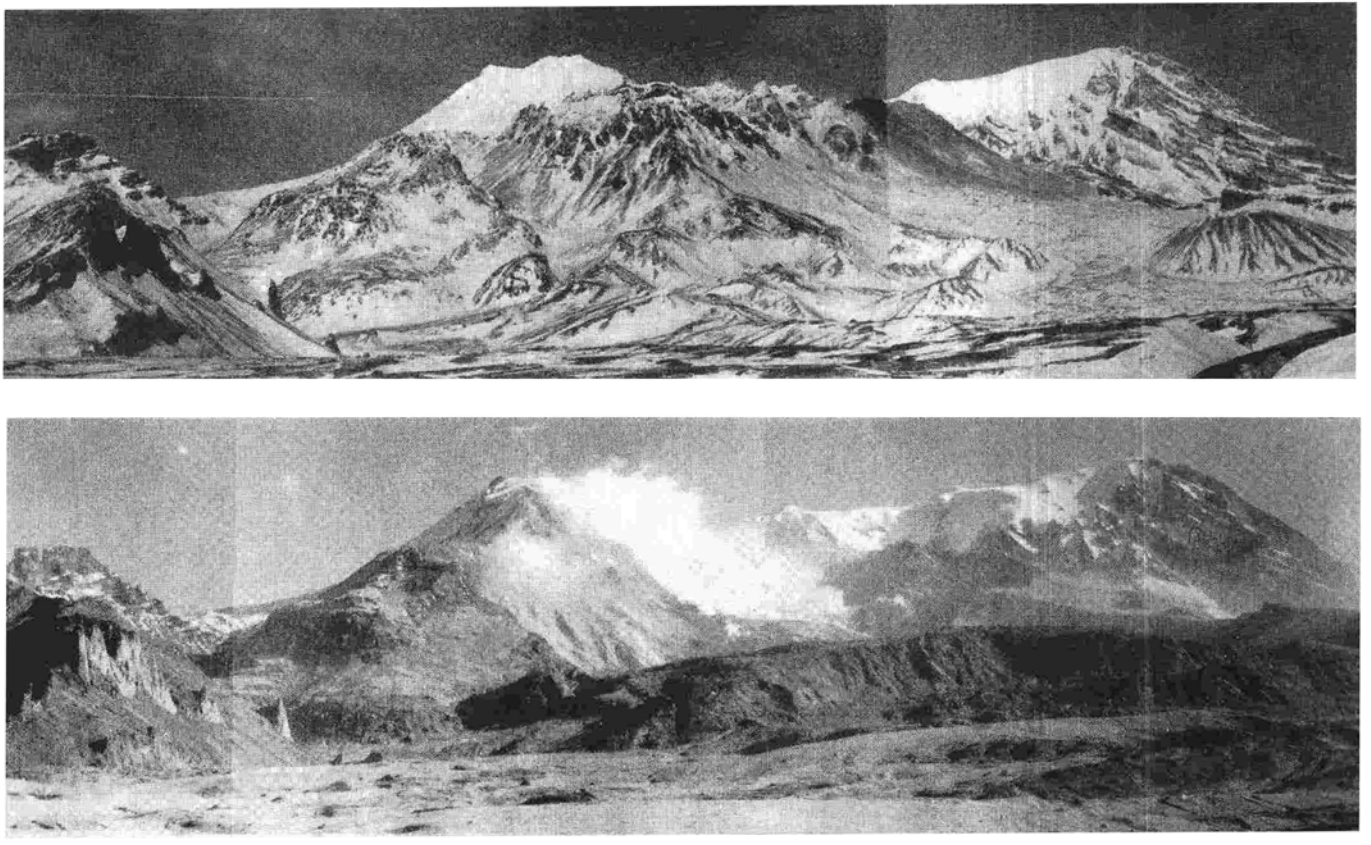

FIG. 6 - A - Domes of Crater top before the eruption (in 1949), B - crater of 1964. Both pictures are made from the same point. Main top on background. *(Photo by G. S. Gorshkov).*

Thus it was destroyed mainly that part of the volcano-building, which was composed of extrusions and of their agglomerate mantles. The considerable mass of the explosive breccia fell down on the southern sector of the volcano foot directly adjoining to the crater and overlapped it with two large thick terraces. The most part of the

FIG. 7 - Northern part of the new crater. (*Airphoto by the Institute of Volcanology*).

explosive material was ejected at a distance up to 10 km from the crater, and formed a continuous cover from few to some tens of meters thick (Fig. 8). The total area of the cover is equal to 98 sq. km. Its side boundaries are rather right and clear, but its frontal boundary is dim. The obvious traces of the material movement are seen in the frontal and middle parts of the cover after the fall on the slopes. The frontal margin of the cover up to 1 km wide (and

somewhere even more) was moving over the surface, cutting off the powerful layers of loose pumice deposits. The cover was stopped by negligible obstacles of the relief, but in the places without any obstacles the material advanced as far as movement inertia allowed to do it. Such character of the explosive deposits explains well such a sharp boundary of its spreading: living forest is absolutely untouched at a distance only one metre from the stony desert and chaos

FIG. 8 - Deposits of directed blast. *(Photo by G. S. Gorshkov).*

(Fig. 9). Only not far from the crater one can find separate fragments, ejected by the blast outside the sector, occupied by the main mass of explosive deposits. There is an impression, that the lateral walls of the new explosive crater were as « guides » for the ejected material. In such a case the outburst angle shouldn't be more than 30°. The small value of the outburst angle and corresponding angle of the material fall is corroborated by the fact that negligible obstacles in the fall zone of the explosive material (*e.g.* hills of 10-20 m height) were the reason of the « Shady zones » formation on their opposite slopes. It is, narrow places of untouched-by the explosion-forest, which are oriented in each point of the sector radially with respect

to the crater. These places are absolutely free of explosive deposits, and only crones of high larches are cut off with obliquely falling debris that corroborates again the explosion was oblique. The relief of the directed blast deposits is monticulate-arranged. The ridges like

FIG. 9 - Boundary of the deposits of the directed blast. (*Airphoto by the Institute of Volcanology*).

the « shady zones » are radially situated with respect to the eruptive centre. Their elevation over the whole surface of the cover makes up from 2-3 up to 20 m. Formation of such ridges could take place only in the case of a small angle of material falling.

Distribution of material according to its thickness in the deposit zone of the directed blast is not uniform. Immediately at the lower boundary of the crater the considerable masses of the explosive material gave a morphological unit in the form of thick terraces with the overfall of heights up to 100 m. In the zone at a distance of 1-5 km from the eruptive centre the thickness of the explosive material is not large, here the river valleys are almost free of deposits and there are some quite uncovered area. A mass-scale fall of the explosive material took place in a zone 5-10 km from the crater. In this place the thickness of the cover reaches 50 m. Pre-eruptive relief is quite levelled, the deep canyons (up to 70 m deep) of dry rivers are almost fully filled up in some places.

The thickness of the explosive deposits reaches its maximum at a distance of 1-2 km from the frontal boundary of the cover. In this place there is one more transverse scarp up to 50 m high.

Describing the material of the explosive deposits, it is necessary first of all to underline that this material is resurgent. Ten days after the eruption this material was absolutely cold and inert.

The volume of the directed blast material is minimum 1.5 km^3. The detailed study of the explosive deposit composition showed that it fully corresponds to those rocks which formed the destroyed part of the volcano. They are grey and pink hornblende andesites of the domes and weakly cemented agglomeratic breccias of their foots. Massive monolithic fragments of extrusions with volume up to tens of cubic meters were intensively crushed during their fall, but it is rather interesting that mutual arrangement of separate fragments is not disturbed. Loose material formed very distinctive small hills with steep slopes and narrow ridges, which are oriented radially to the eruptive centre.

Old pumices constitute also a considerable part in the material of explosive deposits. We met whole blocks of slightly cemented pumice andesites (Fig. 10). Ten and more km from the eruption centre we also met enormous blocks of dense ice up to 10-15 m^3 in volume, the only source of which could be the glacier to the east of the Forth top.

Such was the nature of the material ejected by the directed blast many kilometres from the crater. It is necessary to add that the formely picturesque volcano foot having been rich in animals and vegetation, turned into a barren stony desert, covered with

thousands of large and small hills. The birch and larch forests in an area of 45 sq. km are buried now under 20 m-thick deposits of directed blast.

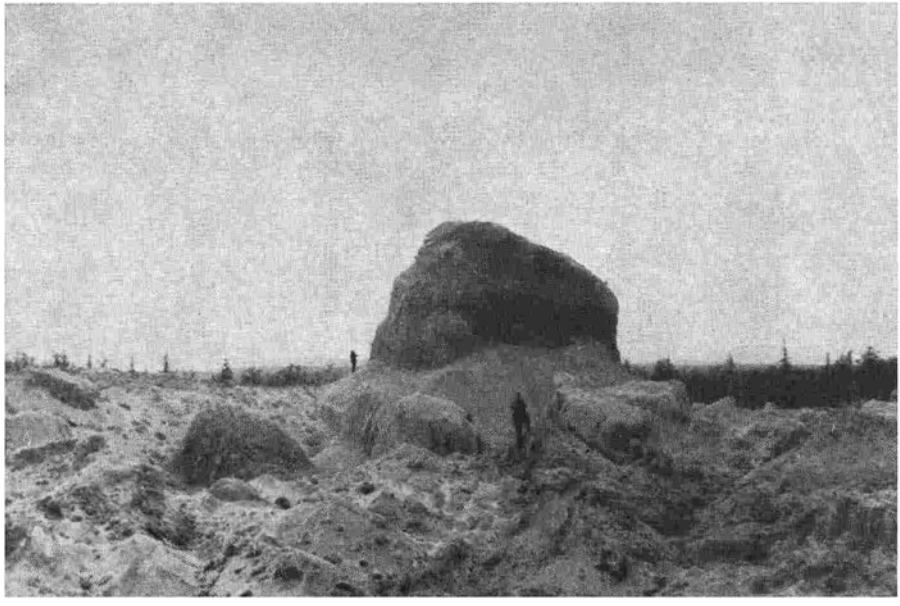

FIG. 10 - A big boulder thrown by the directed blast at a distance of 12 km from the crater. *(Photo by G. S. Gorshkov).*

Pumice- and ash falls.

Just after the directed blast from the opened new crater it was ejected vertically up enormous quantity of gases and ashes which formed an eruptive cloud.

The strong north-western wind determined the direction of movement of the ash cloud and the margins of the ashfall zone, the area of which was more than 100,000 sq. km. In immediate proximity of the volcano it was possible to see that the material, which fell out from the eruptive cloud, overlapped the deposits of the directed blast. Here the whole district in an area of about 90 km^2 is covered with large debris of pumiceous andesite which formed a layer from 20 to 50 cm thick depending on a distance from the eruption centre. At the moment of falling pumice material was almost cold because snowlayer was preserved everywhere under it.

The forest in the pumice fall zone perished. All the small twigs and rind were barked uniformely from all sides as the material from the eruptive cloud was falling vertically. Volume of pumice deposits is equal to 0.05 km^3. Moving off from the volcano, debris sizes and deposit thickness decrease gradually. At a distance of 30-40 km from the crater there is already coarse volcanic sand with a small quantity of pumiceous lapilli. In the district of Ust-Kamchatsk (80 km from the volcano) the material is already represented by normal ash. Morphology of pumice particles indicates that at the moment of ash formation the initial material was already in solid condition. Total quantity of ash is determined by us as about 0.3 km^3.

Pyroclastic flows.

However the main mass of juvenile material was ejected in the form of pyroclastic flows (Fig. 11). Their formation took place during the last stage of the eruption. Really the deposits of the pyroclastic flows overlap both material of the directed blast and airborn pumices. Within the limits of the crater the pyrocrastic flow deposits are practically absent and this indicates a high velocity of the material outburst. In the zone, immediately joined to the crater, they form a continuous thin cover. At the distance of 2-2.5 km from the eruptive centre the material of flows is widely spread over the surface of the explosive deposits, but here it already exhibit a tendency to the low parts of the relief, filling up the remained parts of the valleys. Here thickness of the deposits increases up to some metres. At a distance of 5-6 km from the crater the pyroclastic flows completely submit to the relief and form three main branches.

The maximum length of the flows is 18 km. Total area of pyroclastic flows deposits is about 50 sq. km. As the total depth of the deposits has not yet stripped anywhere the volume of the material is estimated only approximately (0.3 - 0.5 km^3). Besides that negligible pyroclastic masses were thrown over the low parts of the crater walls and formed small pyroclastic flows to the east and north-west of the crater.

All the morphological features of the pyroclastic flows in general are peculiar to the flows of Shiveluch too. They are: 1. - a relatively plane surface of the deposits; 2. - a presence of small marginal and frontal ramparts; 3. - a presence of many small ridges oriented in the direction of movement and composed of coarser material.

In some places rough bedding is seen in the flow sections that indicates multiple outflows of pyroclastic material along the same road.

All the vegetation, including trunks of big trees, is completely charred in the flows deposits. In 10 days after the eruption temperature of pyroclastic material at the depth of 30 cm was equal to 250-

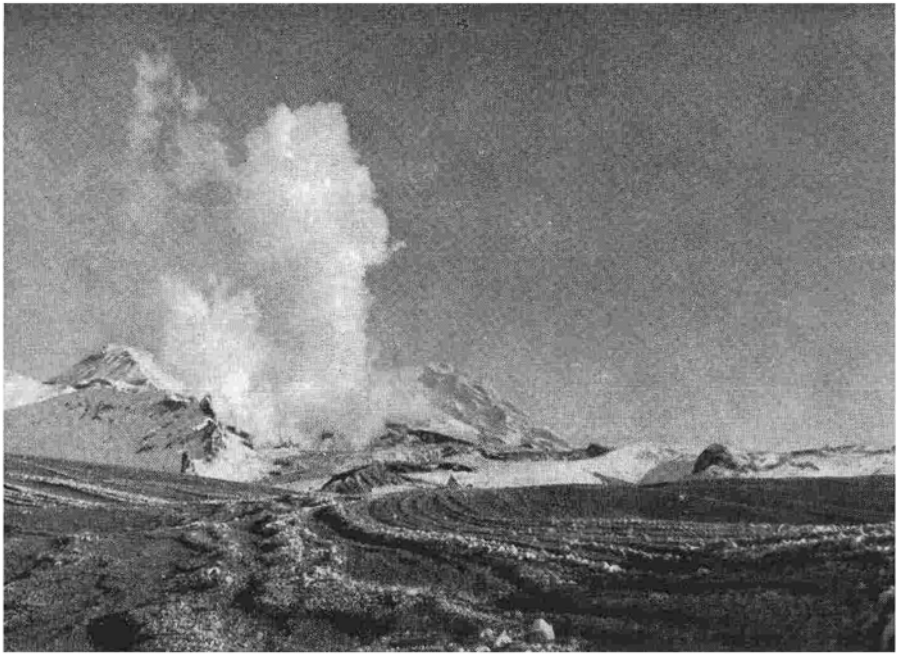

FIG. 11 - Deposits of pyroclastic flows. The Volcano on background. *(Photo by Yu. M. Dubik).*

300°C; temperature of some fumaroles was 400°C. It is necessary to point out a lineation of fumaroles, and as a rule their chains are drawn to the maximum thickness of the pyroclastics in the axial parts of valleys.

In the deposits of pyroclastic flows it is possible to distinguish two varieties of andesites which have a negligible difference in chemical composition and petrography. The most mass of the material is pumiceous light grey andesites with numerous phenocrysts of green hornblende. Degree of rock crystallization is not large: it consists of

70-80 % glass with microlites. The second variety of andesite in pyroclastic flows is notable for greater density, pink colour and presence of the outer chilled zone in debris. Often it is stripy porous andesites. They have both green and brown hornblende; the content of pyroxenes is slightly higher. By their features they are near to pumice of the first eruption stages and perhaps they took higher position in the magmatic column.

In conclusion it is necessary to say that the material of pyroclastic flows differ from the similar in genesis rocks of the former eruptions of Shiveluch volcano very little and it is a product of differentiation of andesite-basaltic magma.

Chemical analyses of some old rocks and juvenile products of the eruption are given in Table 1.

TABLE 1 - Chemical composition of rocks from Shiveluch volcano.

	1	*2*	*3*	*4*	*5*	*6*	*7*
SiO_2	52,83	57,64	62,16	60,00	59,57	58,80	60,78
TiO_2	0,63	0,76	0,60	0,60	0,51	0,85	0,90
Al_2O_3	15,63	17,10	15,88	16,10	16,44	16,18	15,69
Fe_2O_3	5,85	3,35	5,11	2,77	4,11	3,66	2,98
FeO	2,95	3,64	0,36	2,50	2,49	2,83	2,67
MnO	0,10	0,11	0,07	0,10	0,29	0,14	0,12
MgO	7,92	4,05	3,81	3,72	4,04	4,98	3,87
CaO	10,25	7,41	5,62	5,96	6,43	6,78	5,80
Na_2O	2,45	3,76	4,59	4,31	3,27	4,40	4,40
K_2O	1,00	1,65	1,36	1,56	2,72	1,59	1,87
P_2O_5	0,45	0,29	0,19	0,54	n.d.	n.d.	n.d.
H_2O^+	0,07	0,24	0,24	1,30	0,28	0,32	0,42
H_2O^-	0,20	0,12	0,12	0,06	0,12	0,03	0,06
Total	100,32	100,12	100.11	100,17	100,25	100,56	99.51

1 - Pyroxene basalt of Main Top.
2 - Hornblende andesite of Main Top.
3 - Pinck hornblende andesite of Forth Top.
4 - Old pumice.
5 - Hornblende andesite of Suelich dome (eruption 1944-50).
6 - Hornblende andesite of pyroclastic flows of 1964.
7 - Airborn pumice of 1964.
No 1-5 according to MENAILOV (1955).

Lahars.

Deposition of incandescent material of pyroclastic flows on a vast area provoked a rapid melting of snow and formation of lahars. The most powerful and lengthy mudflows correspond to the Western and Eastern pyroclastc flows having reached those parts of foot of the Volcano which were not filled up with explosive material. Lahars swept as narrow flows (300-400 m of width) at the distance of 2-3 km, cutting off trees and carrying along large blocks with them. In some lower parts of the foot the lahars left their load in the form of piles from tree trunks and blocks and widely overflowing in the forest advanced 5-6 km more. Here they did not destroy anything.

Air Wave of the Blast and Volcanic Tremor

The record of only one blast is seen in the barograms of the meteorological statons n Kliuchi, Kozyrevsk, Ust-Kamchatsk and Uka. In Kliuchi the displacement reached 2 millibars at the period up to 25 min. Determination of energy according to the previously deduced formula (GORSHKOV, 1962) gave a value from $0.6 \cdot 10^{21}$ ergs up to 3.10^{21} ergs. The average value according to data from three stations (Kliuchi, Kozyrevsk and Ust-Kamchatsk) amounts to $1.8 \cdot 10^{21}$ ergs. At the stations in Kliuchi and Kozyrevsk record of the blast was done by microbarographs too. According to the construction, sensitivity of them is sharply decreased at the period of more than 2 min. and oscillations with the period of more than 30 min. are not registered at all. That is why the microbarographs did not record and couldn't record the main blast the period of which was 25 min. These instruments registered only high frequency components of air waves, which are taken by mistake for the series of relatively weak blasts (PIIP, MARKHININ, 1965; TOKAREV, 1967).

Energy calculation of shortperiod component according to microbarograms for the time from 7.07 till 8.50 a.m. gives a value of 1.14×10^{20} ergs.

Undoubtedly the records of the following explosions was superimposed on the record of main blast and these following explosions accompanied discharge of pyroclastic flows. However it is imposible to mark out them on the microbarograms. Perhaps a sharp increase in energy of shortperiod oscillations from 7.30 till 8.20 a.m. corresponds to the outpouring of pyroclastic flows.

It was already said in the beginning of the article that the eruption was accompanied by volcanic tremor. It began at 7.20 a.m. and on the records of Kharin's seismographs it had at the beginning an amplitude of 0.25 μ with period of about 0.5 sec. At 7.47 a.m. tremor amplitude exceded 1 μ and the period increased up to 1 sec. From 8.08 till 8.10 a.m. the maximum amplitude of tremor was 7 μ. By 8.17 a.m. the amplitude of volcanic tremor dropped to 1 μ and by 8.22 a.m. it fully stopped. Total energy of volcanic tremor, calculated by records of Khasin's seismographs amounts to 1×10^{16} ergs.

On the records of Kirnos' instruments in Kliuchi, volcanic tremor has an amplitude up to 30-35 μ with the period of 1.5 sec.

Volcanic tremor was recorded by all regional seismic stations of Kamchatka. In Petropavlovsk at a distance of 430 km from the volcano the amplitude of tremor was 0.1 μ with the period of 1.5 sec.

In all described cases up to now volcanic tremor had a surface source and was recorded only in the immediate environs of any erupted volcano, quickly damping with the distance of the first tens kilometres.

Record of volcanic tremor at the distance over 400 km is mentioned for the first time in the world's literature on volcanology.

An attempt was made to determine the depth of the source of volcanic tremor according to the diagram of damping with distance of the ratio A/T, where A are the maximum amplitudes of transverse and surface waves, and T are the corresponding periods. The family of such diagrams for Kamchatka's earthquakes with different depth of focus is done by S.A. Fedotov. According to the preliminary data made by him at our request, the source of the volcanic tremor could be 90-120 km deep. Though one should be very careful to the accuracy of this data but still it is obvious that rather deep and in any case subscrustal source of volcanic tremor was connected with the eruption of Shiveluch volcano on November 12, 1964.

In the conclusion of this part we give data which characterize thoroughly the energetical indices of the eruption.

Methods of calculation were given in another reports (Gorshkov, 1959; Gorshkov and Bogoyavlenskaya, 1965) and are not repeated here.

1. The energy of air wave of the directed blast determined according to barograms of three meteorological stations (Kliuch, Kozyrevsk, Ust-Kamchatsk) amounts to 1.8×10^{21} ergs.

2. Kinetic energy of the blast, proceeding from the volume of ejected material of 1.5 cub. km at the density of 2,0 and from average outburst distance of 7.5 km, amounts to 1.1×10^{24} ergs. Hence the initial velocity is equal to 275 m/sec, and the initial pressure - 750 atm. If the value of maximum distance is 10 km then kinetic energy will increase up to 1.5×10^{24} erg, and the initial velocity and pressure - up to 310 m/sec and 1000 atm correspondingly.

3. Thermal energy of juvenile products of the eruption, proceeding form their total volume (0.75 cub. km), initial temperature of 800° and thermal capacity of 1.1×10^{7} erg/g, amounts to 1.3×10^{25} ergs.

Hence kinetic energy of the explosion makes up 8-10 % of thermal energy. About 0.1 - 0.15 % of the explosion energy converted to the air wave (when determined according to barograms of local stations).

Chronology and Character of Previous Eruptions

« *Catalogue of Kamchatka volcanoes* » (VLODAVETZ and PIIP, 1959) gives the following dates of eruptions for Shiveluch volcano: 1793, 1854, 1879-1883, 1896-1897, 1925-1930 and 1944-1950. The Russian edition of the book add 1790-1810. Besides A. Gumboldt informs of the eruption in 1739.

Careful analyses of all the available literature and notes of travellers in Kamchatka allows us to come to the conclusion that the eruption dates of 1739, 1793, 1790-1810 are not correct. For all XVIII and the first half of XIX centuries Shiveluch volcano kept silence and showed only weak fumarolic activity.

The first positively recorded eruption took place on the night of February 18th 1854. K. Ditmar, who was that time in Petropavlosk, wrote about it according to eye-witness accounts.

« On the night of February 18th 1854, the top of the northern most volcano of the peninsula, Shiveluch, collapsed with a terrible crash and... began a heavy eruption of this volcano... Shiveluch, which according to men's memory, never had eruptions and only slightly smoked, but now it showed its large force. Yet before this catastrophe, in October and December 1853 Shiveluch was smoking more on its northern side, and now lava flows were running down from all sides, almost reaching the Elovka river. Volcanic sand and ash were

falling in such considerable quantity that snow in Kliuchi village was covered with them one foot thick, and in Tigil (1) it was even fine ash raining » (DITMAR, 1890).

Not everything is correct in this information. So the value of ash thickness in Kliuchi is considerably exaggerated (30 cm) Now thickness of ash layer of 1854 in the soil section of Kliuchi is equal to 4-5 cm. If one considers that the ash was 2-3 times pressed (as it was with ash of Bezymianny volcano eruption in 1956) then the ash thickness in 1854 hardly exceeded 10-15 cm. The fact of liquid lava outpouring was disproved by Bogdanovitsh in 1897, but it should mean that natives could consider pyroclastic flows and mudstreams to be lava (as it was in 1956 during the eruption of Bezymianny volcano). There are deposits of 1854 pyroclastic flows both on the southern slope and in the valleys of the western slope.

The eruption in 1854 was really grandiose. 25 years later a priest of Kliuchevskaia church I. Krakhmalev wrote:

« Sopka Sivelych » on the other side of the river was burning so heavy in 1855 (2) that its half was destroyed and with its enormous stones all the forest at the foot was moved down, and the river having broken ice was running. Now the appearance of this sopka is dark, disfigured and terrible at the same time ». (KRAKHMALEV, 1880, p. 110).

Radiocarbon dating of charred trunks from the very high pyroclastic flows in the valley slope of Kamenskaya river showed that this flow appertains to the eruption of 1854. It extends down for 17-18 km from the crater, that corroborates once more grandiosity of the eruption in 1854.

According to the available data Shiveluch volcano kept silence for a long time, at least from the beginning of XVIII century *i.e.* more then 150 years. In all probability the dome « Fourth top » was intact before the eruption. The explosion on February 17/18, 1854 almost completely destroyed this dome: a large, about 2 km in diameter crater was formed from which extremely powerful pyroclastic flows up to 20 km long gushed out to south, and west. Powerful mud streams were formed lower, which reached Elovka river in the west and Kamchatka river in the south, where they broke ice. Pyro-

(1) Tigil is 200 km NW of Shiveluch.
(2) Really in 1854.

clastic flows and mud streams destroyed large areas of forest at the volcano foot. In the whole the eruption in 1854 was more powerful than the eruption in 1964 and it is compared with the Bezymianny volcano eruption in 1956 and probably it was even more powerful.

The next eruption started in 25 years. In 1879-83 a new dome appeared in the crater which was then completely or partially exploded with the formation of pyroclastic flows (KRAKHMALEV, 1880; GUILLEMARD, 1886).

Fourteen years later in 1897 the next eruption began; it probably went on in 1898 (SLIUNIN, 1900; and BOGDONOVITSCH, 1904) Perhaps at this time the Central dome appeared. Most probably the eruption took also place in 1905 (DERZHAVIN, 1916).

The next eruption began in 1928 (NOVOGRABLENOV, 1932). The eruption began in January 27 (RECK, 1928). It went on till the spring of 1929 (NOVOGRABLENOV, 1932 **b**). The eruption in 1928-29 ([3]) was probably weak and it did not bring any considerable changes to the volcano relief.

The last eruption before 1964 took place in 1944-50. It was studied in detail and described by scientific workers of the Volcanological Station.

The first explosion was marked out on December 23, 1944. Little by little explosions became more frequent and strong. In the winter 1945-46 dense eruptive clouds with ash often rose to the height of 5-6 km over the crater. At the beginning of 1946 an extrusive dome appeared in the explosive crater. By autumn 1946 it reached the height of 380-400 m. In 1947 it grew 100-150 m more. Since July 1947 the dome formation was accompanied by incandescent avalanches, the movement features of which were studied at a short distance (Fig. 12). They passed the distance up to 4 km, leaving deposits in the form of chaotic mixture of large subrounded blocks and fine ash. Distinctive narrow embankments of large poorly rounded blocks, like a glacier moraine, were presented at the margins of the deposits. In the end of the deposits there was a « nucleus » of hot avalanche consisting of the incandescent rounded blocks. It was striking to see almost noiseless movement of the incandescent avalanches. In March 1949 the last incandescent avalanche was seen. Then till April 6, 1950 vertical and oblique explosions took place from time to time at the top of the dome. With that the eruption stopped. The new dome

([3]) The dates 1925-27 and 1930 are not correct.

Suelich had a height of 500-600 m; the top diameter was equal to 500 m, and base diameter was up to 1 km.

Considering activity of Shiveluch for historical period of time it is necessary to note that two types of eruptions are taking place at Shiveluch volcano; 1) in long time intervals (of one hundred and

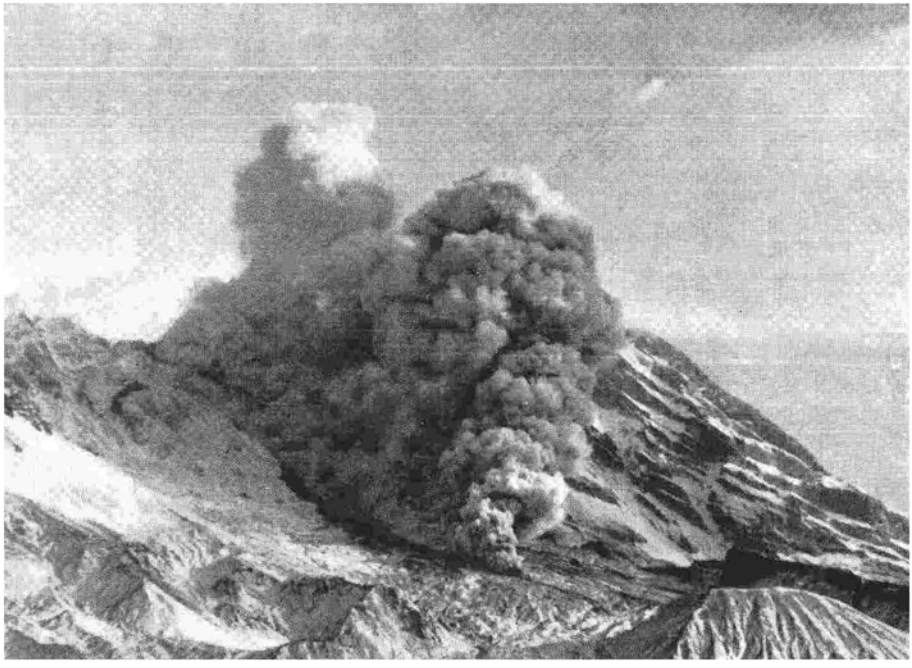

FIG. 12 - Incandescent avalanches from Suelich dome, September 1948. *(Photo by G. S. Gorshkov).*

more years) short-term paroxysmal explosions take place, which destroy the Crater top and are accompaned by vast pyroclastic flows, burning vegitation at the foot of volcano; 2) in the periods between paroxysmal explosions at the intervals from 14-15 up to 30 years continuous (for some years) but relatively weak interparoxysmal eruptions take place during which new extrusive domes are often formed.

Hence it is possible to suppose that in the period between 1980 and 1995 a new eruption will take place and a new dome will be extruded.

Radiocarbon dating of vegetation remnants from the pyroclastic flow deposits or from the thick ash layers can give us some data about the previous paroxysmal eruptions.

So one of the pyroclastic flows in the valley of Kamenskaya river (at a depth of 60 m) has an age of 1500 ± 170 years. One of the lower layers of ash from Shiveluch volcano in Kliuchi village has an age of 3100 ± 200 years.

Conclusion

The eruption at Shiveluch volcano on November 12, 1964 is referred to the category of directed blasts. Here only one (perhaps doubled) extremely powerful explosion took place but not a series of relatively weaker explosions, as it was considered before our studies.

By its power the eruption of Shiveluch volcano belongs to the most powerful eruptions of XX century and it is quite possible to compare it with Bezymianny volcano eruption on March 30, 1956. (Table 2).

TABLE 2 - Power characteristics of Shiveluch and Bezymianny Eruptions.

	Shiveluch volcano on November, 12, 1964	*Bezymianny volcano on March 30, 1956*
Thermal energy	1.3×10^{25} ergs	$3.8\text{-}4 \times 10^{25}$ ergs
Kinetic energy of explosion	1×10^{24} ergs	1.2×10^{24} ergs
Air wave energy	1.8×10^{21} ergs	3×10^{22} ergs
Initial velocity of explosion	280-310 m/sec	360-500 m/sec
Initial pressure	800-1000 atm	1500-3000 atm

The distinctive feature of Shiveluch volcano eruption was its short duration. All the eruption lasted a little more than one hour. In contrast to Bezymianny volcano eruption the material of the directed blast of Shiveluch volcano was crushed considerably less, and air wave energy (at the same kinetic energy) was 10 times less.

The characteristic feature of Shiveluch volcano was generation of volcanic tremor of special type possibly with subcrustal source.

In the last years in Kamchatka two powerful directed blasts took place, which were rather in detail studied, and a new category of eruptions was marked out by one of the authors (GORSHKOV, 1962). Such kind of eruptions took place previously in the other districts but they were not understood in a proper way.

The eruption of Bandai-San volcano in 1888 in Japan is more close by its nature to eruption of Shiveluch in 1964.

Usually the eruption of Bandai-San volcano is taken as an example of phreatic eruption. The deposits at the northern foot of the volcano was considered to be as not explosive but as formed in the result of a downfall or a landslide (SEKIYA and KIKUCHI, 1889). To our mind a directed blast took place here similar to the explosion at Shiveluch volcano, and all the deposits are of volcanic origin.

This eruption lasted less then one hour. 15-20 strong explosions took place; the last one was the most powerful and was directed almost horizontally northward. A deep horseshoe-shaped crater of about 2.5 km width was formed at the nothern slope of the mountain. It was ejected more then 1 km^3 of loose material; the debris were falling at a distance up to 9 km from the crater. A vast intermountain basin with area of about 70 km^2 was buried under a thick layer of « ground and stones ». A plane sandy desert was formed in the place of hilly surface. The surface of deposits was covered by thousands small steepy hillocks, landforms which are very typical of the deposits of directed blasts. Pyroclastic flows were also formed at Bandai-San volcano; one of them got down at the distance of 4 km along Nagase river and had thickness up to 40 m; the second flow passed along the Biva-Sava canyon at the distance of 5 km and had a thickness up to 60 m.

Five villages were buried under deposits of loose material. Besides that seven villages were partially destroyed by air wave.

According to the classification of explosive eruptions offered by one of the authors (GORSHKOV, 1962) the eruptions of Shiveluch volcano in 1964 and Bandai-San in 1888 are referred to the « type of Bezymianny volcano eruption ».

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