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The Shiveluch volcanic eruption of 12 November 1964—explosive eruption provoked by failure of the edifice

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Abstract

Restudy of deposits at Shiveluch in comparison with other data has shown that the sequence of eruptive events at Shiveluch volcano on 12 November 1964 was the following: edifice failure involving 1.154 km^3 of material at 07:07 a.m.; phreatic explosion with ejection of resurgent ash with a volume of 0.01 km^3; Plinian activity between 07:20 and 07:47 a.m., during which andesitic juvenile tephra with a volume of 0.3 km^3 erupted. During the final stage of the eruption between 07:47 and 08:22 a.m., pyroclastic flows with a volume of 0.3-0.5 km^3 were erupted. In this sequence, there was no catastrophic directed blast with generation of a destructive pyroclastic density current like those that look place at Bezymianny volcano in 1956 and at Mount St. Helens in 1980. The absence of a directed blast is attributed to the fact that the 1964 eruption occurred before magma had enough time to intrude into the edifice and build a cryptodome. The failure of the edifice depressurized only a hydrothermal system that existed around the old domes. This appears to have been insufficient for the generation of a catastrophic directed blast.

The case history of volcanic activity at Shiveluch before 1964 suggests that if the edifice of the Young Shiveluch had been stronger and had not failed by landsliding, the eruption of 1964 might have consisted of prolonged dome extrusion with relatively weak explosive activity.

1. Introduction

The eruption of Shiveluch on 12 November 1964 is regarded as one of the great historical explosive eruptions of Kamchatka with respect to the volume of juvenile pyroclastic material thrown out (about 0.8 km^3). The eruption was of short duration and occurred during the hours of darkness, so the main conclusions about its character have been based on studies of the deposits, seismograms and barograms (Gorshkov and Dubik, 1970).

The main factor in the interpretation of the sequence of events for this eruption was the identification of the so-called "directed blast agglomerate": coarse-grained resurgent deposits with a particular hummocky surface, which formed a thick deposit covering an area of 98 km^2 at the southern foot of the volcano. This type of deposit was identified for the first time in the work of Gorshkov and Bogoyavlenskaya (1965), who investigated the results of the catastrophic eruption of Bezymianny volcano that occurred on 30 March 1956. Gorshkov and Bogoyavlenskaya thought that the directed expulsion of several cubic kilometers of the old volcanic edifice could occur as a result of a powerful volcanic explosion with the materials being thrown on ballistic trajectories over distances exceeding 10 km. Simultaneously with the "directed blast agglomerate" at Bezymianny, the deposits of "directed blast sand" were described as thin, relatively fine-grained juvenile deposits, distributed around the "agglomerate" covering an area of about 500 km^3. The areal pattern of the "sand" deposits coincided with the area with fallen

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trees and the deposits were interpreted as the deposits of "nuee ardente" that formed during the explosion.

In spite of the fact that the equivalent of the "directed blast sand" has not been found among the deposits of the 12 November 1964 eruption ol Shiveluch, the Shiveluch eruption was regarded by Gorshkov and Dubik (1970) as being similar to the 1956 Bezymianny eruption, i.e., the "directed blast" type.

After the 18 May 1980 eruption of Mount St. Helens volcano (Voight et al., 1981) it became evident that the "'directed blast agglomerate" deposits could have formed as a result of failure of a portion of the volcanic edifice (Siebert, 1984).

Restudy of the deposits of the Bezymianny eruption (Belousov and Bogoyavlenskaya, 1988; Belousov, 1993) showed that the "directed blast agglomerate" deposits had originated by landsliding and suggested a blast genesis for the "directed blast sand".

Knowledge accumulated after the 1980 eruption of Mount St. Helens (Voight et al., 1981; Siebert, 1984) and restudy of the deposits of the 1956 eruption of Bezymianny suggested the possibility of a new approach to interpreting the events of the 1964 eruption of Shiveluch.

The paper presented here discusses the results of a restudy of the deposits of the Shiveluch eruption and compares these results with data from visual observations and the results of analysis of seismograms and barograms. The objective of this paper is determination of the sequence and character of the events of the 1964 eruption and clarification of the influence of failure of the edifice on the character and intensity of the eruption.

2. Volcanic edifice and brief history of the Shiveluch activity before 1964

The edifice of Shiveluch volcano consists of two parts: Old Shiveluch and Young Shiveluch. Old Shiveluch (major summit, height 3335 m) is the remain of a giant stratovolcano built mainly of lava flows of basalt and andesite (Menyalov, 1955). The summit and the southern pan of Old Shiveluch edifice have been destroyed by a landslide whose volume exceeded 10 km^3. According to Melekestsev et al. (1991), the age of the deposits from this event is about 30,000 yr B.P. After the failure, the formation of the Young Shiveluch edifice (crater summit, height 2763 m) began in a new, 7-km diameter horseshoe-shaped crater which opened toward the south. The formation of Young Shiveluch was followed by strong explosive eruptions; there were six ones during the past 10,000 yr (Melekestsev et al., 1991). However, the most characteristic display of the volcanic history of Shiveluch volcano was dome formation. Practically the entire edifice of Young Shiveluch consists of domes and short flows of andesite.

In 1854 a strong eruption of Young Shiveluch occurred. As a result of this event, a horseshoe-shaped crater, 1.5 km in diameter and open toward the south, was formed. Several extrusive domes grew in the crater during the following 100 yr. The domes filled the 1854 crater completely. The last dome, 0.9 km^3 in volume, was formed in 1946-1949 (Menyalov, 1955). Weak explosive activity continued there until 1950. Following 1950, the Young Shiveluch domes displayed only intensive fumarolic activity.

3. Precursors to the 1964 eruption

A long period of seismic preparation preceded the eruption (Tokarev, 1967). The first earthquake under the volcano was registered on 24 January 1964. After a swarm of earthquakes detected at the beginning of May, a decrease in seismic activity was observed. Following a relatively strong earthquake on 25 July a gradual new increase in the frequency of earthquakes began. Beginning in October there was a sharp increase in the frequency and energy of earthquakes. Seven hours before the eruption the earthquakes became so frequent that their records interfered and seemed to be unreadable. Some of these earthquakes were felt in Kluchi (50 km away) and Kozyrevsk (80 km away). The strongest earthquakes occurred at 07:07 and 07:13 a.m., local time. After the earthquake at 07:07 the eruption began. There is no evidence that noticeable deformation and volcanic activity preceded the eruption. Svyatlovskiy from the Kamchatka Volcanologic Laboratory climbed on the Young Shiveluch domes on 11 July and noted that the volcano "continued to be in a calm state .... no changes have occurred in the regime of the fumarolic activity in spite of the continued seismic activity" (Piip and Marhinin, 1965).

4. The 1964 eruption

The eruption on 12 November 1964 was sudden, brief, and occurred during the hours of darkness. As a consequence, there are only a few observations made by observers about the event. Analysis of the data presented in the paper by Piip and Marhinin (1965) together with the results of the studies of the seismic regime and eruption air waves (Tokarev, 1967; Gorshkov and Dubik, 1970; Adushkin et al., 1984) allow the following conclusions to be made about the eruption process:

(a) Before 07:07 a.m. no volcanic activity was observed.

(b) The eruption began directly after the earthquake at 07:07 a.m. At that lime air waves began to be registered (Fig. 1). The eruption began with relatively weak explosive activity that gradually increased.

(c) The outbursts of incandescent (juvenile?) materials began at 07:20 a.m., a little later than the beginning of the explosive activity. The event was marked by the beginning of volcanic tremor and by a sharp increase in the energy of air waves.

(d) Movement of incandescent material (pyroclastic flows) along the slopes occurred during the final stage of the eruption. The moment of formation of pyroclastic flows may have coincided with a sharp increase in volcanic tremor energy and maximum energy of air waves registered between 07:47 and 08:17 a.m.

(e) The eruption stopped coincident with rapid attenuation of the volcanic tremor intensity. The moment of the end of the eruption is inferred to be at 08:22 a.m., when volcanic tremor stopped being registered.

(f) The maximum height of the eruption column was about 15 km.

A horseshoe-shaped crater, 1750 m in diameter and open toward the south, was formed during the eruption (Fig. 2; Dvigalo, 1984). The new crater almost exactly repeated the contours of the 1854 crater. The volume of the portion of the edifice that was destroyed is estimated to be 1.154 km^3 (Dobrynin, 1991). After the eruption and up until 1980, only fumarolic activity was observed in the crater. From 1980 until 1981 a dome with a volume of 0.0198 km^3 was extruded in the crater (Ivanov et al., 1981; Dobrynin, 1991).

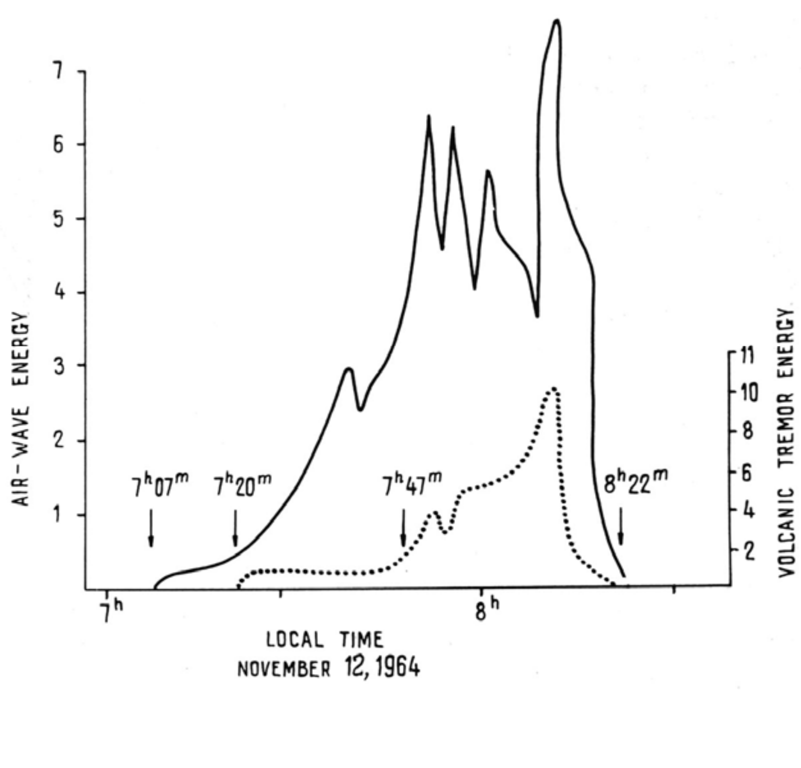

Fig. 1. Air wave energy (solid line) and volcanic tremor energy (dotted line) against time for the 12 November 1964 eruption of Shiveluch volcano (after Tokarev, 1967). Energy in conventional units.

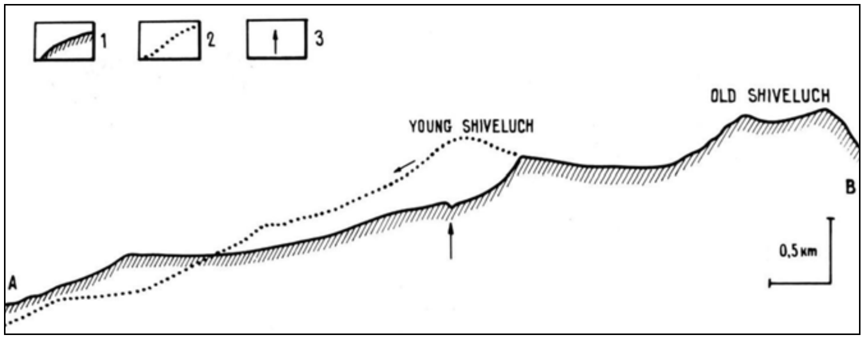

Fig. 2. Topographic profile across the Young Shiveluch summit (line A-B on Fig. 3). 1 = after eruption; 2 = before eruption; 3 = vent location. Arrow indicates the failure direction.

The data presented above will be used to estimate the lime of formation of the deposits of the 12 November eruption, but it is necessary to recognize that there are some ambiguities in doing this.

5. Deposits

Study of sections of the deposits of the 1964 eruption was carried out at the southern and southeastern foot of the volcano (Fig. 3) because all eruption products spread in these directions as was based on observational data and previous investigations. Moreover, the northern and northwestern slopes are not available for investigations because they are very sleep and covered with icefields. In one outcrop (section 3, Figs. 3 and 4), in the southeastern sector of the debris avalanche deposit, all deposit types of this eruption can be seen. Section 3 includes from bottom to top debris avalanche deposits, phreatic ashfall deposits, Plinian fall deposits and pyroclastic flow deposits. Airborne observations several hours after the eruption stopped showed that a small mudflow, 5 km in length, appeared on the western slope of the volcano (Piip and Marhinin, 1965).

5.1. Debris avalanche

Debris avalanche deposits—the "directed blast agglomerate" of Gorshkov and Dubik (1970)—form the lowest part of the stratigraphic section of the 1964 sequence (Fig. 4). The debris avalanche deposits overlie ancient deposits Shiveluch eruptions (mostly debris avalanches and pyroclastic flows), which are covered by a thin layer of soil.

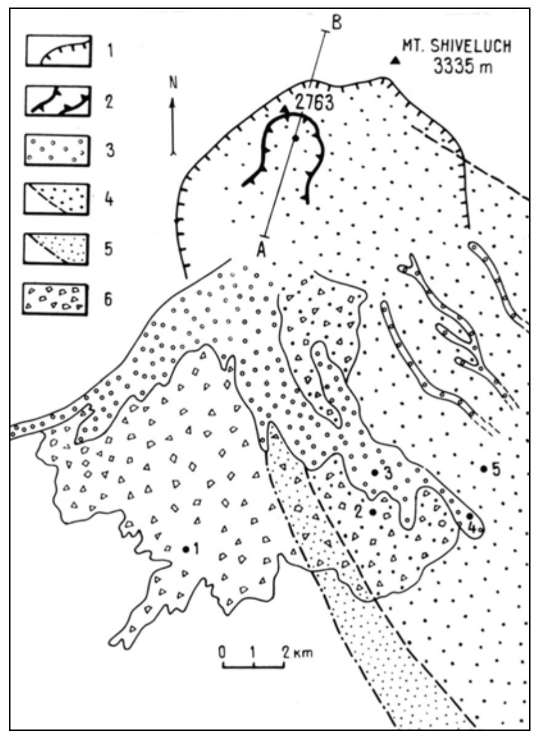

Fig. 3. Sketch map of the 12 November 1964 deposits (with additions after Melekestsev et al., 1991). 1 = rim of the 30,000-yr-old avalanche caldera; 2 = crater of the 1964 eruption; 3 = pyroclastic flow deposits; 4 = Plinian fall deposits; 5 = ashfall deposits of the phreatic explosion; 6 = debris avalanche deposits. Dots with numbers = location of sections on Fig. 4.

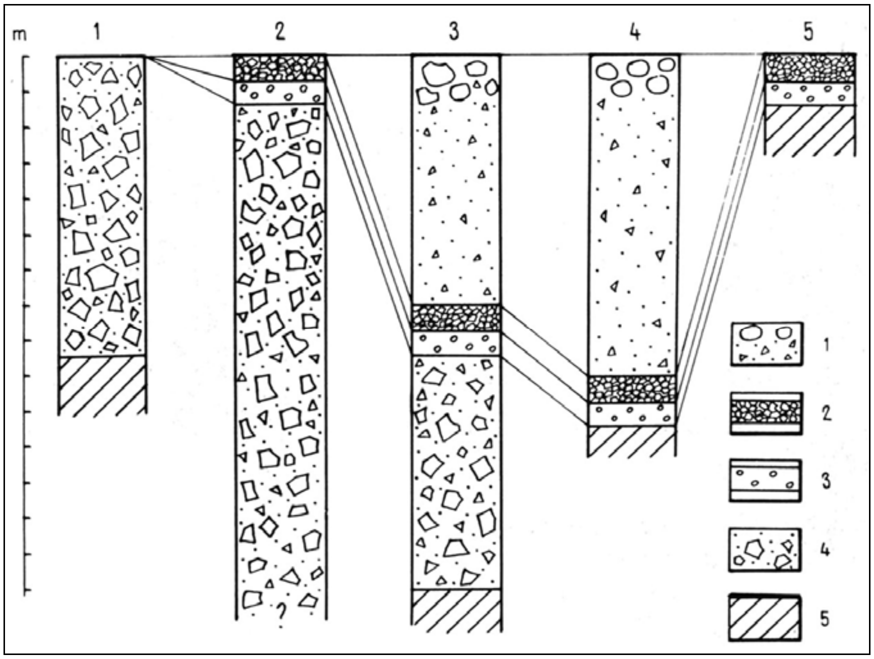

Fig. 4. Stratigraphic sections of the 12 November 1964 deposits. 1 = pyroclastic flow deposits; 2 = Plinian fall deposits; 3 = ashfall deposits of the phreatic explosion; 4 = debris avalanche deposits; 5 = pre-1964 deposits or soil. Reference numbers above sections are identical to Fig. 3. Thicknesses of the fall deposits are shown without scale and are about 4-6 cm for each layer.

In some places a 1-cm-thick layer of ash from the 1956 Bezymianny eruption is preserved under the Shiveluch debris avalanche deposits. Trunks of trees and bushes are often observed at the base of the debris avalanche; many of them are aligned and oriented away from the volcano.

Debris avalanche deposits consist of strongly fragmented rocks of the old volcanic edifice. In general, this material originated in the summit crater domes and their margins. The composition of most rocks is andesite. Unaltered as well as extensively altered rocks occur. Among the altered rocks, gypsum-bearing debris blocks as large as 0.5 m are observed. Juvenile material has not been found in the debris avalanche deposits.

Debris avalanche material is represented for the most part by “block facies” of debris avalanche (according to the terminology of Glicken, 1991). Some blocks are composed of tephra and pyroclastic flow deposits with undisturbed primary layering. A small volume of "mixed facies" were found only along the southeastern edge of the deposits. Sometimes it forms a layer with a thickness up to 1 m at the base of the avalanche. Temperature measurements of debris avalanche deposits carried out 10 days after the eruption showed that the deposits were cold and part of the material was in a frozen state. Pieces of ice up to several cubic meters in volume were found in the deposits (Gorshkov and Dubik, 1970).

On the slightly dissected foot of the volcano, the debris avalanche deposits have formed a wide tongue that extends as far as 16 km from its source (Fig. 3). Maximum width of the tongue is about 15 km. Deposits cover an area of 98 km^2 and, as a rule, have a thickness of 3-15 m. In depressions in the underlying surface, the debris avalanche deposits can reach a thickness of 150 m. Where the slope of the volcano joins the crater, portions of the landslide stopped and several sharp steps were formed with a height up to 100 m. Perhaps these are the last portions of the ruined edifice. The volume of the debris avalanche deposits has been estimated to be 1.5 km^3 (Gorshkov and Dubik, 1970).

At sites where pyroclastic flows are absent, the avalanche deposits, as a rule, have a particular hummocky surface. Many of the hummocks have a form similar to a cone (Fig. 5). The height of the hummocks reaches 15 m. Over most of the debris avalanche the hummocks

Fig. 5. Surface relief of the debris avalanche deposits. Height of the large hummocks is approximately 2 m.

are grouped in radially oriented ridges. Sometimes small lakes occur between the hummocks. Separate parts of the avalanche surface, constructed of highly altered rocks or friable pyroclastics, have wave-like relief. Sometimes the debris avalanche surface looks like a chaotic pile of large blocks of dense andesite with diameters up to several meters. The front of the deposit is steep and its height reaches 3 m. In front of the debris avalanche margin in many places, long mounds of fallen tree trunks were formed, which were scrambled by the avalanche during its movement. Beyond the margin of the debris avalanche deposit trees remained standing vertically and are untouched, except at the southeastern margin where they were disturbed by pumice that fell from the eruptive cloud.

The character of the deposits described above leaves no doubt about their origin as debris avalanche deposits, formed as a result of failure of a portion of the edifice of Young Shiveluch volcano. Characteristics of the debris avalanche are presented in Table 1.

Table 1
Debris avalanche characteristics

H(km)	*L (km)*	*H/L*	*M (m)*	*S* (km^2)	*V* (km^3)
2.3	16	0.14	3-150	98	1.154

H = height dropped by the landslide; L = maximum path passed by avalanche; M = deposit thickness; *S* = deposits area; V = volume of landsliding portion of the edifice.

5.2. Ash of phreatic explosions

A layer of olive-gray ash with a thickness of 4—8 cm overlies, with a sharp contact, the debris avalanche deposits. The character of the contact shows that ash deposition took place after the debris avalanche has stopped moving.

Beyond the edges of the debris avalanche the ash lies directly on the soil (Fig. 6). The character of buried vegetation indicates that ash deposition took place as a calm vertical ashfall from the eruptive cloud. The ash layer consists of numerous accretionary lapilli whose diameters reach 1.8 cm.

The ash is fine grained with an admixture of larger particles as large as 1 cm. The ash particles consist of clasts of various rock types similar to those that constitute the sliding part of the edifice, along with crystals of plagioclase, pyroxenes and hornblende, and rare fragments of glassy debris. Many of the particles are oxidized; some of them have traces of hydrothermal alteration. The nature of the ash particles shows that they originated as crystalline, partially altered andesite of the old volcanic domes, subjected to explosive destruction.

Fig. 6. Ashfall deposits of phreatic explosions and overlying pumice fall deposits representing Plinian activity, and uppermost pyroclastic flow deposits. Pre-1964 soil is at the base. Section number 4, Figs. 3 and 4.

An unusual component of the ash is formed by abundant, well-formed gypsum crystals which constitute a significant part of the - 2 to 30 fraction. The regular form of the crystals supports the idea that they formed as a result of recrystallizalion from an intergranular gas phase, after deposition of the ash. However, gypsum may have initially been present in the ash and did not migrate later from the underlying and overlying deposits. Naboko (1959) noted that gypsum was one of the more widespread minerals on the dome fumaroles of Young Shiveluch. A case during which gypsum crystals were ejected along with ash was described for the phreatic eruption of Ebeko volcano in 1967 (Menyalov etal., 1969).

The characteristics of the ash allow one to suppose that it was erupted by a phreatic explosion, which occurred when the failure of the edifice depressurized the old dome hydrothermal system. The resulting ash cloud spread in a southeasterly direction. The volume of the phreatic ash is calculated to be approximately 0.01 km^3.

5.3. Juvenile tephra of Plinian eruption

Coarse tephra represented by juvenile pumiceous andesitic lapilli overly the resurgent ash deposits; the contact between the two materials is sharp. At the foot of the volcano the thickness of the lapilli unit reaches 20 cm. The transport direction of the Plinian eruption cloud was almost the same as the direction of the preceding phreatic explosion cloud, namely toward the southeast. The volume of the erupted juvenile tephra is estimated to be about 0.3 km^3.

5.4. Pyroclastic flows

The last unit emplaced during the eruption consists of the pyroclastic flow deposits, which covered an area of 50 km^2. In the western part of the area of deposition, pyroclastic flows overlie the debris avalanche deposits. The thickness of the pumiceous pyroclastic flows depends on underlying relief and reaches a maximum of 50 in. The volume of pyroclastic flows is calculated to be 0.3-0.5 km^3.

6. Reconstruction of the sequence of eruptive events

Comparison of the results of restudying the deposits with visual observational data and the results of seismic and air wave studies allows the following reconstruction of 1964 eruptive events.

Seismic precursors to the eruption were associated with the rise of magma towards the surface (Tokarev, 1967). At the moment of the eruption magma was situated at a shallow level, but it did not have enough time to intrude into the volcanic edifice.

The eruption began with the failure of a group of domes, that had filled the 1854 crater. A landslide was triggered by intensive seismicity, and most probably by the earthquake at 07:07 a.m. Landsliding material in the form of the debris avalanche spread in a south direction. The failure of the edifice led to the rapid release of pressure from the hydrothermal volcanic system. As a result, a phreatic explosion occurred that ejected resurgent ash. A large amount of vapor in the eruptive cloud was the reason that ash was deposited in the form of accretionary lapilli. There is no evidence that this explosion triggered any pyroclastic surge or flow.

Failure of a portion of the volcanic edifice hastened the rise of magma toward the Earth's surface. Eruption of juvenile material perhaps began at 07:20 a.m., when volcanic tremor began to be registered. After this moment the character of volcanic activity may be defined as Plinian.

Formation of pyroclastic flows took place during the final stage of the eruption, possibly beginning about 07:47 a.m. The eruption stopped at 08:22 a.m., when the volcanic tremor ceased to be registered.

7. Conclusions

The eruption studied above may be considered as an example of the influence of volcanic edifice failure on the character and intensity of explosive processes. The history of activity of Shiveluch volcano suggests that the formation of a new dome in the 1854 crater was "inevitable". The character of eruption was to resemble the dome growth in 1946-1949, i.e., it was to last for a long time and to be followed by relatively weak explosive activity.

In initialing the next series of events, the volcanic edifice collapsed, triggered by seismicity related to the rise of magma toward the surface. Failure of the volcanic edifice activated the eruption process, and juvenile material was erupted in the form of tephra and pyroclastic flows. The explosion, which followed the landslide directly, has a particular place in the sequence of eruptive events. The character of the eruption products shows that crystallized andesite with traces of hydrothermal alteration was subjected to explosive destruction. The small volume of erupted ash, the presence of a great amount of gypsum crystals in it, and deposition in the form of accretionary lapilli suggest that the phreatic explosion was relatively weak and was related to rapid decompression of the hydrothermal system that existed around the destroyed domes. The roots of the last extrusive dome possibly had some input in the explosion process; they had little time to cool, and perhaps partially maintained their "explosive capability".

The absence of a catastrophic directed blast with formation of a destructive pyroclastic density current like those observed in the 1956 Bezymianny and 1980 Mount St. Helens eruptions suggests that the existence of a hydrothermal system alone may not necessarily serve as an adequate "charge" for events of this type.

The presence of a cryptodome in the volcanic edifice, i.e., a volume of partially crystallized magma, may more readily provide the necessary condition for occurrence of a catastrophic directed blast. If pressure is removed as a result of a landslide, the cryptodome is destroyed explosively and the erupted material forms destructive pyroclastic density currents. As of 12 November 1964 magma had not yet had time to intrude inside the volcanic edifice of Shiveluch. This fact probably accounts for the absence of a catastrophic directed blast in the sequence of events of this eruption, and distinguishes it from the eruptions of Bezymianny in 1956 and Mount St. Helens in 1980.

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