average quantitative-mineral composition was determined for them by taking into account the composition of every size fraction. As is seen from Fig. 6, the mineral composition of all types of Bezymianny deposits is very similar; the main difference appears to be that there are different percentages of juvenile and resurgent material. This was determined by studying the coarse fraction (0.5–2 mm) of the matrix. The juvenile material of Bezymianny volcano was light-gray, fresh, slightly vesicular debris, that

2

Bezymianny volcano eruption

Character of deposits		T° at time of deposition (°C)	Thickness (m)	Area (km^2)	Volume (km^3)
Lithology	Composition				
Hornblende-pyroxene andesite and bipyroxene andesite		700–800	—	—	0.4 by 1976
Coarse to fine ash	Nearly 50 percent juvenile material consisting of hornblende-pyroxene andesites	< 100			0.4–0.5
Sandy-aleurite material with rounded debris of vesicular andesite with a mixture of rocks of old edifice	Juvenile material (hornblende andesite up to 80 percent)	500–600	≤ 30–40	40	0.8
Sand with wood and small debris	Dominantly rocks of old edifice; up to 10–15 percent (10–15%) juvenile material	> 100	0.5–0.1	500	0.2
Coarse-rock agglomerate with sandy-aleurite matrix	Predominantly rocks of old edifice; up to 10–15 percent (10–15%) juvenile material	(?)	10–30	60	0.8
Coarse to fine ash	Juvenile material consisting of hornblende pyroxene andesite	100	0.2	—	0.4–0.5

resulted from fracturing of magma solidified in the conduit(s) of the volcano. The resurgent material consisted of solid fragments of the volcanic edifice, in the form of dense angular lava debris. Our study further supports the inference that both facies of directed-blast deposits consisted of resurgent material, while deposits of pyroclastic flows and tephra are composed mostly of juvenile material. For comparison, we studied the composition of the matrix in different units of the directed blast, pyroclastic flow and the debris avalanche deposits of the Mount St. Helens eruption using the same procedures and size fractions. The mineral composition of the Mount St. Helens deposits is close to that of the Bezymianny eruption deposits: the main difference is in the proportions of juvenile and resurgent material.

1964 SHIVELUCH ERUPTION

Eight years after the 1956 directed-blast eruption of Bezymianny volcano, a catastrophic explosion occurred at Shiveluch volcano, one of the Klyuchevskoy volcanic group.

Shiveluch volcano is the northernmost edifice among the active volcanoes of Kamchatka. This deeply dissected volcanic massif began to develop approximately 60,000–70,000 yrs ago. Before the 1964 eruption, it was a massif made up of (1) a partially destroyed edifice of Old Shiveluch (the highest northern summit is about 3335 m), (2) an enormous crater 9.5 km across and open to the south, and (3) Young Shiveluch volcano composed of numerous coalescing andesite extrusive domes (one of which, the south summit, is 2700 m high). Formation of the old crater occurred as a result of a catastrophic directed-blast about 30,000–35,000 yrs ago. The characteristic behaviour of Young Shiveluch volcano has been powerful catastrophic eruptions that produced great volumes of juvenile tephra and pyroclastic flows. Within the last 10,000 yrs, eruptions of this type occurred on an average of about once per 500 yrs.

During historic time, a catastrophic eruption occurred in 1854; it formed a large crater and produced extensive pyroclastic flows. Subsequent volcanic activity has included episodic growth of domes (1879–93, 1897–98, 1928–29 and 1944–45) (Gorshkov and Doubik, 1969).

The 1964 Shiveluch eruption repeated the main stages of the catastrophic eruption of Bezymianny volcano including:

1. A preclimactic stage characterized by prolonged seismic activity.
2. A climactic stage including formation of a directed-blast agglomerate, followed by Plinian activity.
3. A post-climactic stage that has consisted of fumarolic activity and, beginning in 1980, growth of an intracrater dome.

The 1964 eruption has been studied in detail by Gorshkov and Doubik (1969), Piyp and Markhinin (1964) and Tokarev (1964; 1967). The main details of the 1964 eruption are cited here according to the accounts of these investigators.

Preclimactic stage

The 1964 eruption was anticipated, because it was preceded by a long period of seismic aactivity. The first small earthquakes under the volcano were recorded in January. A well-defined swarm of earthquakes occurred at the beginning of May (Tokarev, 1964). Then a prolonged decline in seismic activity began in the second half of October and preceded the eruption. During the last day prior to the eruption, 73 earthquakes were recorded and for the 7 hr period immediately before the eruption began, earthquakes occurred practically without interruption.

Climactic stage

The eruption began on November 12, at 0705 (local time) with the destruction of the summit of the volcano and the formation of a crater, about 1.5×3 km in size, in place of the former summit. The form of the crater is compound, consisting of two parts; the northern part has an oval form with a cross section of 1.5×1km, and the height of the northern wall is about 700 m. The southern part of the crater is shaped like a trapezoid; its area is about 4 km^2 and it is covered by friable agglomerate material that forms a high, steep ledge at the south flank of the crater. According to Gorshkov and Doubik (1969), such a morphology may be accounted for if crater formation resulted from two or more successive paroxysmal explosions. As a result of the explosions, a layer of friable agglomerate, with a thickness ranging from several meters to a few tens of meters, was deposited in a sector to the south of the crater to a distance of about 10 km from the volcano (Fig. 8). The total area covered by this deposit is 98 km^2. The topography of the deposit is irregular and hummocky with longitudinal ridges disposed radially away from the eruptive center (Fig. 9).

The thickness of deposits along the axis of the directed-blast is irregular: the deposit is well developed near the mouth of the crater and out to a distance of 5–10 km from the crater, where the thickness of the cover reaches 50 m. The volume of directed-blast deposits was estimated by Gorshkov and Doubik (1969) to be about 1.5 km^3.

After the debris moved from the crater, features on the surface and near the front of the deposit suggest that it flowed out to its present position. The boundary of the directed-blast deposit is clearly defined and lobate in form.

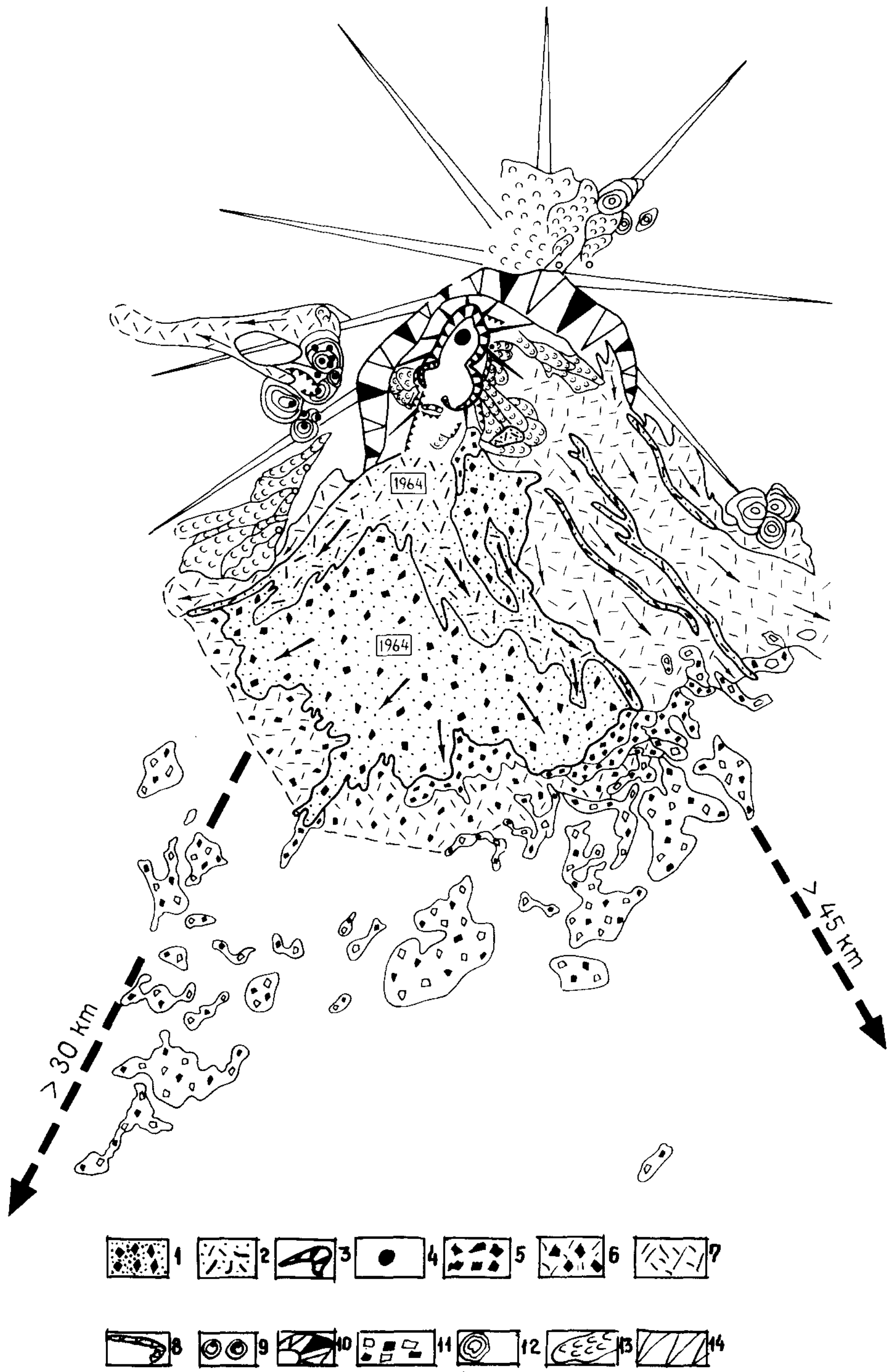

Fig. 8. Schematic map of deposits at Shiveluch volcano after the 1964 eruption. Volcanic formations in 1964: 1. directed-blast deposits; 2. pyroclastic-flow deposits; 3. crater of the blast; 4. extrusive dome in 1980–1981. Holocene volcanic formations; 5. directed-blast deposits; 6. pyroclastic-flow deposits; 7. undissected directed-blast and pyroclastic-flow deposits; 8. craters; 9. extrusions. Upper-Pleistocenic volcanic formations; 10. craters; 11. directed-blast deposits; 12. extrusions; 13. lava flows; 14. the edifice of Old Shiveluch.

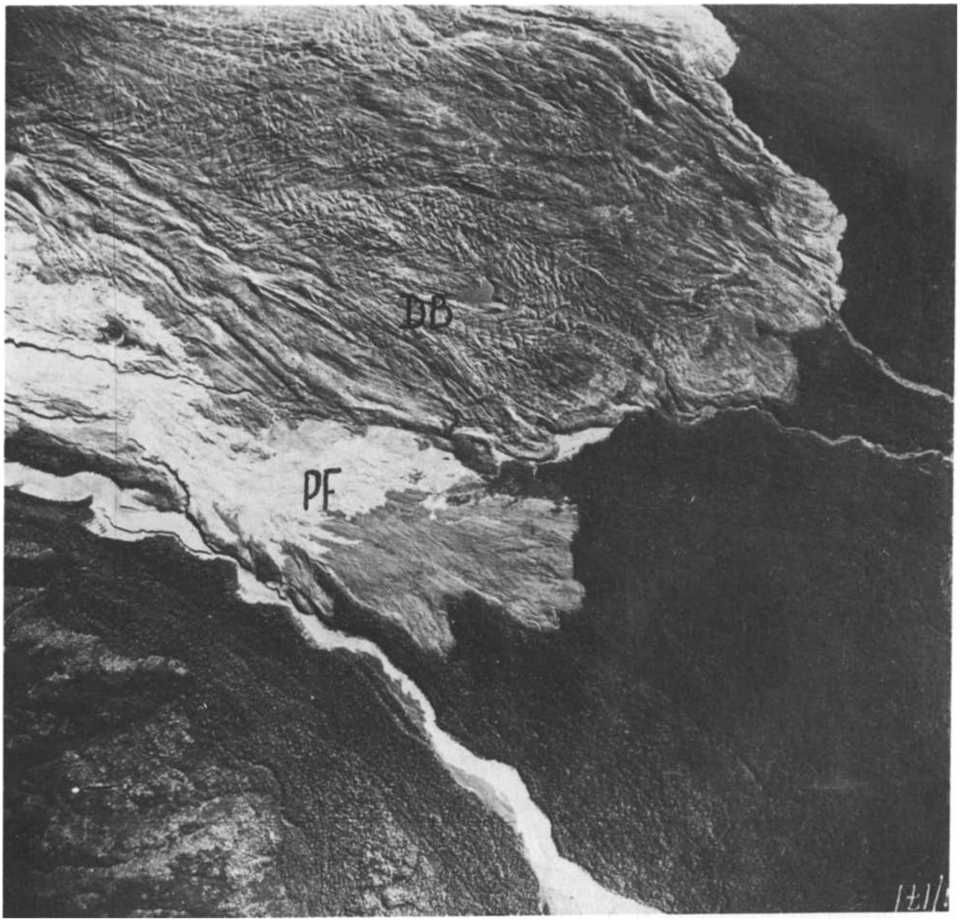

Fig. 9. Directed-blast deposits at Shiveluch volcano. Photograph by G. S. Shteinberg. DB-directed-blast PF-pyroclastic flows.

At a distance of 1 m beyond the front, the forest was left absolutely untouched (see Fig. 10), indicating that a blast like those at Bezymianny and Mount St. Helens did not occur.

The blast deposit consists of unsorted and unstratified agglomerate that includes debris and large blocks of rock that formed the old edifice before its destruction, including: dense gray, vesicular pink, and pumiceous andesites. Large blocks of massive ice from the summit glacier with volumes of 10–15 km^3 were also identified in the deposits. Gorshkov and Doubik (1969) believed that the material that resulted from the directed-blast was completely resurgent and contained no juvenile component and they noted that it was cold when examined a few days after the eruption. The blast deposit at Shiveluch is comparable to the directed-blast agglomerate at Bezymianny and the debris avalanche at Mount St. Helens.

The kinetic energy of the Shiveluch blast amounted to 1×10^{17} J (Gorshkov and Doubik, 1969); the initial velocity was 280–310 m/s.

After the explosions that destroyed the old edifice, Plinian activity began. The eruption cloud rose to a height of about 10–15 km. The tephra covered an area of about 100,000 km^2. In close proximity to the volcano, a layer of coarse pumiceous andesitic debris from 20 to 50 cm thick covered an area of 90 km^2. At a distance of about 30–40 km from the crater, the airfall deposit consisted of sand-sized ash with small amounts of pumiceous lapilli. An ash layer 3 cm thick was deposited about 80 km from the volcano at the settlement of Ust'-Kamchatsk. The total volume of erupted ash was about 0.3 km^3.

TABLE

Characteristics of the 1964

Stages of eruption	Main events		Duration	Type of deposit	Character of occurrence
POSTCLIMACTIC	Dome growth. Fumarolic activity		Nov.–Jul. 1980–1981	Lavas of the extrusive dome	Intracrater extrusion
CLIMACTIC	PLINIAN ACTIVITY	Eruptive cloud about 12–15 km high	1 hr	Tephra	Pyroclastic layer
		Pyroclastic-flow eruption	Several min	Pyroclastic flow	Low-lying ground and valleys filled with pyroclastic flow material
	Directed blast. Formation of crater 1.5 × 3 km in size.		A few tens of sec.	Directed-blast agglomerate	Hummocky-surfaced deposit covers area independent of topography
PRECLIMACTIC	Seismic preparation		Jan.–Nov. 1964		

The composition of ashes is shown in Fig. 6; the juvenile component is dominant (up to 90 percent) over resurgent material.

Pyroclastic flows, erupted along with the airfall deposits, covered the surface of the blast deposits extensively out to a distance of 2–2.5 km from the crater; at a distance of 5–6 km from the crater, the flows filled low-lying areas with a deposit a few tens of meters thick. The maximum lenght of pyroclastic flows is 18 km and the total volume is 0.3–0.5 km^3 over an area of 15–20 km^2 (Table 3). The flow deposits consist of homogeneous juvenile material with a small mixture of allogenic debris. Pumiceous light-gray andesite is the dominant rock type; along with rare, dense pink andesite. All vegetation, including large tree trunks, is charred in the pyroclastic flow deposits. Ten days after the eruption, the temperature of pyroclastic flows at a depth of 30 cm was 250–300°C and at some fumaroles as high as 400°C.

Deposition of hot pyroclastic flows onto a large area covered with snow

3

Shiveluch volcanic eruption

Character of deposits		T° at time of deposition (°C)	Thickness (m)	Area (km^2)	Volume (km^3)
Lithology	Composition				
Hornblende pyroxene andesite		≈ 700	—	—	~0.02
Coarse to fine ash	90–95 percent hornblende andesite, juvenile material	100	—	—	0.3
Agglomerate-sandy-aleurite material with rounded debris of pumiceous andesite ⩽ 0.5 m in size	80–90 percent hornblende andesite, juvenile material	500–600	⩽ 40	15–20	0.4–0.5
Coarse-rock agglomerate with sandy-aleurite matrix	Rocks of the old edifice. Juvenile material 2 percent	(?)	⩽ 50–60	100	1.5

resulted in the formation of lahars; their maximum length did not exceed 5–6 km.

The 1964 eruption of Shiveluch was of very short duration and lasted for no more than an hour.

Post-climactic activity

Post-climactic activity consisted of fumarolic activity in the newly formed crater. Sixteen years later, in August 1980, an extrusive dome began to erupt nonexplosively on the floor of the crater (Fig. 10). Dome growth was preceded or accompanied by neither seismic nor explosive activity. Lava was squeezed out in the central part of the crater. During the first two

Fig. 10. The 1980–1981 extrusion in the crater of Shiveluch volcano. Photograph by V. N. Podtabachny.

months the dome grew most intensively with an average velocity of 2.5 m/day. According to photogrammetric measurements (Dvigalo, 1984), by mid-October 1980 the dome had the following dimensions: the height 140–168 m, the base 460–610 m in diameter, and the volume 0.11 km^3. Calm lava extrusion continued throughout the whole of 1981. In March 1982, when lava extrusion was over, the dome attained a height of 180 m, its base was 540–800 m and the volume was 0.020 km^3. Lavas comprising the dome are gray hornblende pyroxene andesite, with $\sim$60% SiO_2.

The results of studying the composition of the Shiveluch deposits are given in Fig. 6. An examination of the relationship between juvenile and resurgent material has shown that the tephra of the 1964 Shiveluch eruption is almost totally juvenile and that the matrix of the pyroclastic flows consists of about 75 percent juvenile material. The absence of juvenile debris in the Shiveluch directed-blast agglomerate is probably due to the fact that no significant volume of crystallized magma (cryptodome) existed in the upper parts of the conduit before the eruption. This is supported by the observation that the preclimactic phase of the eruption was not accompanied by deformation of the edifice. Magma apparently did not accumulate within the edifice and thus, juvenile debris is practically absent in the directed-blast deposits.

COMPARATIVE CHARACTERISTICS OF THE CATASTROPHIC ERUPTIONS AT MOUNT ST. HELENS, BEZYMIANNY AND SHIVELUCH VOLCANOES

All of the eruptions considered above may be classified as directed-blast-type eruptions as defined by Gorshkov (1962; 1963).

This type of eruption may be characterized by the catastrophic nature of the climactic stage and the associated extremely hazardous consequences. Directed-blast eruptions usually are preceded by intense seismic activity that may be accompanied by deformations of the volcanic edifice. The deformation may consist of localized lateral or vertical movements of as much as 100 m or more, resulting from intrusion of magma and formation of a cryptodome within the volcanic edifice. The climactic stage includes the following main events:

1. A directed explosion that destroys the volcanic edifice and results in formation of a large horseshoe-shaped crater, and an explosion that devastates an area of several hundred square kilometers.
2. The mass ejection of juvenile pumice (or pumiceous) pyroclastics following the blast and formation of pyroclastic flows and ashfall from the eruption cloud.
3. The formation of extensive lahars.

The events of the climactic stage for the three eruptions considered in this paper are quite similar with respect to: the kinetic energy of the blast (10^{16}–10^{17} J), the initial ejection velocity of the debris (300–500 m/s), the duration of events (a few tens of seconds for the blast, and hour to several hours for Plinian activity), the nature and the initial temperature (600–800°C) of juvenile pyroclastics and the morphology and the dimensions of the resulting craters (1.5 × 3 km in size, 0.6–0.8 km deep). The deposits of this stage cover a sector as wide as 90–180° that extends from the base of the volcano to a distance of as much as 30 km, with a range of deposits having characteristics described in Tables 1, 2, 3 and 4.

Directed-blast eruptions are typically followed by growth of an extrusive dome in the crater.

In spite of the fact that the eruptions described in this paper are of the same general type and are similar with respect to the main events, it is nevertheless important to note that there are differences between them.

The preclimactic stage for Bezymianny and Mount St. Helens was characterized by deformation of the edifice, and by strong explosive activity of Vulcanian type that lasted for a month at Bezymianny, and only phreatic activity that lasted for nearly 2 months at Mount St. Helens. At Shiveluch volcano these preclimactic eruptive events were absent.

At Mount St. Helens, the directed-blast of the climactic stage was initiated by failure of the flank of the volcano caused by a large earthquake. The deposits resulting from the failure consisted almost wholly of material of the old edifice (the total volume of those was about 2.8 km^3) (see Fig. 1). A directed-blast occurred after the failure; the resulting deposits consisted of both the fractured material of the destroyed parts of the old edifice and juvenile dacite of the destroyed cryptodome; the volume of the latter amounted to about 50 percent.[1] The blast material was deposited as a relatively thin layer (10–40 cm thick) over an area of about 600 km^2; the total volume of the blast deposit was only 0.2 km^3.

At Bezymianny volcano, there was no such differentiation of initial events. The volcano was destroyed by a direct blast through the flank of the volcano that caused disruption of about 1 km^3 of material. The directed-blast deposits are represented by two facies: (1) a hummocky deposit of coarse debris that consists of 85–90 percent material of the old edifice and 10–15 percent juvenile material. The deposit covers a narrow sector with an area of more than 60 km^2 and has an average thickness of 30–40 m; (2) a directed-blast "sand" deposit that covered an area of about 500 km^2

[1] The deposits of coarse blast debris contain about 50 percent juvenile dacite. The relations between juvenile and resurgent material in the matrix of the directed-blast, pyroclastic flow is somewhat different (Fig. 8).

TABLE 4

Some characteristics of catastrophic eruptions.

Eruptions	Directed blast			Pyroclastic flows		Tephra volume, km^3	Heat power of eruptions, J	Kinetic energy of blast, J	Energy of air wave, J
	are of deposits, km^2	volume of deposits, km^3	size of crater	length in km	volume of material km^3				
Bezymianny 1955–1956	500	1.0	1.5×2.8	18	0.8	0.8–0.9	$3.8–4.8 \times 10^{18}$	1.2×10^{17}	3×10^{15}
Shiveluch 1964	100	1.5	1.5×3	18	0.4–0.5	0.3	1.3×10^{18}	1×10^{17}	1.8×10^{14}
Mt.St.Helens 1980	600	0.2	1.5×3	7–8	0.12	1.1	10^{17}		

with a deposit ranging in thickness from about 0.5 m to 1 cm; the deposit contains old debris from the edifice and juvenile material in about equal proportions ($\sim 10\%$).

Because failure of the edifice preceded the blast, the Mount St. Helens eruption resulted in deposits that are clearly separable; the deposit of the debris avalanche and directed blast are composed of different materials and have different volumes, thickness and distributions. At Bezymianny, however, failure did not precede the blast and the directed-blast occurred through the flank of the volcano. The resulting deposits have characteristics of both the debris avalanche and blast deposit at Mount St. Helens; mixing of the two processes may also explain a significantly lower juvenile component in the Bezymianny deposits.

It is noteworthy also, that the lowest unit of the Mount St. Helens blast deposits is significantly enriched in the remains of vegetation, soil, and wood, a feature that is not present in blast deposits at Bezymianny volcano. It is likely that this can be accounted for by the eruption of Bezymianny occurring in the spring when the ground surface was covered with snow 1–3 m deep.

At Shiveluch volcano, the edifice was also destroyed during the climactic stage of the eruption. There, however, a succession of smaller directed blast may have occurred rather than one explosion, as is evidenced by the morphology of the crater and by barometric data. The resulting deposit is represented by a hummocky, coarse-blocky agglomerate that covers a rather wide sector (120–130°), has an area of about 100 km^2, and has a total volume of about 1.5 km^3. The directed-blast sand facies or blast deposit proper, seen at Bezymianny and Mount St. Helens, respectively, is absent at Shiveluch.

The coarse-debris in the blast deposits at Shiveluch is wholly composed of the old edifice material; thus, the blast deposit at Shiveluch volcano resembles the debris avalanche deposit at Mount St. Helens. Thus, the blast deposits of Shiveluch volcano are essentially an analog of the directed-blast agglomerate facies at Bezymianny volcano and the debris-avalanche deposit at Mount St. Helens, to which they are very similar with respect to topography and composition. The presence of coarse juvenile debris in similar deposits at Bezymianny is related to disruption of a crystallized magma body or cryptodome within the conduit; a feature that apparently was lacking at Shiveluch volcano.

The zone of destruction at Shiveluch coincides with the area covered by the directed-blast agglomerate deposit. Outside the boundaries of this deposit, there was no trace of a blast or its influence on the vegetation and topography. This is a main difference between events at Shiveluch and those at Bezymianny and Mount St. Helens, where the area of destruction corresponds to the distribution of the directed-blast sand deposit and covers 500–600 km^2.

During the post-climactic period of Plinian activity, the total volume of juvenile material (tephra and pyroclastic flows) erupted at Mount St. Helens and Bezymianny were roughly comparable (in both cases, about 1.2 km^3) and exceeded the volume of juvenile material erupted at Shiveluch (0.8 km^3). However, the volume of pyroclastic-flow deposits erupted at Mount St. Helens is much less (0.12 km^3 in comparison with 0.5 km^3 at Shiveluch and 0.8 km^3 at Bezymianny).

The heat energy of all three eruptions is also comparable: $1{,}3 \times 10^{18}$, $3.8\text{–}4.8 \times 10^{18}$, and 1×10^{17} J for Shiveluch, Bezymianny and Mount St. Helens, respectively. They represent the most powerful eruptions in the world during the 20th Century.

Regardless of the differences in the character of eruptive events at Mount St. Helens, Bezymianny, and Shiveluch, the events are within the limits of directed-blast eruptions as defined by Gorshkov (1962).

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