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The September 7 – October 2, 1994 Eruption of Klyuchevskoi Volcano, Kamchatka

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An extrusive-explosive, mainly Strombolian eruption occurred in the crater of Klyuchevskoi Volcano on September 7 – October 2, 1994. The eruption grew more violent and changed to a kind of subplinian activity during the closing phase. The volume of the erupted material was 0.02–0.04 km^3 of lava and 0.05 km^3 of ash. Its composition was high-Al basalt, typical of all Klyuchevskoi eruptions. This paper is based on the results of studies that were carried out by a team of volcanologists from the Institute of Volcanology, the workers of the Kamchatkan Volcanological Station, and the seismologists from the Experimental Seismological Team of the Geophysical Survey of the Russian Academy of Sciences.

Introduction. Klyuchevskoi is one of the most active volcanoes of the world. It produced more than half of the juvenile material deposited on the surface of the Kuril–Kamchatka volcanic area. Its magma discharge averages $\sim 6\times10^7$ tons per year [9].

This volcano is a member of the Klyuchevskoi volcanic group, which includes Bezymyannyi and Tolbachik, the known active volcanoes of the world. The volcanoes of the group are located in the Central Kamchatka depression, at the junction of the Kuril–Kamchatka and Aleutian island arcs.

Klyuchevskoi Volcano was born in Holocene time, its age is 6–7 thousand years [1]. It is a central-type stratovolcano complicated by numerous cinder cones. Its cone consists of lava flows intercalated with pyroclastic layers and ice sheets.

The height of the volcano before the 1994 eruption (as of August 3, 1993) was 4822 m above sea level and 2900 m above the base. Its summit crater is ~750 m across. The northwestern wall of the crater is indented by the Krestovskiy trench, which dissects the slope of the volcano in a NNW direction to a height of 3200 m above sea level. Prior to the 1994 eruption the trench was ~50 m deep and had a width of 700 m in the near-crater portion, getting narrower and pinching out down the slope.

A distinctive feature of the Klyuchevskoi eruptive activity is the occurrence of summit and flank eruptions. The eruption that preceded the event discussed (March–September 1993) occurred at the summit crater, where explosions took place, and lava flowed.

Generally, the Klyuchevskoi eruptions are preceded by an augmentation of seismic activity: volcanic earthquakes of ranks I–II (after Tokarev [7]) take place.

Seismic activity in the area of the Klyuchevskoi volcanic group is monitored by a telemetry network consisting of nine seismic stations, whose information is collected at a data storage center in Klyuchi City. The network uses a TESI-2 type telemetry equipment [2]. Combined with this equipment, each station provides three-component records of ground motion velocity. Each seismometer channel has a plateau-type frequency response characteristic in a frequency range of 0.8–20 Hz. Seismic information is recorded by high-precision tape recorders and conventional photographic-paper recorders. Records of volcanic tremor and earthquake swarms are processed and analyzed using a set of techniques described in [11]. Rms ground-motion velocity (X), a generalizing energy characteristic of the seismic process, is determined automatically. Additionally, average amplitudes (A_{av}) of the vertical tremor component are measured using conventional seismic records. The records of all stations are processed promptly to provide data of the number and energy of volcanic earthquakes.

In our analysis of seismic activity prior to and during the 1994 eruption, we used the data obtained at the Zelenaya (ZLN) and Podkova (PDK) seismic stations located at distances of 11 and 14 km from the summit crater, respectively (Fig. 1).

In January–February 1994, seismic activity in the Klyuchevskoi area did not exceed the usual background level: averagely 50 volcanic earthquakes of types I–II were recorded at stations ZLN and PDK during each month. Their monthly number began to increase slowly in March and was as great as 500 events in July and August (one to two months before the eruption). Their epicenters were grouped within a range of 10 km around the vent. Most of the events were of energy class $K_{S1,2} \leq 8$. The maximum number of weak quakes ($K_S \leq 6$) were recorded at a depth of 20–30 km. Their number decreased slowly toward the Earth's surface; no quakes were recorded from a depth below 30 km.

No changes were observed in the behavior of the volcano that might be interpreted as precursors of the impending eruption: as during the previous months, the volcano was in the state of mild fumarolic activity.

Record of the eruption. The eruption began on September 7 in the summit crater and

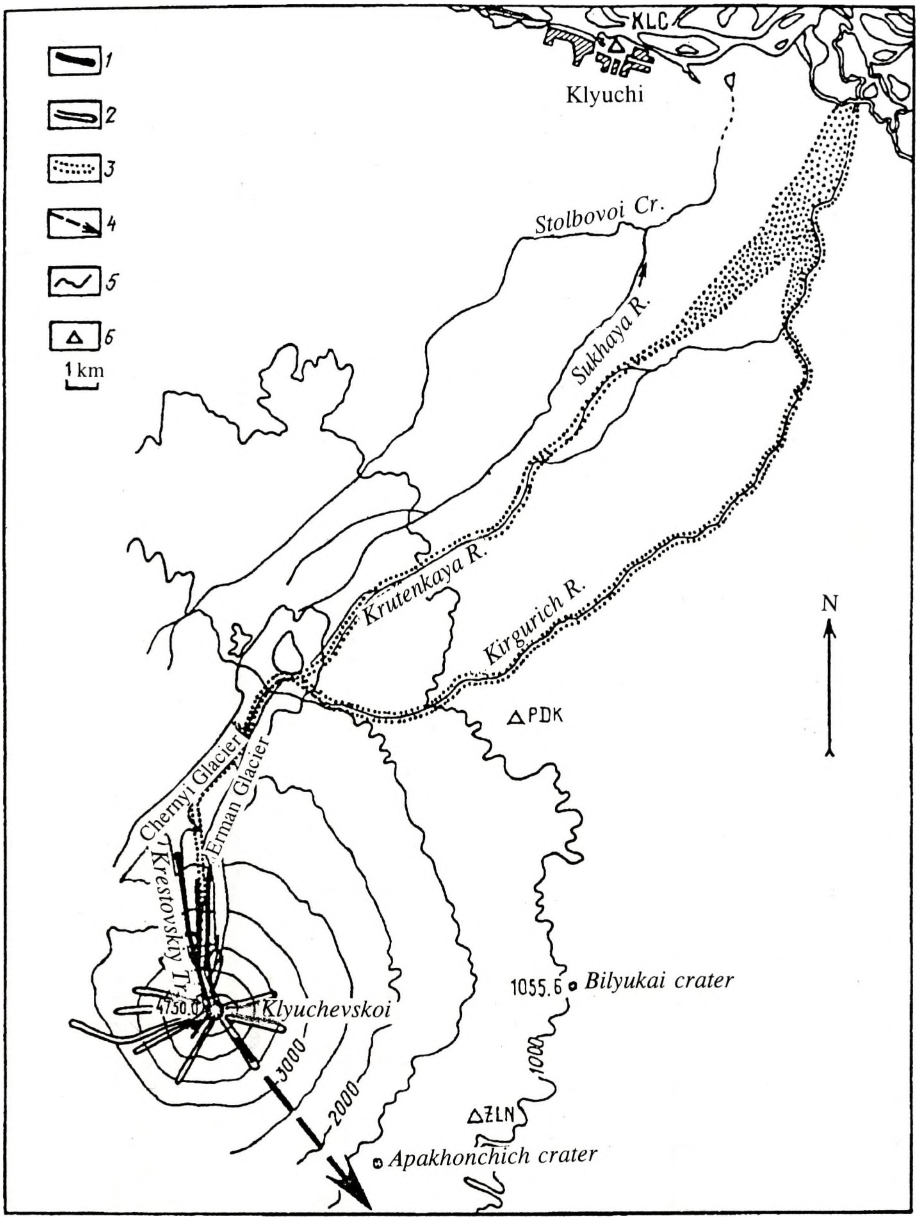

Figure 1 Schematic map showing the distribution of the materials erupted during the paroxysmal phase of the 1994 eruption of Klyuchevskoi Volcano: *1-3* – lava flows (*1*), pyroclastic flows (*2*), and mudflows (*3*); *4* – ash-fall axis; *5* – contour lines; *6* – seismic stations (ZLN – Zelenaya, PDK – Podkova, KLC – Klyuchi).

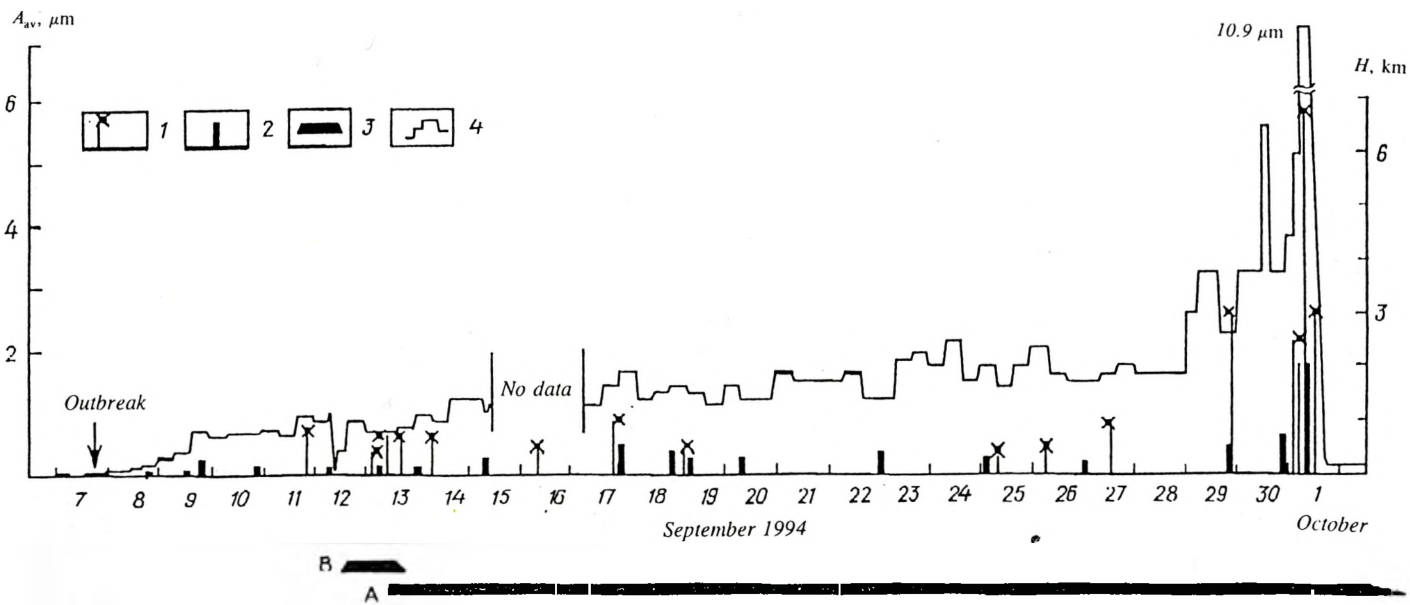

Figure 2 Dynamics of Klyuchevskoi eruptive activity in September–October 1994. X axis – time (local); Y axes: H – height above the crater, A_{av} – average tremor amplitude (Z component). *1* – height of eruption cloud above the crater; *2* – height of bombs; *3* – lava flowing on the slopes: A – along the Krestovskiy trench, B – along the SW slope; *4* – average amplitude of tremor recorded at station ZLN (Z component).

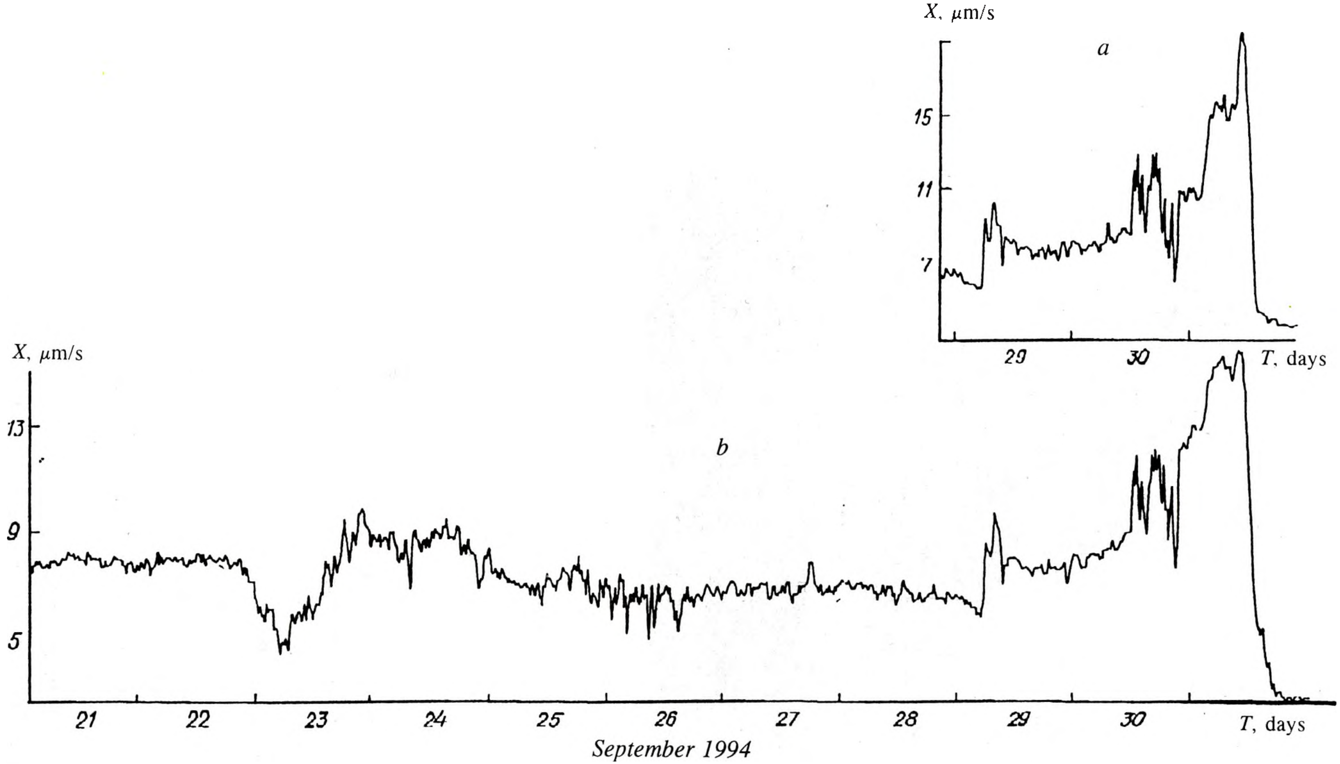

Figure 3 Rms ground motion velocity (Z component), recorded at stations ZLN (*a*) and PDK (*b*). Averaged using a 170-second time constant. *T* – local time, *X* – rms ground motion velocity.

Figure 4 Eruption of Klyuchevskoi on October 1, 1994, 9:30 a.m. View from Klyuchi City. The height of the eruption column is 12.5 km above sea level. Phreatic explosions (lower left) in the Krestovskiy trench. Photo by V. A. Podtabachnyi.

continued till October 2, 1994. It consisted of four phases: (1) the explosive phase, (2) the extrusive and explosive phase, (3) the paroxysmal extrusive and explosive phase, and (4) the closing extrusive and explosive phase.

Explosive phase (September 7–11). The first signs of the eruption were noted at 17 h (hereinafter the local time is used) on September 7, when steam-gas ejections were seen above the crater. In the morning of the next day, September 8, the volcano was obscured by a heavy fog, but sounds of explosions were heard from it at the ZLN seismic station (11 km). During the evening red hot bombs were seen above the crater; they were hurled to a height of up to 50 m.

The early phase of the eruption can be classified as Strombolian. Red hot bombs were thrown intermittently out of one or two vents to heights of 100–200 m above the crater. A steam and gas column, occasionally containing a small amount of ash rose to a height of 1 km above the crater, sometimes as a brief ejection and sometimes as a persistent column lasting for several hours.

The outbreak of the eruption was fixed exactly by seismic data. The volcanic tremor recorded at the ZLN station started to increase slowly from a background value of 0.1 μm, recorded at 15 h of September 7, to 0.3 μm at 19 h of September 9. It then increased sharply more than two-fold (0.8 μm) and remained at that level, with some fluctuations, till September 12 (Fig. 2).

No weak volcanic earthquake of types I–III were recorded since the outbreak of the eruption. This can be explained either by a significant attenuation of this type of seismicity or by the appearance of volcanic tremor that masked earthquake signals.

Extrusive-explosive phase (September 12–30). On September 12 lava began to flow. The first lava flow traveled along the southwestern slope of the cone and was 1.5 km long. Apparently it flowed only for a two or three days. On September 13 lava began to flow from two boccas that developed at the northwestern foot of a cinder cone in the crater. The lava from both boccas flowed into the Krestovskiy trench. The two flows traveled a distance of 4 km for less than 24 hours and descended to a height of 3100 m above sea level. The width of the lava flows between the marginal ridges ranged between 10 and 30 m.

The second-phase lava flows were observed in the Krestovskiy trench from the beginning to the end of this phase. Usually two and, less commonly, three lava flows were seen to move in the trench simultaneously. Sometimes they meandered and formed a lava field which in some places was as wide as 200 m by the end of that eruptive phase.

Powerful phreatomagmatic explosions[a] occurred as the lava came in contact with the ice, especially at the fronts of the lava flows. The resulting steam clouds, often loaded with ash, rose to a height of 3–4 km. These phreatic events produced mudflows, which traveled along the channels of the Krutenkaya and Kirgurich Rivers as far as 20–25 km from the sites of their origin.

The explosive activity of the second phase was characterized by the frequent ejections of red hot bombs hurled to a height of 300–500 and occasionally 700 m from the summit crater. The eruption column that rose as high as 1 km above the crater rim almost always

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[a] The terminology concerning phreatic phenomena continues to be revised in volcanological literature. The terms "phreatic explosion" and "phreatomagmatic explosion" are still not crearly defined, and the classification of some volcanic events can be ambiguous. Some volcanologists believe that the products of phreatic explosions must not contain fresh (juvenile) material. On the other hand, Mackdonald [4] gave the following definition: "Eruptions, during which a partially or wholly magmatic material is erupted, but the explosion is the result of the action of secondary steam (formed outside the magma chamber), can be called hydromagmatic or phreatomagmatic events". In the case of Klyuchevskoi Volcano, secondary explosions occur as a result of the interaction between a juvenile magmatic material (incandescent lava) and ice. We believe that the term "phreatomagmatic explosion" can be used in this situation.

Figure 5 Eruption cloud during the paroxysm of October 1, midday, view from the south. Bezymyannyi Volcano and Kamen Volcano (behind it) are seen in the foreground. The Klyuchevskoi cone is obscured by the eruption cloud. Photo by V. A. Podtabachnyi.

contained some ash. The slopes of the volcano were dark because of the ash fallen from the clouds risung from the summit crater to a height of 2500–3000 m above sea level. Sounds of powerful explosions were heard in Klyuchi City at a distance of 32 km from the volcano.

During September 29–30 the eruptive activity was characterized by short periods (a few hours) of the intensification and decline of extrusive and explosive activity. During the high-intensity periods the gas–ash eruption column rose to a height of 3 km above the crater rim.

Based on the existing classifications, such periods can be classified as a moderate Strombolian activity.

The relatively stable manner of eruptive activity during these periods was reflected in the behavior of seismic records. The values of the average tremor amplitude were in the range of 0.7–1.6 μm at the ZLN station with a tendency of a slow increase (Fig. 2). At the end of one of these periods (September 29) the tremor amplitude increased jumpwise and continued to vary within a range of new, higher values.

These variations are illustrated by a curve of an rms ground motion velocity X in Fig. 3. Before September 29 the tremor had a fairly stable level ($X \sim 7$ μm/s). On September 29 the tremor magnitude decreased slowly during the first five hours, then increased abruptly to $X = 9.5$ μm/s, then after four hours, dropped to 8 μm/s, and remained at this level, with mild fluctuations, till 13 h of September 30. From that time to the end of September 30, the tremor magnitude varied from 9 to 12 μm/s with a period of ~1 h, and during the following six hours, the tremor level stabilized at ~13 μm/s.

Paroxysmal extrusive-explosive phase (October 1). The final paroxysm began at 5 h in the morning of October 1 and lasted some 9 or 10 hours. A powerful ash-loaded eruption column rose from the summit crater to a height of 12 or 13 km above sea level (7–8 km above the crater) (Figs 4 and 5). Fountains of red hot bombs were expelled out of the vent to a height of 2–2.5 km above the crater; some of the fragments were as large as 1.5–2 m in size.

A dark, ash-laden cloud drifted from the column to the southeast driven by the strong northwesterly wind. The surface of this huge ominous veil had a cauliflower pattern. As ash-fall wall stretched oceanward for dozens of kilometers and vanished beyond the sky line. The upper limit of this ash wall was fairly even. The ash cloud was 3–5 km wide near the volcano and grew wider away from it. On October 1 it was as long as 2000 km (Fig. 6). Abundant tephra fell from the cloud. The size of some lapilli was as large as 50 mm on the ash-fall axis 15 km from the crater.

Lava flowed on the NNW slope mainly along the Krestovskiy trench; some of the lava flows were as long as 5 km. Numerous block and ash flows swept down the NW, W, S, and E slopes (Fig. 1). They ranged between 2 and 6 km in length and between 50 and 80 m in width.

The lava flows came in contact with the ice throughout their extent and at the fronts. As a result, phreatomagmatic explosions took place and produced huge black dense cauliflower clouds rising as high as 7 km above the sites of their origin, and also mudflows (lahars).

Large mudflows followed the channels of the rivers, traveled as far as 25–30 km, and reached the Kamchatka River. The rock fragments transported by the main lahar course near the Kamchatka River were as large as 1.5 across. The mudflows scoured an unpaved motor road running along the southern bank of the Kamchatka River over a 6th to 12th-km stretch from Klyuchi City.

The eruptive activity started to decline perceptibly at about 14–15 h on October 1.

The paroxysm is clearly seen in the behavior of the tremor variation curves in Figs 2 and 3. The main distinctive features are a rapid increase (1–2 hours) and as rapid decline of the tremor level. According to the records of the PDK station, the rms ground mo-

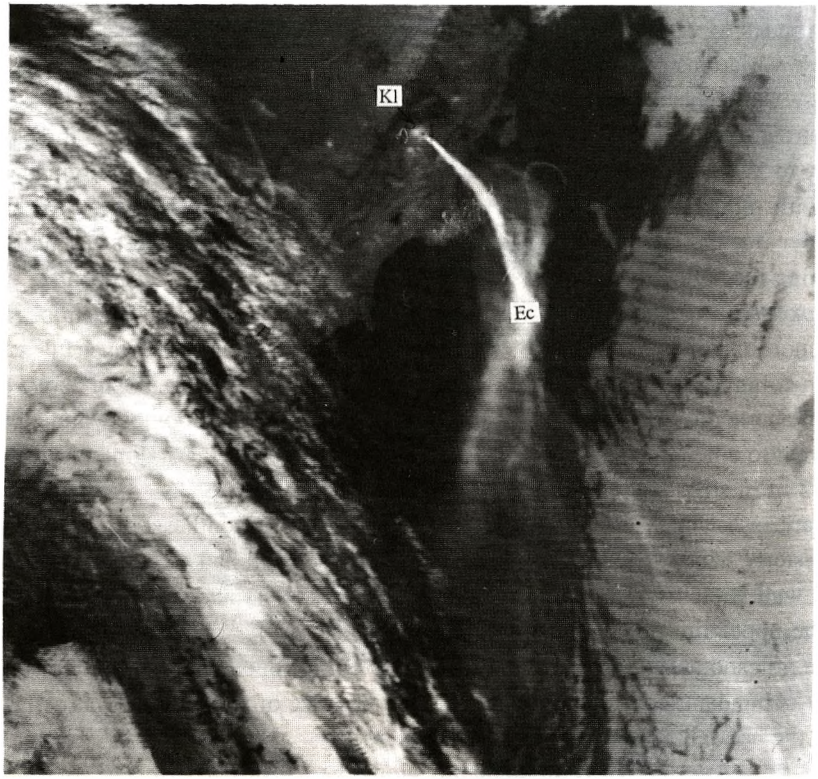

Figure 6 Eruption cloud of the paroxysmal eruption, October 1, 8:15 p.m., photographed by the American NOAA-1 spacecraft. The left part of the picture is closed by clouds. Kl is the Klyuchevskoi crater, Ec is the drifting eruption cloud (white).

tion (tremor) velocity increased suddenly to 15–16 μm/s at the outbreak of the paroxysm (at 5 h, October 1) and remained at this level during 8–10 hours (Fig. 3). A similar pattern was recorded at the ZLN Station (Fig. 2): the vertical component of the average tremor amplitude amounted to 10.9 μm at 5–6 h and remained at this level during several hours; at 12 h on October 1 the tremor started to decline rapidly and dropped to a background value by 18 h (Fig. 2).

During the paroxysm the eruption power was two or three orders of magnitude higher as compared with the previous phases (visual evaluation). This type of activity is usually classified as a Plinian eruption producing large amounts of ash. Because the third, paroxysmal, phase of the Klyuchevskoi eruption did not produce much ash, it can be classified as subplinian.

Closing extrusive-explosive phase (October 2–3). On October 2 explosive activity declined suddenly: some ash ejections continued but never exceeded a height of 300 m. A similar decline was observed in the extrusive activity: lava continued to flow along the Krestovskiy trench, but the length of the lava flow was less than 1 km. On October 3 visual observation was impossible because the cone was covered by dense clouds. The tremor recorded on October 3 indicated the end of the eruption. On October 4 and later merely moderate fumarolic activity was observed: fumarolic gas ejections did not rise higher than 50 m. The number of volcanic quakes of types I–III corresponded to the background level.

Discussion of results. The growth of seismic activity at a depth of 20–30 km, recorded five or six months before the eruption, was obviously caused by the growth of stresses around the magma conduit. These events are interpreted as medium-term precursors of Klyuchevskoi eruptions [3].

The eruption discussed was a short event; it lasted less than a month. It began with explosive activity (5 days), then changed to an explosive and extrusive eruption (19 days), and was terminated by a one-day paroxysm, after which the volcanic activity subsided slowly during two days.

As a first approximation, this eruption can be treated as a continuous operation of an energy source, during which the rise of the eruption column and the spread of the drifting cloud were controlled by the power of the source and the state of the atmosphere. The temperature and the wind direction and velocity were measured at altitudes up to 25 km on September 30 and October 1, 1994, at the zonal weather station in Klyuchi City and are presented in Fig. 7, *a* and *b*. The comparison of the curves shows that the atmosphere was stable during the eruption.

At the time of the paroxysmal event, the outer limit of the tropopause was at an altitude of 10 km. This is clearly marked by the inflection of the temperature variation curves (Fig. 7, *a* and *d*), where a temperature inversion took place: the steady temperature decline (from +10 to -50°C) ceased abruptly at an altitude of 10 km, and between this level and an altitude of 25 km, the range of temperature variation was extremely small (-50 to -55°C).

In physical terms, this atmospheric temperature structure was favorable for the rise of the eruption cloud to the tropopause altitude and unfavorable for a further rise: the ascent of the cloud was retarded, and it began to spread in the lateral direction. As mentioned in the above record, the gas and ash eruption column rose to a height of 12–13 km. The minor excess of its height over the tropopause altitude could be caused by its inertia and turbulent convection.

The further distribution of the rising masses (drifting cloud formation) was controlled by the direction and velocity of the wind. The maximum wind velocity (35–40 m/s) was

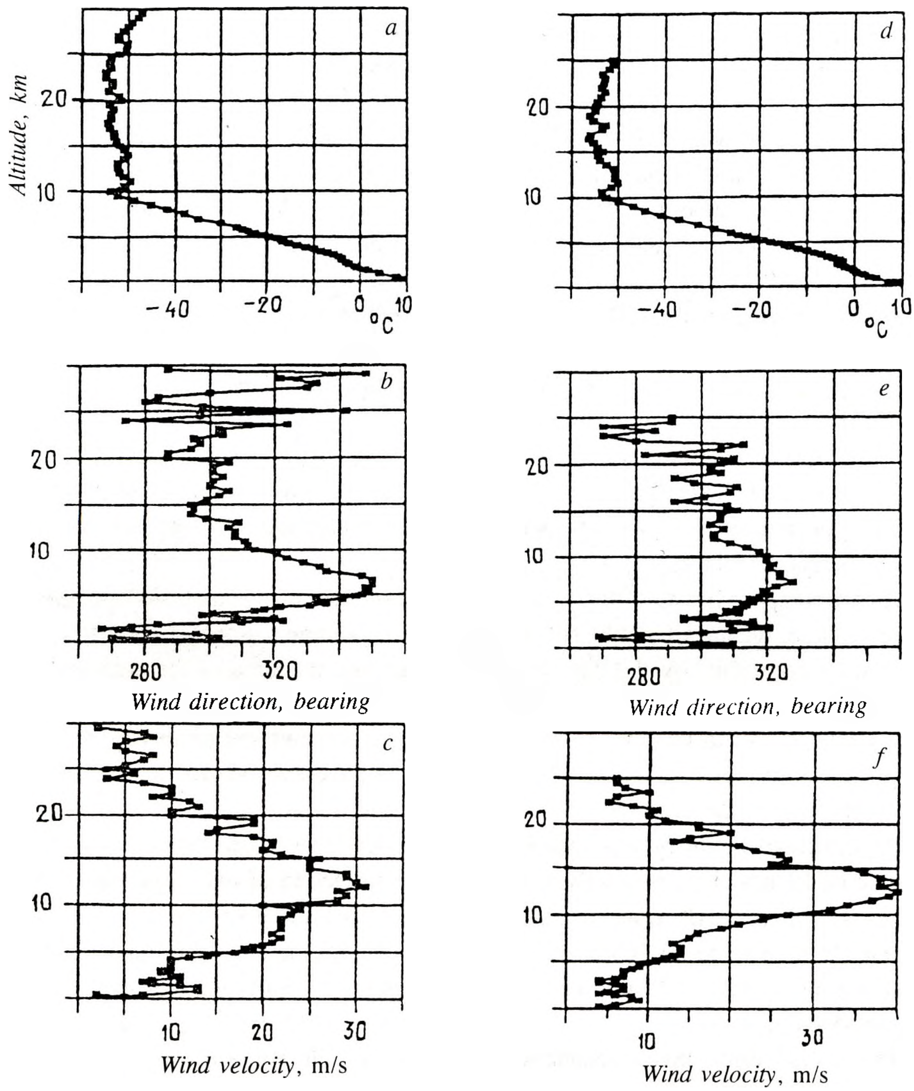

Figure 7 Variations of temperature (*a, d*), wind direction (*b, e*), and wind velocity (*c, f*) at altitudes of up to 25 km measured at the Klyuchi weather station from 23 h 30 min of September 30, 1994 (*a, b, c*) to 11 h 30 min of October 1, 1994 (*d, e, f*).

observed at altitudes of 10–15 km; the bearing of the apparent wind was 305°. It should be noted that the bearing and velocity of the air motion were measured to be 325° and ~25 m/s, respectively, in an altitude range of 5–10 km. This difference resulted in the layering of the eruption cloud, which was clearly seen in the pictures returned by spacecrafts.

A large volume of tephra, represented by a highly porous juvenile scoriaceous material, fell from the eruption cloud during the paroxysmal event. A special survey revealed that the tephra deposit extended as a belt in a SE direction and was as wide as 25 km at a distance of 20 km from the vent. The maximum tephra thickness (50 mm) was measured on the ash-fall axis in the area of the famous Ambon Rock, 15 km from the top of the cone along a bearing of 135°. (The bulk of the tephra thickness and particle-size measurements were made a year later, in September 1995; measurements around the ZLN seismic station and the Bilyukai Cone were made on October 4, 1994.) In the Ambon Rock area the tephra showed an inverse gradation: the particle size increased from 1–3 mm at the bottom to 10–30 mm at the top of the layer. The maximum size of some flat lapilli was 50 mm. The fact that they had broken edges indicates that the lapilli shattered on landing and had been larger before. The weight of the tephra deposited in the Ambon Rock area was estimated at 32 800 kg/m^2.

The thickness and maximum particle size of the tephra was found to decrease away from the ash-fall axis. For instance, northeast of the axis, the tephra thickness was 40 mm and the maximum particle size was 24 mm in the area of the Karpinskiy cinder cone near the axis; these values were 3 mm and 1 mm, respectively, with a weight of 3333 kg/m^2, in the area of the ZLN seismic station (Gorshok Cone), away from the axis; and only traces of fine ash were found on the crater rim of the Bilyukai Cone, farther away. Southwest of the ash-fall axis, the tephra thickness and particle size decreased to 30 and 13 mm, respectively, at the eastern foothill of Bezymyannyi Volcano, and to 25 and 7 mm, respectively, at the head of the Sukhaya Zimina River. The southwestern limit of the tephra distribution was not located. Presumably, the tephra was not deposited farther than the northern slopes of Zimina Volcano.

The amount of ash removed during the paroxysmal phase of the eruption was estimated from the height of the eruption column using Fedotov's nomogram [8]. It was assumed that the bulk of the heat of the eruption cloud was transferred by the ash. Proceeding from the above mentioned height of the eruption column and wind velocity, the rate of the pyroclastics discharge was found to be $\sim 8 \times 10^3$ tons/s. Knowing that the paroxysmal eruption lasted 8–10 hours, the volume of the ash removed during that time was found to be 0.05 km^3. The total volume of the lava that flowed from September 11 to October 2 was estimated roughly, from the results of an eye survey, to be 0.02–0.04 km^3.

The occurrence of a paroxysm during the eruptive process with a continuously operating magma supply system indicates that a sudden change occurred in the magma supply. This might be caused by a change in the composition of the magma or in its gas content, by the enlargement of the vent diameter, the rise of pressure in the magma plumbing system, or by some other factors.

The composition of the rocks erupted during the 1994 event is identical to the composition of the typical Klyuchevskoi rocks – calc-alkalic high-Al basalts (Table 1). The basalt samples collected during phase 2 (explosions and lava flows) and phase 3 (paroxysmal extrusive and explosive eruption) were identical to the basalts of the previous 1993 and 1984–1986 eruptions [5]. Megascopically, these are dark-gray and black, poorly crystallized rocks. The major rock-forming mineral is plagioclase, the usual grain size of which is 1.0–1.5 mm (occasionally 2 mm). Single small phenocrysts of olivine and pyroxene have been noted.

The terminal 1994 eruption can be classified among the most powerful historic eruptions of the volcano. It is comparable with the terminal 1944–1945 eruption, which was studied comprehensively by Piip [6], and during which a similar paroxysm occurred. The paroxysms lasted 8–10 hours in 1994 and 15 hours in 1945. The eruption columns rose to the heights of 13 and 15 km, respectively. According to our data, the volumes of the ash removed during these events were comparable[a]. The rocks erupted during the 1994 and 1945 eruptions were calc-alkalic high-Al basalts.

At the same time, there are some differences. In 1994 the eruption subsided after the paroxysm and terminated after 1.5 days. In 1945 the eruption continued for a month after the paroxysm. In 1994 lava flowed before and after, in 1945 only after the paroxysm. The 1994 eruption did not produce any substantial changes in the morphology of the volcanic edifice, whereas the 1944-1945 eruption produced a deep trench (Krestovskiy), which is still there.

The 1994 eruption had no perceptible impact on the population of Klyuchi City. The only damage was that the mudflows scoured a 6-km streach of the motor road east of the city. The bulk of the ash was removed by the strong westerly wind to the Pacific.

It should nevertheless be emphasized that the paroxysmal phase of the eruption was one of the most spectacular and violent events in the Klyuchevskoi eruptive history.

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[a] The volume of ash removed during the paroxysm of the 1944–1995 eruption and estimated by Piip [6] was considerably larger, 0.6 km^3, compared to 0.05 km^3 in 1994. Piip's estimate was based on the report from the Kozyrevsk settlement that the ash cover there was 32 mm thick. A. B. Belousov and A. Yu. Ozerov, the coauthors of this paper, proved that the ash thickness was highly exagerrated. They carried out a special study of the soil and pyroclastic cover along the road from Kozyrevsk to Klyuchi City and did not find a separate ash layer produced by the 1945 eruption. It is known from the experience of tephrochronological investigations in Kamchatka (O. A. Braitseva, personal communication) that a separate ash layer formed where the thickness of an ash cover was greater than 5 mm. So an ash layer must have been formed, if the thickness of an ash cover had been 32 mm. It follows that the thickness of the ash deposited by the 1945 eruption was less than 5 mm, and the volume of the ejected ash was an order of magnitude smaller than the value reported by Piip, namely, it was ~0.06 km^3, which is comparable with the ash volume of the 1994 eruption.

Table 1 Average chemical composition of the 1994 lavas compared with the lavas of previous eruptions.

Date	Number of samples	Oxide contents, wt %										
		SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Cr_2O_3
1994*	2	53,31	1,16	18,37	8,95	0,16	5,09	8,20	3,37	1,10	0,21	0,00
1993**	2	53,32	1,13	17,91	9,22	0,17	4,89	8,30	3,54	1,07	0,23	0,03
1984–1986*	13	53,28	0,99	18,25	8,75	0,17	4,96	8,12	3,24	1,23	0,17	0,00

* Analyzed at the Central Chemical Laboratory of the Institute of Volcanology, Petropavlovsk-Kamchatskiy, analyst A. M. Okrugina.
** Analyzed at the Chemical Laboratory of the Institute of Geochemistry and Analytical Chemistry, Moscow. Analyses for this eruption have also been reported by Fedotov *et al.* [10].

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