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VOLCANIC ERUPTIONS AND SEISMIC ACTIVITY AT KLYUCHEVSKOI, BEZYMYANNYI AND SHIVELUCH IN 1986–1987

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This paper describes volcanic and seismic activities at Klyuchevskoi, Bezymyannyi and Shiveluch volcanoes in 1986–1987 from volcanological and seismological observations and geodetic measurements. Different types of volcanic earthquakes are considered and their relations to volcanic eruptions are discussed.

Three volcanoes of the North Kamchatka volcanic group, Klyuchevskoi, Bezymyannyi, and Shiveluch, were active in 1986–1987 and two, Ploskii Tolbachik and Ushkovskii, were in the state of fumarolic activity.

KLYUCHEVSKOI

In 1986–1987 frequent explosive and effusive eruptions of the Strombolian and Vulcanian-Strombolian types occurred in the Klyuchevskoi summit crater[†]. In late February 1987, a flank eruption took place on the southeast slope.

The total duration of the eruptive periods was 25 percent of time in 1986 and 41 percent in 1987. Weak fumarolic activity was observed in the crater during the repose periods. Time variations of the height of eruption clouds, bomb flight, and the duration of lava flow are plotted in Figure 1.

Below follows the chronological description of the eruptive events. The eruptions are subdivided into phases dominated by explosions, lava flow, or both. The dates of the outbreaks and terminations of the eruptions (as well as of the eruptive periods) are not always given with certainty, especially for the periods when no other observations but field trips were carried out, which were often irregular and intermittent.

21 January 1986, was the day when the terminal eruption, which was described by Zharinov *et al* [2], came to an end. The repose period that followed lasted till early June.

[†] The volcano was kept under regular surveillance by E. Zhdanova, A. Belousov, and M. Belousova, workers at Kamchatkan Volcanological Station.

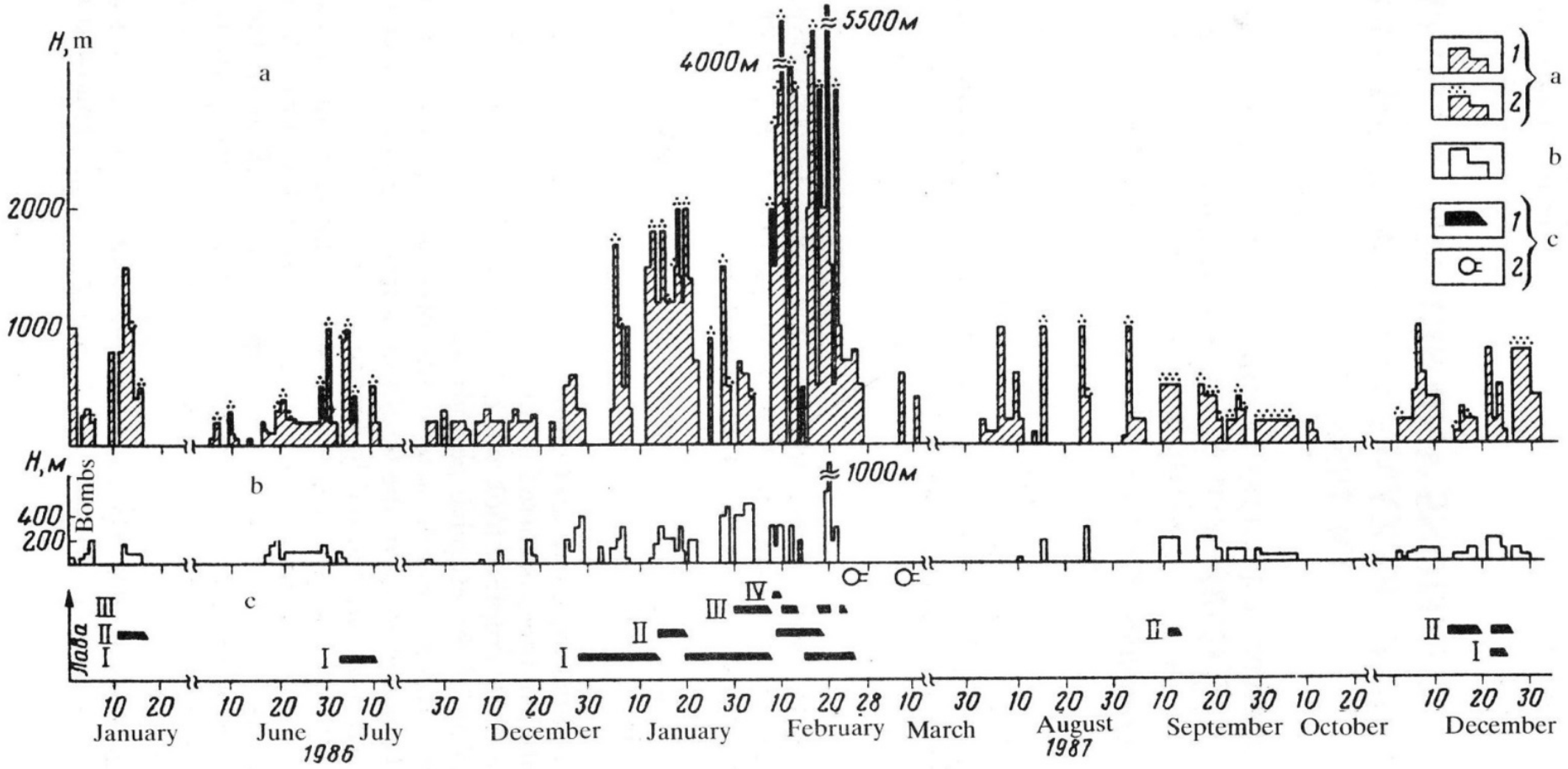


Figure 1 Eruptive activity at Klyuchevskoi in 1986–1987: a — heights of steam (1) and ash (2) columns from visual observations; b — bomb heights; c: 1 — duration of lava flow in west (I), northwest (II) and southeast (III) trenches and on north slope (IV); 2 — flank eruptions

Summit explosive and effusive eruption of 6 June – 11 July 1986

The eruption was rather mild and consisted of three phases: I – explosive phase from 6 June to 3 July II – explosive and effusive phase, July 4–5, and III – effusive phase, 6–11 July.

Explosive phase

The first symptoms of the eruption were noted on 6 June when small steam and gas columns rose in the crater to a height of 20–30 m. On 7 June the columns contained ash and rose as high as 200–300 m. Occasionally, ring-shaped steam and gas ejections were observed.

On 18 June incandescent bombs were thrown out of the crater. Since that time the activity became typically Strombolian. Bombs were hurled from two vents to a height of 100–200 m. A large amount of ash was erupted and the eruption cloud rose to a height of 200–400 m and occasionally to 800 m. Activity of this kind continued till 3 July.

Explosive-effusive phase

On July 4 lava began to flow in the west trench and bombs were hurled from the crater to a maximum height of 150 m. Steam and gas columns, sometimes containing ash, rose as high as 200–400 m.

Effusive phase

On 5 July practically no bombs were thrown out and the activity consisted largely in lava outpouring. A steam and gas cloud rose to a height of 200 m. On 11 July the eruption terminated. The lava flow descended to a height level of 4100 m. Before the eruption came to an end, several dozens of gas and ash ejections took place; the columns had a maximum height of 500 m.

The repose period that followed lasted till late November, 1986. On 25 November fumarolic activity intensified.

Summit explosive and effusive eruption of 27 November 1986 – 6 March 1987, and a flank eruption of 23 February – 12 March, 1987

The events of that period of time can be subdivided into three phases: I – explosive phase from 27 November to 28 December, 1986; II – explosive and effusive activity from 29 December to 22 February 1987; and III – flank eruption (lava flow) from 23 February to 12 March, 1987.

Explosive phase

The eruption began on 27 November with small steam and gas ejections having a maximum height of 200–300 m.

At night, a pulsating glare was seen above the crater. On 8 December incandescent bombs were hurled to a height of 100 m and fell in the crater. By the end of December the steam and gas columns were as high as 400–600 m. Bomb ejections followed one another at intervals of 2 to 10 minutes and their height increased to 200–300 m.

Explosive-effusive activity

On 29 December lava began to flow into a channel along with explosions of Strombolian type. Bombs were hurled from several vents to a height of 150–200 m, some of them rising as high as 300 m. A white eruption cloud, in places with ash, rose to a height up 1000–1800 m. On 8–12 January 1987, explosive activity attenuated and bomb ejections ceased. A slight pulsating glare was seen above the crater. On 13 January intensive Strombolian activity renewed and by the end of January bombs were hurled occasionally to a height of 400 m and the eruption cloud was as high as 1.5 to 2 km.

Intensive lava outpouring continued throughout the whole of January. Most of the lave flowed down the west trench and the largest flows descended to a height level of 3500 m. From the 15th to 20th of January lava flowed in the northwest trench and reached a height of 3700 m.

In February the relatively uniform Strombolian activity changed to violent Strombolian–Vulcanian eruptions which continued till 22 February. A distinctive feature of that period was that beginning from 7 February the periods of strong explosions and voluminous lava flows lasting a few hours were followed by periods of notably subdued activity or repose periods. During the renewed active eruption phases the eruption column grew rapidly in height from 1–2 km to 3–4 km, much more ash was ejected, and lava flows were more voluminous.

During the night of 19 February pyroclastic material was ejected to a height of 800 m at 16 minute intervals. Some bombs were hurled to a height of 1.5 km and incandescent pyroclastic material was thrown outside the crater and fell on the flanks of the volcano.

At 9 h 30 min local time on 19 February explosive activity began to subside and ash column rose to a height of 1.5 km above the crater. At 13 h 30 min intensive activity in the central crater renewed again: a gas and ash column rose to a height of 4.5 km, ash was ejected as high as 1.5–2 km, and the upper part of the eruption cloud stretched laterally to form a disc-shaped electrified cloud about 400 km^2 in area. Continuous roar was heard at a distance of 15 km from the crater. By 5:00 p.m. the vertical ash column was 5.5 km high above the crater (Figure 2). At the climax of the eruption the rate of discharge of pyroclastic material was 100 metric tons per second.

In February lava flowed alternately in all three, west, northwest, and southeast trenches. On 9 February a small amount of lava flowed on the northern slope between the northwest and southeast trenches.

The outflow of lava involved intensive phreatic activity in the trenches: phreatic clouds rose to a height of 5 km and more. Where lava flowed on the ice cover, mud flows were formed and descended to absolute levels of 1 or 2 km above sea level.

Flank eruption

On 23–24 February a radial fissure developed at a height of 3570 m on the southeast slope from which lava issued quietly to form an approximately 1 km flow (Figure 3). On 6 March, when lava was still flowing from that fissure, another fissure developed on the same slope at a lower level of 3000 or 2000 m and a small lava portion flowed under the Shmidt glacier (saddle between Klyuchevskoi and extinct Kamen volcano). On 22–23 February at the time of the first fissure development, explosive activity in the summit crater subsided (scarce ash ejections

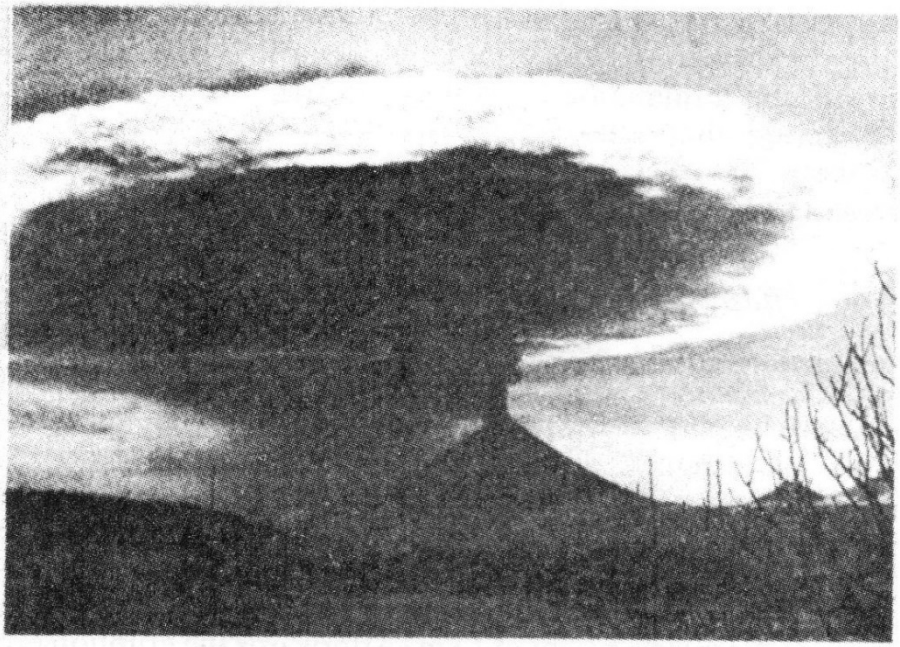


Figure 2 Klyuchevskoi on February 19, 1987. The height of the eruption column is 5.5 km. View from Klyuchi. Photo by A.B. Belousov

Figure 3 Lava flow from a fissure on the southeast flank of Klyuchevskoi, February 25, 1987. Photo by A.B. Belousov

were observed) and lava continued to flow in the southeast trench till 25 February. The outpouring of lava from both fissures lasted a few days and ceased by 13 March along with the termination of explosive activity in the summit crater.

The repose period that followed lasted till late July 1987. A well-shaped collapse sink about 200 m across was formed at that time, evidently in the first half of June, on the top of a cinder cone that had grown in the crater.

Summit explosive-effusive eruption of 28 July – 11 October, 1987

Volcanic activity during that period was dominated by Strombolian eruptions. Eruption products filled the well-shaped cauldron and that was probably the reason why lava did not flow down the slope except for a minor amount.

The observers noticed that the volcano renewed its activity on 28 July: the crater was steaming and red glow was seen above it. On 10 August bombs began to be hurled out of 2 to 5 vents to a height of 200–300 m. Steam and gas columns rose to heights of 400 to 1000 m; sometimes they were loaded with ash. By the end of August this activity subsided till September 2 when several dozens of ash columns rose, some reaching a height of 1 km. Afterwards the eruption proceeded in the previous manner. On September 11–12 lava flowed from the crater into the northwest trench. The flow was not more than 700 m long. In late September-early October eruptive activity diminished and on October 11 the eruption came to an end. The repose period lasted till 1 December.

Summit explosive-effusive eruption of 1–31 December, 1987

A series of ash ejections was followed by a typical Strombolian activity. A steam and gas cloud rose to a height of 200–800 m. From time to time it was seen to contain a small amount of ash. Bombs were thrown to a height of about 100 m. From the 13th to the 26th of December lava flowed into the northwest trench and on 21–23 December into the west trench. The amount of lava was small and the lava flows were less than 300–400 m long. Single ash columns rose to a height of 400–800 m on 26–28 December. On December 29–31 all kinds of activity diminished and the summit eruption terminated to be renewed in 1988. The 1988 eruption will be described in the next paper.

As mentioned by Fedotov *et al.* [6], in spite of the fact that large eruptions occurred at Klyuchevskoi in the last years, magma continued to accumulate in reservoirs at depth.

Seismicity

In 1986–1987, like in the previous years [3], [6], seismic activity at Klyuchevskoi was associated with its summit and flank eruptions and concentrated in the seismic zone around the central crater.[†] Maps showing the epicenter distribution of the earthquakes that occurred in the Klyuchevskoi and Bezymyannyi area in 1986–1987 are presented in Figure 4. Depth intervals were chosen proceeding from the knowledge of the usual localization of epicenters with respect to the summit

[†] The seismic data were processed and analyzed by V. Garbuzova, G. Rait, E. Stepanova, V. Levina, and A. Zharinova. The group was headed by V. Gorelchik.

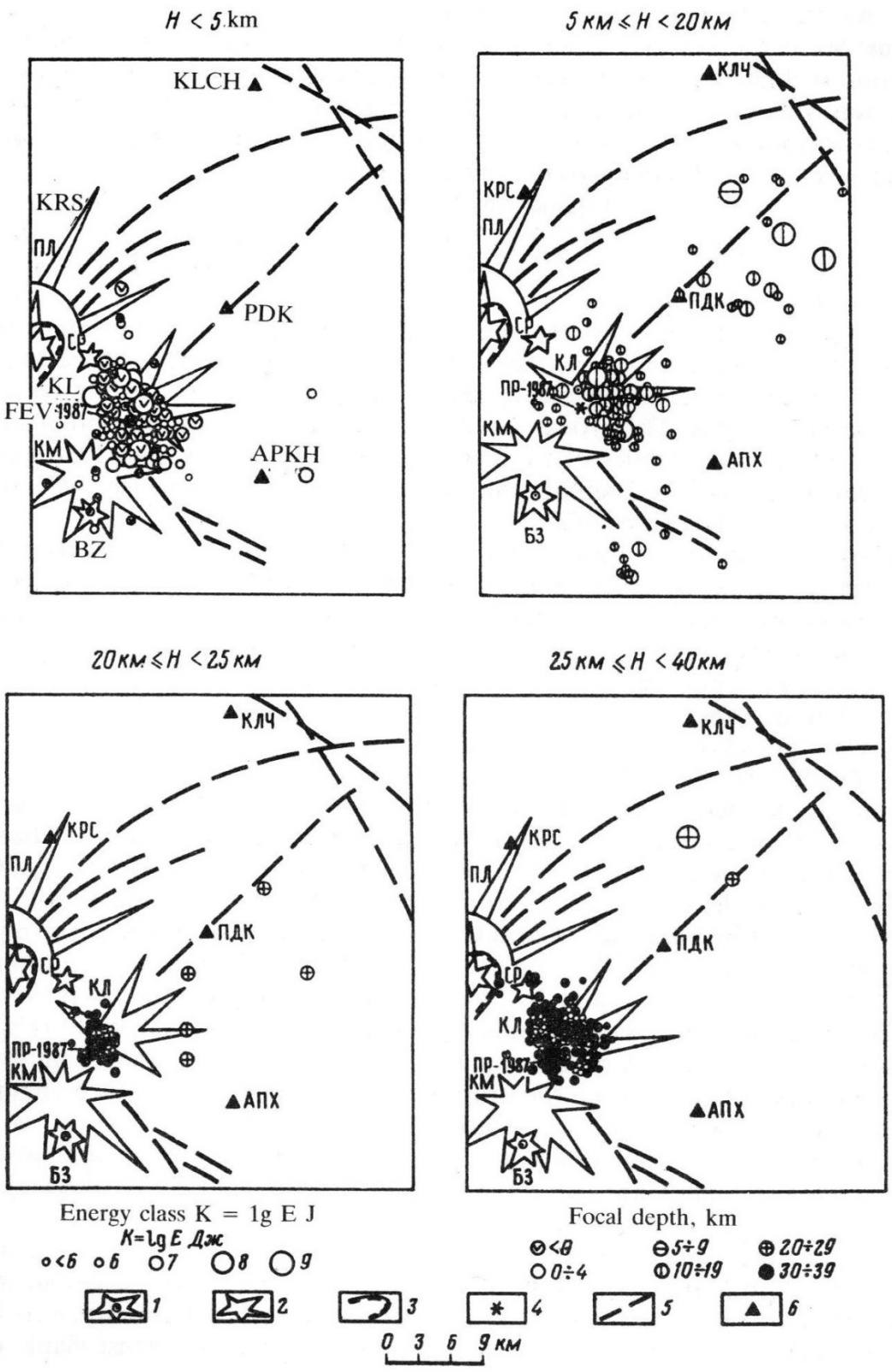


Figure 4 Maps of earthquake epicenters in the Klyuchevskoi and Bezymyannyi area in 1986–1987. 1 — active volcanoes: KL — Klyuchevskoi, BZ — Bezymyannyi; 2 — extinct volcanoes: PL — Blizhnii Ploskii (Krestovskii), SR — Srednii, KM — Kamen; 3 — Blizhnii Ploskii caldera; 4 — flank eruption vent (FEV), 1987; 5 — inferred fault; 6 — seismic station

crater. As seen in Figure 4, the 1986–1987 seismic activity involved the whole of the crust from the volcanic cone to a depth of ~40 km. Epicenters were most numerous at depths above 5 km and in the interval of 25 to 30 km. An aseismic region was registered around the summit crater in the depth interval of 5 to 20 km. It was found to be about 3 km across in the W-E direction. So, formally its size did not exceed the epicenter location error.

The same pattern of earthquake distribution had been observed for a longer observation period, 1971–1985 [6]. This proves that a horizontally small but vertically extensive (5 to 20 km) aseismic region does exist under the Klyuchevskoi summit crater.

In the lower crust, below 20 km (see Figure 4) seismic activity was concentrated in a local zone about 6 km across, where groups and swarms of earthquakes occurred which were smaller than class 7 in magnitude and exhibited a very similar record pattern. The groups and swarms lasted from a few hours to several months. The largest number of earthquakes was recorded in May 1986 during a repose between two large summit eruptions, one in late 1985 to early 1986 and the other in late 1986 to early 1987.

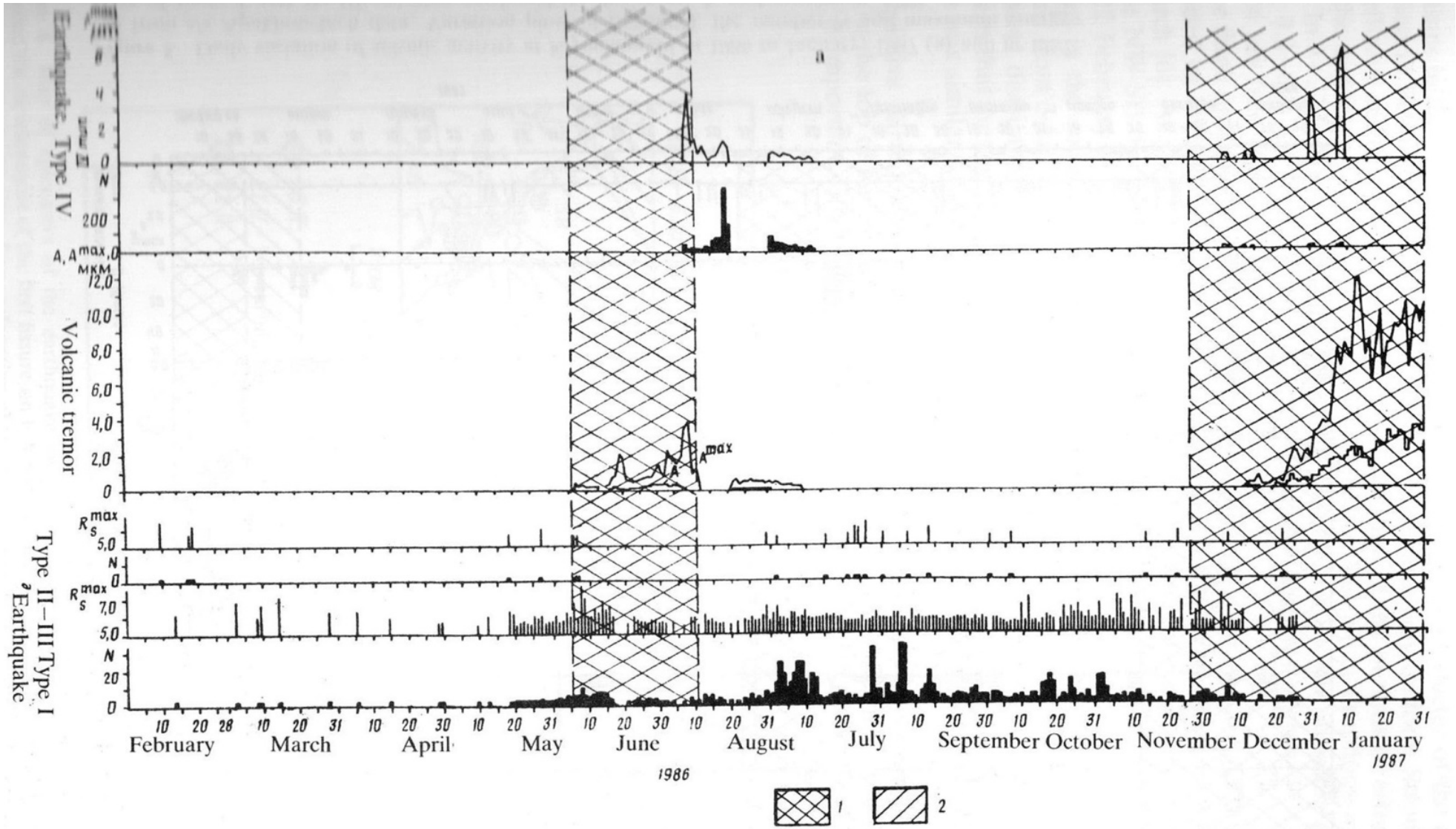
In 1986–1987 the distribution of the earthquakes of type I ($H \geqslant 5$ km) and type II–III ($H < 5$ km) [5] in the seismic zone under Klyuchevskoi showed the same pattern as was observed previously [6]: most of the earthquakes occurred in the volcanic structure during the renewed active periods and at 5 to 30 km depths during the repose periods. As forthcoming eruptions were approaching, seismic activity shifted from 25–30 km depth upward to 10–15 km and the maximum energy class grew to 7.5 and more (Figure 5 *a*, *b*).

On July 28, 1987 at 10 h 30 min Greenwich time, earthquakes of class $K_S = 9.2$ and four smaller shocks were recorded 6 km southeast of the summit crater at a depth of ~15 km. At about the same time, a pulsating glow was seen above the crater (onset of summit eruption), tremor appeared, and somewhat later earthquakes occurred in the volcanic structure (see Figure 5). In contrast to the previous years, the 1986–1987 period witnessed a larger number of earthquakes with a focal depth below 5 km which continued after the summit eruptions had begun. This can be explained by the growth of the potential activity of the volcano which continued to accumulate magma in its feeding system [6] in spite of eruptions in 1983–1987. A partial explanation is the above mentioned uncertainty in time discrimination between the eruptive and repose periods, which augmented as active periods became longer in the last years.

The summit eruptions were accompanied, as before, by earthquake swarms at depth shallower than 5 km, continuous tremor, and explosive earthquakes (see Figure 5).

The most significant shallow earthquake swarms occurred in the periods of 20 February to 6 March 24 August to 1 September, and on 28 December in 1987 and from late 1987 to 8 January, 1988. The swarm of 20 February – 6 March preceded the development of fissure eruptions on the southeast flank of the volcano.

Low-frequency volcanic tremor was recorded during all phases of the eruptions and reflected their general character and intensity. Tremor amplitudes rose with the intensification of Strombolian activity in the summit crater (red-hot bombs hurled to larger heights) and also during large explosions and intensive lava flow (see June–July 1986 and December 1986–January 1987 in Figure 5). Distinct


Earthquake, Type IV
N
A, A^max, MKM
Volcanic tremor
A^max
R_S^max
Type II–III
Type I
Earthquake
February
March
April
May
June
August
July
September
October
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1986
1987
1
2

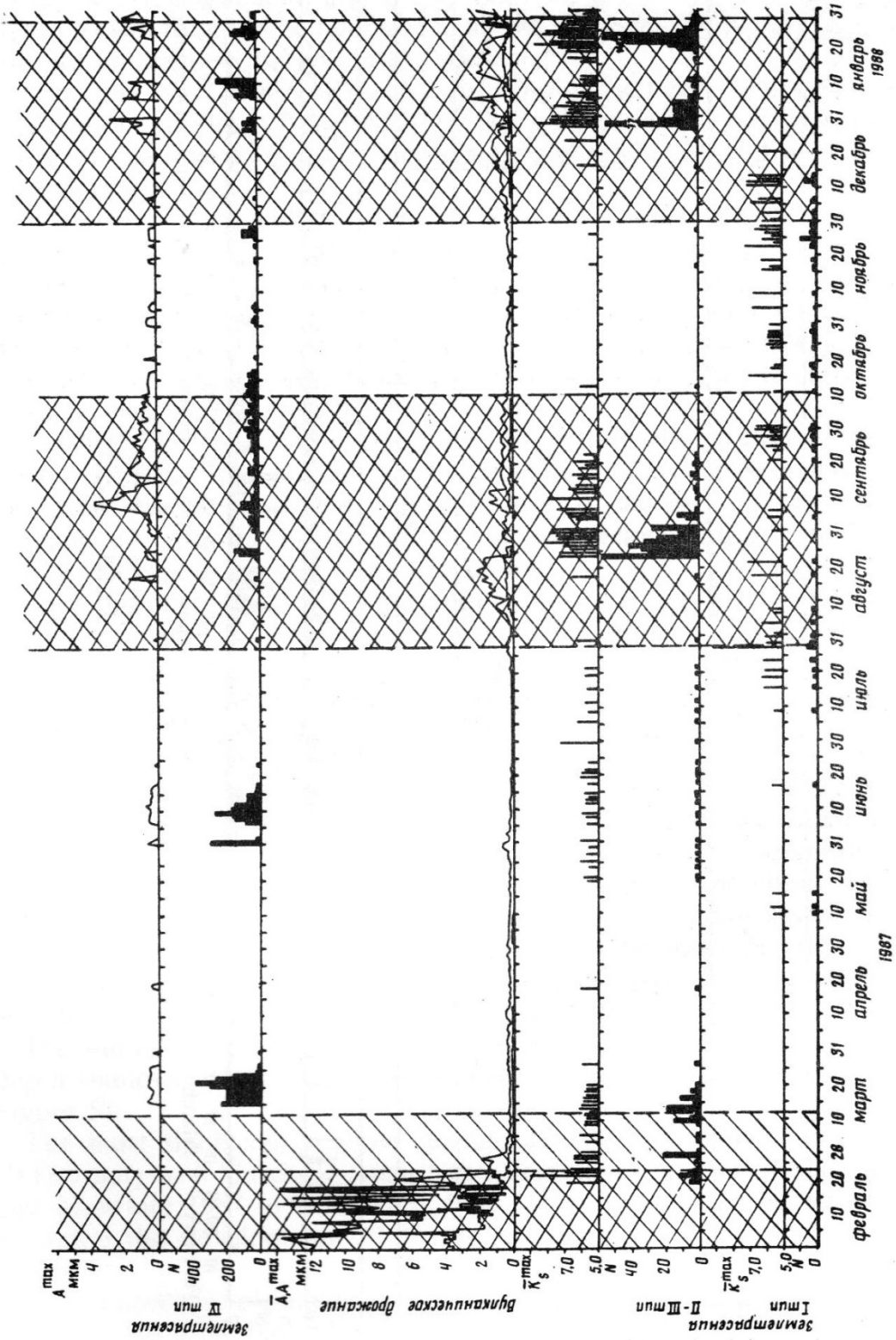

Figure 5 Daily variation of seismic activity at Klyuchevskoi in 1986 to January, 1987 (a) and in 1987 (b) from s/s Apakhonchich data. Variation plots of (upward): the number N and maximum energy class of types I and II–III volcanic earthquakes, the mean A and maximum A^{max} amplitudes of volcanic tremor, the number N and max. amplitude A_{max} of type IV earthquakes. 1 — duration of summit eruptions with lava flowing on the slopes; 2 — duration of flank eruptions

variations in the tremor behavior marked a change in the character of the summit eruption in February 1987, when a period of comparatively uniform Strombolian and effusive activity was followed by the alternation of the periods of attenuation and the sudden renewals of intensive Strombolian-Vulcanian eruptions and lava flow. In 7–22 February, the mean tremor amplitude varied in a pulsatory manner from 0.3–0.4 μm to 3–4 μm and the maximum amplitude from 3–4 μm to 13–14 μm (see Figure 5).

The flank eruption of 23–24 February, 1987, known as Predvidennyi Boca, was heralded by a precursory earthquake swarm of 20 February which continued to 6 March [6]. As seen in Figure 6, the epicentral region of the swarm was elongate in the NW-SE direction and the epicenters of the earthquakes that occurred on 20–22 February before the development of the first flank fissure on 23 February shifted in the same lateral direction without any changes in their depths which ranged from 3 km below to 3 km above sea level. The pattern of the spatial and temporal distribution of the earthquake swarm of 20 February – 6 March 1987 suggests that the seismic activity that preceded the development of the Predvidennyi Boca was similar to the seismic precursors of the March 8 flank eruption in 1980 [9].

Explosive earthquakes (type IV after P.I. Tokarev) were recorded (see two plots in the top of Figure 5) during the active phases of the summit eruptions and, what is important, after the eruptions terminated or, to be more exact, after a

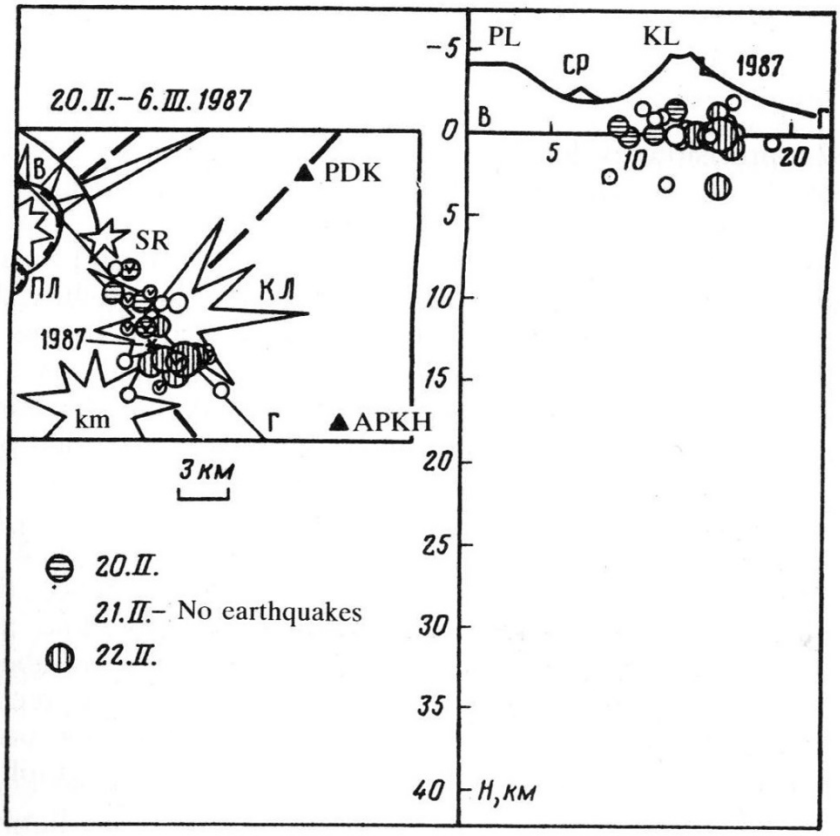

Figure 6 Map of epicenters of the earthquake swarm of February 20 to March 6, 1987, which preceded the development of the first fissure on February 23 and the second fissure on March 6 of the Predvidennyi flank eruption. For explanation of symbols see Figure 4

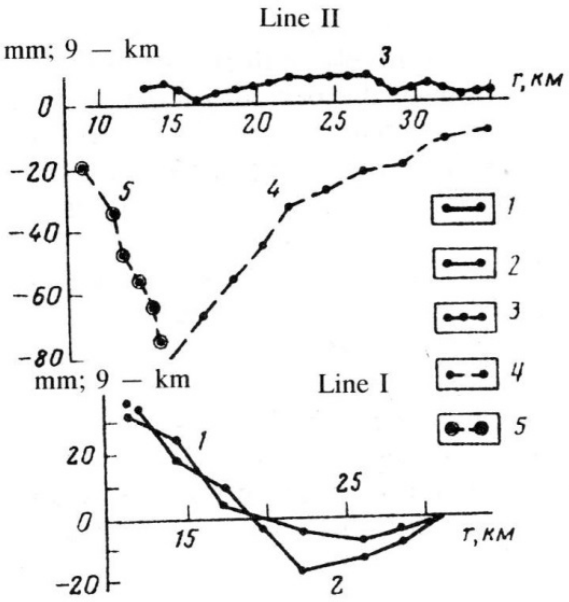

Figure 7 Elevation changes ΔH from leveling lines I and II: 1 — on line I for 1986–1985; 2 — on line I for 1987–1985; 3 — on line II for 1986–1985; 4 — on line II for August 1987–1987; 5 — on line II for September 1987–1985

notable activity in the summit crater came to an end. To judge from Figure 5, explosive activity in the central crater continued for a few weeks and sometimes months after the visible signs of activity were no longer seen: bombs ceased to be ejected, lava flows came to a halt, etc. Apparently, explosions occurred at a greater depth and hence produced better seismic records.

Geodetic leveling

In 1985–1987 a precision leveling survey was carried out on Klyuchevskoi on two lines radial to the center of the volcano.[†] Line I had an azimuth of 45° and followed for the larger part the course of the Kirgurich Creek. The bench mark nearest to Klyuchevskoi was placed at a height of 1150 m and at a distance of 11.5 km from the crater. Line II had an azimuth of 135° and followed the road to the seismic station Apakhonchich. The bench mark nearest to the volcano was located at a height of 750 m above sea level.

The elevation changes measured on line I indicated that the flank had risen ~50 mm from 1985 to 1986. No significant changes were recorded on the line in 1986–1987 (as compared to the period of 1980–1985). Measurements on line II made in 1985–1986 showed that the flank had risen too but to a lesser extent (~10 mm). In 1987, part of line II was surveyed from 24 June to 10 August. All bench marks were found to have lowered relative to the reference, the maximum amount of subsidence being 70 mm. The remaining end of the line, nearest to the crater, was leveled in September and found to have risen by about the same amount (see curve 5 in Figure 7). The differential movements recorded on the lines in different periods of time might be caused by changes that occurred in the volcano during the observation time and/or by the local topography of the line segments.

The growth of the largest cinder cone inside the crater continued to be kept

[†] Leveling was performed by N. Zharinov and Yu. Demyanchuk with N. Zharinov as a supervisor.

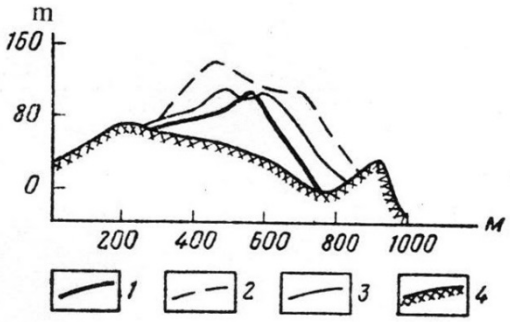

Figure 8 Growth of a cinder cone in the Klyuchevskoi crater (E–W section). Height determined on: 1 — September 5, 1984; 2 — September 8, 1986; 3 — June 19, 1987; 4 — summit crater

under surveillance in 1986–1987 by one-way trigonometric leveling. The height of the cone was determined relative to the northern crater rim and amounted to 108 m on 5 September, 1984, 120 m on 8 September, 1986, and 130 m on 19, June 1987 (Figure 8). The volume of the cone was calculated to be 1.6, 4 and 16 million metric tons, respectively.

BEZYMYANNYI

In 1986 and 1987 the volcano was still active but eruptions were somewhat weaker than in 1984 and 1985. In 1986 two similar explosive and effusive eruptions took place. They did not differ much from the eruptions of the previous years. Lava was extruded and flowed quietly almost throughout the year of 1987.

The eruption of 14 December, 1985, was followed by a period of quiescence which lasted till the middle of April 1986. Indications of a new eruption were noticed on 16 April when a dome-shaped bulge was seen from a flight over the volcano to have grown on the lava flow, which issued in November 1985, in the east sector of the crater near the vent. Changes of this kind have been reported by Seleznev *et al* [4] as indications of forthcoming eruptions. The bulge was growing slowly from 16 April to 16 June. From time to time avalanches of "cold" material fell from the eastern unstable side of the bulge from 21 April to 12 May. On 17 June the squeezing of a lava plug accelerated and rockslide avalanches became more frequent. A spine of almost solid lava about 80 m high and some 100 m across at the base was upthrust from the top of the dome. On 23 June it collapsed and a mass of viscous lava began to be extruded in its place. During the night hours of 25 June, when the volcano was obscured by the clouds, a small explosive eruption took place. It produced a block and ash flow which moved down the east slope for a distance of about 4 km. Explosions ceased on 25 June and lava began to flow slowly. A lava flow descended in a hollow that had been formed by an explosion during an eruption in 1985. It overlapped all of the 1985 lava flows. The eruption terminated on June 26.

From 27 June to 11 August the volcano was in the state of moderate fumarolic activity. On 12 August new fumaroles developed on the slope of the Novyi dome, the slope being the southeastern side of an abrasion trough. Outbreaks of gas jets triggered rockfalls from the middle of the side which occurred at a rate of six in an hour. A 24 hour timing showed that the gas outbreaks that caused the rockfalls were accompanied by earthquakes. The taluses of the fallen material were short and never extended beyond the trough. On 19 September a dome-shaped bulge

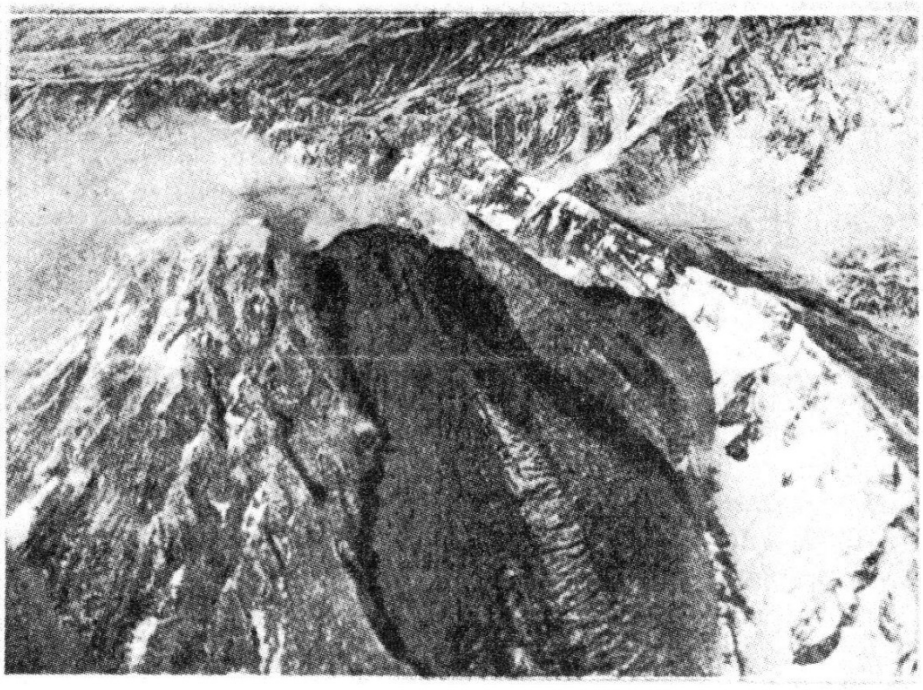

Figure 9 Bezymyannyi dome on March 10, 1987. Photo by A.B. Belousov

appeared on a bend between the crater and the abrasion trough. The slow extrusion of an upheaved plug began with the falling off of cold lava blocks. Later, a spine was extruded from the vent and on 15 December blocks of red-hot material avalanched. When the spine collapsed, viscous lava was extruded in portions on 16 December. On 17 December and 18, when the summit was obscured by the clouds, a mild explosive eruption occurred which produced a block and ash flow. The flow travelled about 4.5 km and overlapped the pyroclastic flow of 25 June. The eruption terminated on December 22.

The period of quiescence lasted till the middle of January 1987, when an upheaved plug was formed in the vent. In early March viscous lava was extruded (Figure 9). This process continued till February 1988 with periods of lower and higher intensity changing one another. When lava was less viscous, a short lava flow was formed, otherwise a solid lava spine was upthrusted. As a result, by early 1988 the trough on the eastern slope was wholly filled.

Seismicity

The Bezymyannyi activity is usually accompanied by a great diversity of seismic events. Examples of seismic records and the characteristics of various types of seismic events have been presented in [3] and [8]. In 1986–1987 weak earthquakes of types II and III with $K_s = 6.5$ were recorded at depths ranging between 0 and 3 km above sea level. Some of them, whose epicenters were located with certainty, are shown in the maps of Figure 4. The seismic station Apakhonchich, nearest to the volcano, recorded 24 earthquakes of type II–III with $K \geqslant 5$ in 1986 and one event in 1987. The earthquakes of 21 April and 12 May 1986, triggered rockslide avalanches on the eastern side of the dome. The explosive eruption of 17–18 December 1986, was accompanied by spasmodic volcanic tremor which lasted 2.5 hours ($A_{max} = 1.5$ μm, $A_{av} = 0.6$ μm, $T = 0.7$ s). In June, July and November, 1987, rock-fall avalanches were recorded at s/s Apakhonchich.

SHIVELUCH

As has been reported in [1] and [7], beginning from 1984, single gas-ash explosions occurred from time to time on the andesitic dome which had been extruded in 1980–1981. No changes in the activity were observed in 1986 and 1987. Fumarolic gases were emitted to a maximum height of 100 m from fissures on the dome. Explosions were very much alike and occurred in the form of sudden gas and ash blasts lasting a few dozens of seconds. The eruption columns had a cauliflower appearance and occasionally rose as high as 4–5 km. Numerous, differently oriented lightnings up to 50 m long were observed in the lower and middle parts of the columns. Base surges occasionally emerged from their bases and moved radially outward at high velocity to distances less than 300 m. Large amounts of tephra falling on the dome produced numerous small-size avalanches of hot fragmental material. Commonly, they did not travel beyond the agglomerate mantle of the dome. The ejecta did not glow.

In the period concerned, explosions became more frequent and in 1987 amounted to 5–7 events in a month. In contrast to 1984 and 1985, when each explosion produced a new crater ranging from 18 to 48 m across [1], three large craters were formed on the dome and became the major centers of explosive activity. Most of the explosions occurred on the top of the dome and very few in the atrium.

The fragmental material produced by explosions varied greatly in grain size: from 0.5 m blocks to finely pulverized ash. The sharp angles of the particles indicate that the solid material of the dome was fragmented.

Seismic activity

Seismic activity in the Shiveluch area has been monitored regularly by the telemetry seismic stations Baidarnyi (BDR) since 1980 and Kupol (KPL) since 1986, the stations located at 8.5 km and 3.5 km from the dome, respectively. The seismic events of 1980–1985 have been reported in [3]. As seismic monitoring has been started a short time ago, detailed data on the earthquakes and their relation to the volcanic activity on the dome are scarce. Naturally, the seismic activity at Shiveluch is described below with a view of being detailed and interpreted as more data are collected.

The earthquakes that have been recorded can be subdivided into (1) tectonic events and volcanic earthquakes of tectonic origin with focal depths of > 5 km which occur in the range of ~20 km from the crater (S-P < 5 s at s/s Baidarnyi) and generate relatively high-frequency signals ($f > 2$ Hz) with impulse-type first arrivals. They correspond with type I volcanic earthquakes in Tokarev's classification [5]; (2) shallow volcanic earthquakes localized at 0–3 km and shallower depths under the volcano. They have longer periods, show indistinct body wave arrivals, and produce intensive surface waves (type II–III after P.I. Tokarev); (3) surface events associated with avalanches, rockfalls, and gas-ash ejections. More detailed observations are required to interpret their origins. Some of them are high-frequency (5 Hz and more) and the others are low-frequency (0.5 to 1 Hz) events, the latter producing intricate wave patterns, too complicated to pick up first arrivals (type IV after P.I. Tokarev); and (4) volcanic tremor – low-frequency events lasting a few minutes to several hours and often accompanying blast-type ejections of gas and pyroclastic material. Like at Bezymyannyi [8], volcanic tremor at Shiveluch may comprise a sequence of type II–III earthquakes and become a spasmodic tremor of drastically changing amplitude.

Sample records of all types of seismic events obtained at s/s Baidarnyi are presented in Figure 10.

Principal characteristics of seismic activity at Shiveluch in 1986–1987 are listed in Table I. It includes all events with $A^{max} \geqslant 0.2$ μm recorded at s/s Baidarnyi. A map of the epicenters whose coordinates were determined with certainty is presented in Figure 11.

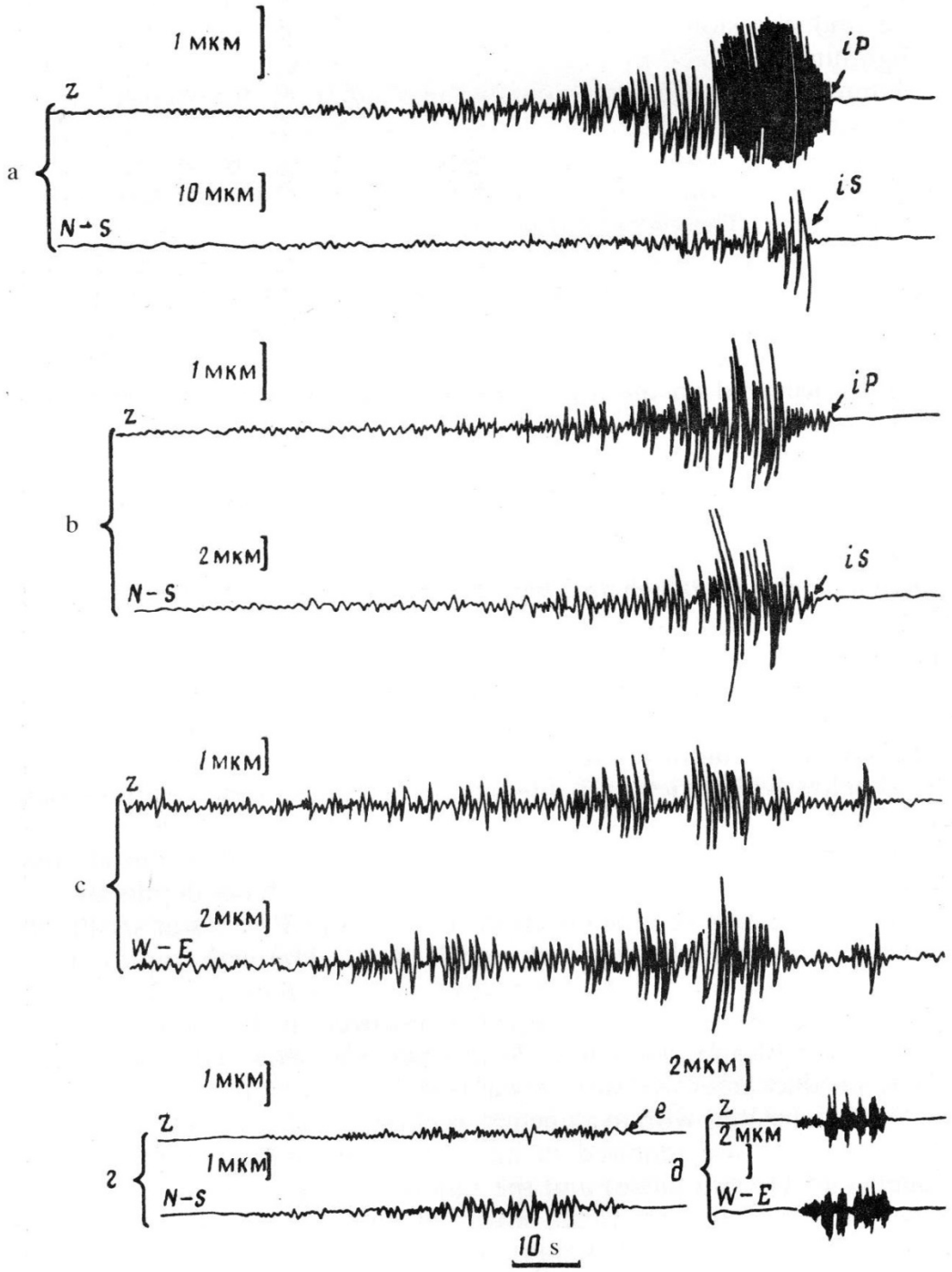

Figure 10 Sample records of earthquakes at Shiveluch obtained at s/s Baidarnyi: a — type I events; b — type II (III) events; c — spasmodic tremor during ash ejections; d — low-frequency events; e — high-frequency events

Table I Seismic Activity at Shiveluch in 1986–1987 from S/S Baidarnyi Data

Year, month		*Seismic activity*											*Visual observations*
		Type I events (S-P < 5 s)		*Type II–III events (S-P < 5 s)*		*High-frequency events (f ≥ 2.5 Hz)*		*Low-frequency events (0.5 ≤ f < 2.5 Hz)*		*Volcanic tremor A^{max} ≥ 0.2 μm*			
		N	K_S^{max}	*N*	K_S^{max}	*N*	A^{max}, μm	*N*	A^{max}, μm	*N*	Δt, hr	A^{max}, μm	
1986	I	2	6.7	—	—	—	—	—	—	—	—	—	
	II	1	6.3	—	—	—	—	—	—	—	—	—	
	III	—	—	1	5.5	—	—	4	2.1	1	1.1	2.1	March 28: ash fall
	IV	1	7.0	7	4.8	—	—	7	0.6	—	—	—	
	V	14	8.4	12	5.9	3.7	1.8	33	1.7	5	4.7	0.6	
	VI	8	5.6	28	6.8	20	0.5	94	1.0	1	2.0	0.5	
	VII	2	4.8	2	5.0	1	0.5	21	0.7	2	1.2	1.4	July 1: ash column, H = 0.6 km
	VIII	—	—	49	5.2	—	—	16	1.7	5	4.2	0.9	August 13 and 26: ash columns, H = 2 km
	IX	1	5.9	2	5.0	—	—	6	0.4	3	1.6	0.9	September 1: ash column, H = 0.6 km
	X	1	7.1	—	—	—	—	4	0.4	3	1.3	1.1	
	XI	—	—	—	—	—	—	—	—	—	—	—	
	XII	—	—	1	5.0	—	—	4	0.4	—	—	—	
1987	I	3	5.6	13	7.5	—	—	8	0.5	4	2.0	2.5	January 12: ash column, H = 3 km
	II	4	4.9	9	5.7	—	—	4	1.0	2	0.9	0.6	
	III	1	4.0	6	5.2	—	—	5	0.2	3	0.3	0.4	March 8: ash fall
	IV	1	4.6	8	6.1	—	—	15	1.5	4	2.2	0.5	
	V	—	—	6	5.8	15	1.2	11	0.7	4	3.1	0.5	May 17, 22, 26: ash columns
	VI	1	6.7	3	5.8	2	0.5	23	1.6	2	1.4	0.4	
	VII	2	5.0	7	5.1	—	—	22	0.6	5	1.2	1.1	July 15, 16, 19: ash columns, H = 5 km
	VIII	—	—	2	5.0	4	0.6	1	0.2	—	—	—	August 12: ash fall
	IX	1	7.1	1	5.6	1	0.3	5	0.4	4	2.5	2.2	September 9: ash fall
	X	2	7.0	1	4.4	—	—	6	0.5	7	6.4	1.7	October 11: ash fall
	XI	—	—	—	—	—	—	1	0.2	2	3.1	0.9	November 9: ash fall
	XII	1	5.4	5	5.1	—	—	1	0.3	2	0.5	1.0	December 6: ash fall

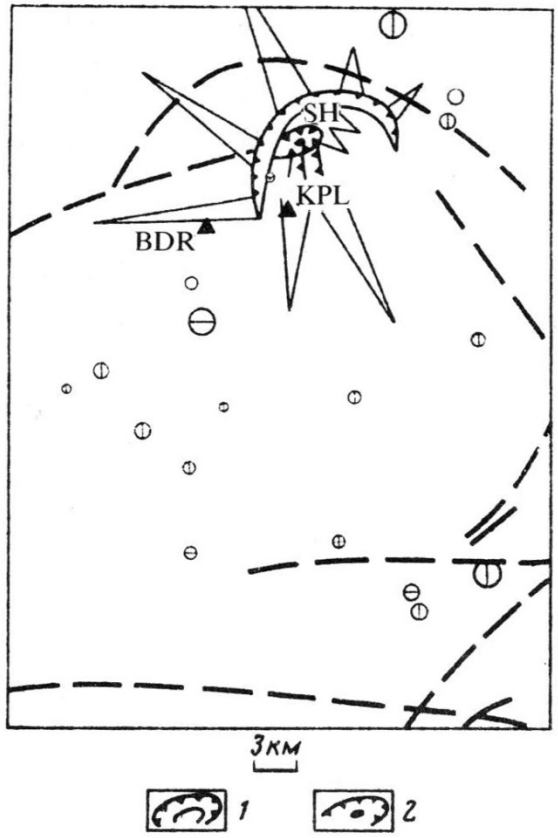

Figure 11 Map of earthquake epicenters in Shiveluch area, 1986–1987. 1 — old caldera; 2 — new dome. For explanation of other symbols see Figure 4

Like in the previous years [3], earthquakes of energy classes 6, 7 and 8 occurred in a 0–20 km depth interval in the range of 15 to 20 km around the volcano, largely south and east of it. The epicenters of smaller earthquakes of types I–III (usually with $K_s < 7.5$) concentrated under or less than 10 km from the active dome, as evidenced by S-P < 0.5 to 2.5 s.

As has been reported earlier [3], seismic activity was at maximum in the first half year of 1981, when the rate of the dome growth was still large (~0.8 m/day). In late 1981 the dome ceased to grow and seismicity diminished to be renewed in 1984, when eruptive activity developed on the dome. As seen in Table I, the number of seismic events of all types, except tremor events in 1986, was somewhat larger than in 1987. Most of the type I–III earthquakes, as well as high-frequency and low-frequency events, occurred in the spring and summer time, probably due to specific hydrogeologic conditions in the dome area [7]. The overall seismic energy of the type II–III earthquakes was larger in 1987 than in 1986, and so were the number and total duration of continuous-spasmodic tremor events (see Table I). The number of explosions was almost an order of magnitude larger in 1987 than in 1984: 4–5 events in 1984 and 35–40 explosions in 1987.

REFERENCES

1. V.N. Dvigalo, *Volcanology and Seismology* No. 2 (1984) (cover-to-cover translation).
2. N.A. Zharinov, E.Yu. Zhdanova, A.B. Belousov *et al*, *Volcanology and Seismology* No. 3 (1988) (cover-to-cover translation).

3. *Razrabotka i oprobovanie sistemy prognoza vulkanicheskikh izverzheniĭ na Kamchatke. Otchet o NIR (zaklyuchit.)* (Development and testing of a system for predicting volcanic eruptions in Kamchatka. Final report) (VNTITsentr, GR 02860046458, File No. 528, Petropavlovsk-Kamchatskii, 1986): 63–227 (in Russian).
4. B.V. Seleznev, V.N. Dvigalo, and N.A. Gusev, *Volcanology and Seismology* No. 1 (1983) (cover-to-cover translation).
5. P.I. Tokarev, *Izverzheniya i seĭsmicheskiĭ rezhim vulkanov Klyuchevskoĭ gruppy* (Eruptive activity and seismicity of the Klyuchevskoi volcanic group) (Moscow: Nauka, 1966) (in Russian).
6. S.A. Fedotov, A.A. Zharinov, and V.I. Gorelchik, *Volcanology and Seismology* No. 2 (1988) (cover-to-cover translation).
7. S.A. Fedotov, B.V. Ivanov, V.N. Dvigalo *et al*, *Volcanology and Seismology* No. 5 (1985) (cover-to-cover translation).
8. O.S. Chubarova, *Volcanology and Seismology* No. 3 (1983) (cover-to-cover translation).
9. V.I. Gorelchik and N.A. Zharinov, in: *Proceedings, Kagoshima Inter. Conference on Volcanoes* (1988): 75–78.