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The Eruptions of the Northern Group of Volcanoes on Kamchatka in 1988-1989: Seismological and Geodesic Data

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The results of observations of the seismic regime and deformations of the Northern group of volcanoes—Klyuchevskoy, Bezymyanny and Shiveluch—1988-1989 are reported. On Klyuchevskoy against the background of the continuing explosive-effusive eruption of the summit crater, intensive fissuring of the volcanic structure was observed in the sector between the north-eastern and southern slopes from a height of 2000 m to the summit of the volcano. Two flank eruptions at heights of close to 4000 m produced an outflow of 0.03 km' of lava each. On Bezymyanny an effusive eruption that had lasted from January 1987 ended in March 1988. A further explosive-effusive eruption took place on 2-3 August 1989. Both eruptions were very similar to the eruptions of recent years. On Shiveluch the number of explosive eruptions increased and the formation of a crater cone covering the central and western parts of the active dome was observed.

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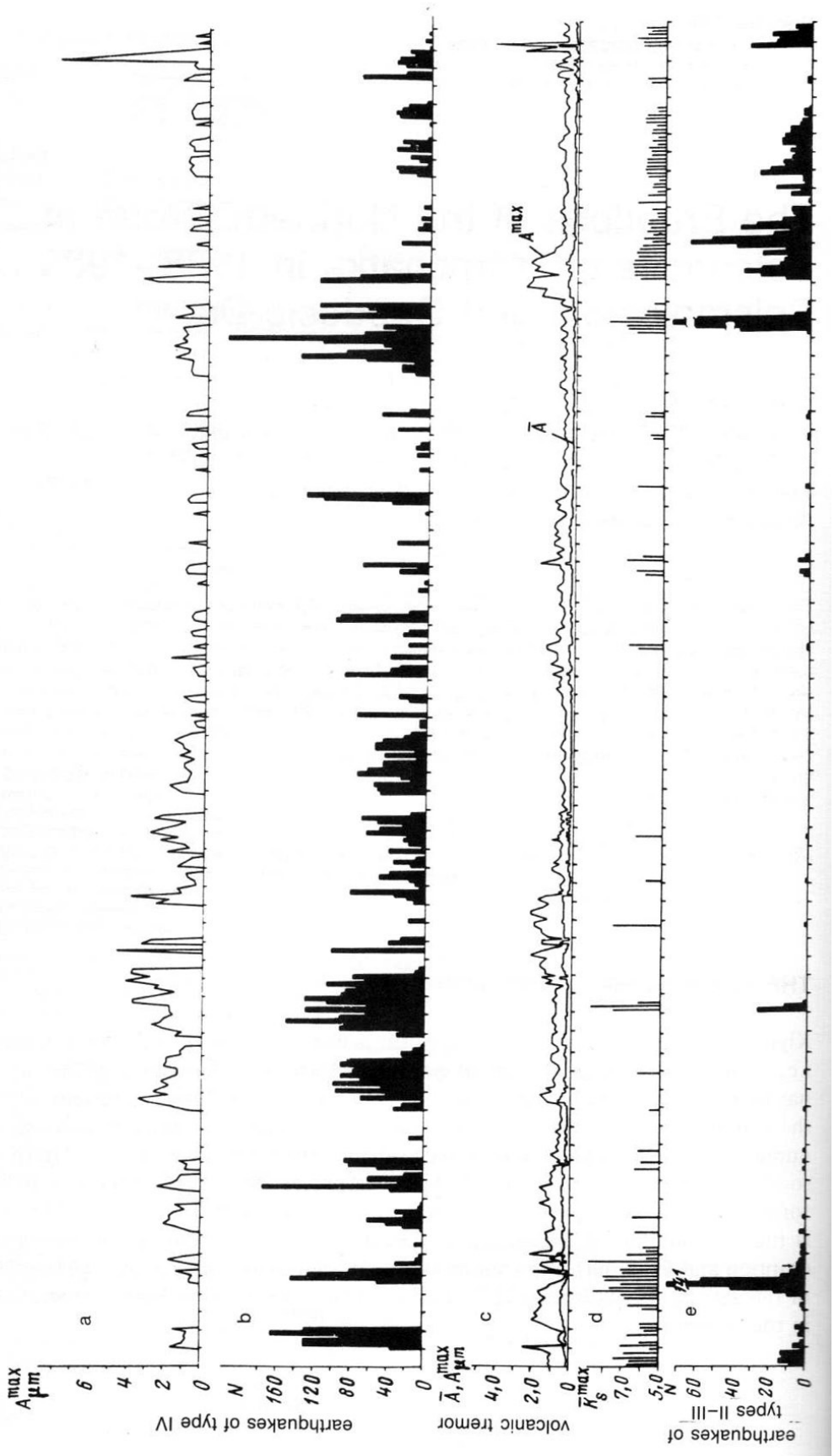
THE KLYUCHEVSKOY VOLCANO

Klyuchevskoy is the most productive of the active volcanoes of the Northern group, i.e. it ejects the greatest volume of products. Since April 1984 its eruptive activity has been characterized by summit and flank eruptions of different durations. During the summit eruptions several cinder cones have formed in the central crater and numerous lava flows have poured on to the northern, north-western, western and south-eastern slopes. During the flank outbreaks of 1987-1989 systems of fissures formed close to the eruptive centres. A distinctive feature of the events of 1988-1989 is the combination of a prolonged, almost continuous explosive-effusive summit eruption and flank outbreaks on the slopes of the volcano. The main characteristics of the activity of Klyuchevskoy in 1988-1989 are presented in Figures 1 and 2 and in the Appendix.

The activity of the volcano was resumed on 1 December 1987 with the weak ejection of bombs to a height of 100-200 m. From 14 December lava flowed along the north-western trench. In 1988 lava flowed out of the summit crater almost constantly along one of the trenches, or two or three at once. Breaks in the outpouring of lava lasted from 2-3 to 10-20 days. The most intensive effusive activity of the summit crater in 1988 was observed in October when lava flowed in three directions at the same time: down the western, north-western and northern slopes. By the beginning of November lava had ceased to flow from the summit crater and it was not until 13-14 December that traces of weak effusive activity were noted in the north-western (Krestovsky) trench (see Figure 1).

Explosive activity of the Vulcanian-Strombolian and Vulcanian types continued in the summit crater almost without interruption for a whole year. An increase in the frequency and intensity of explosions was observed in January-February against a background of weak effusive activity and in April-May and September-October against a background of intensifying effusive activity (see Figure 1 and Appendix).


a
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earthquakes of types II–III
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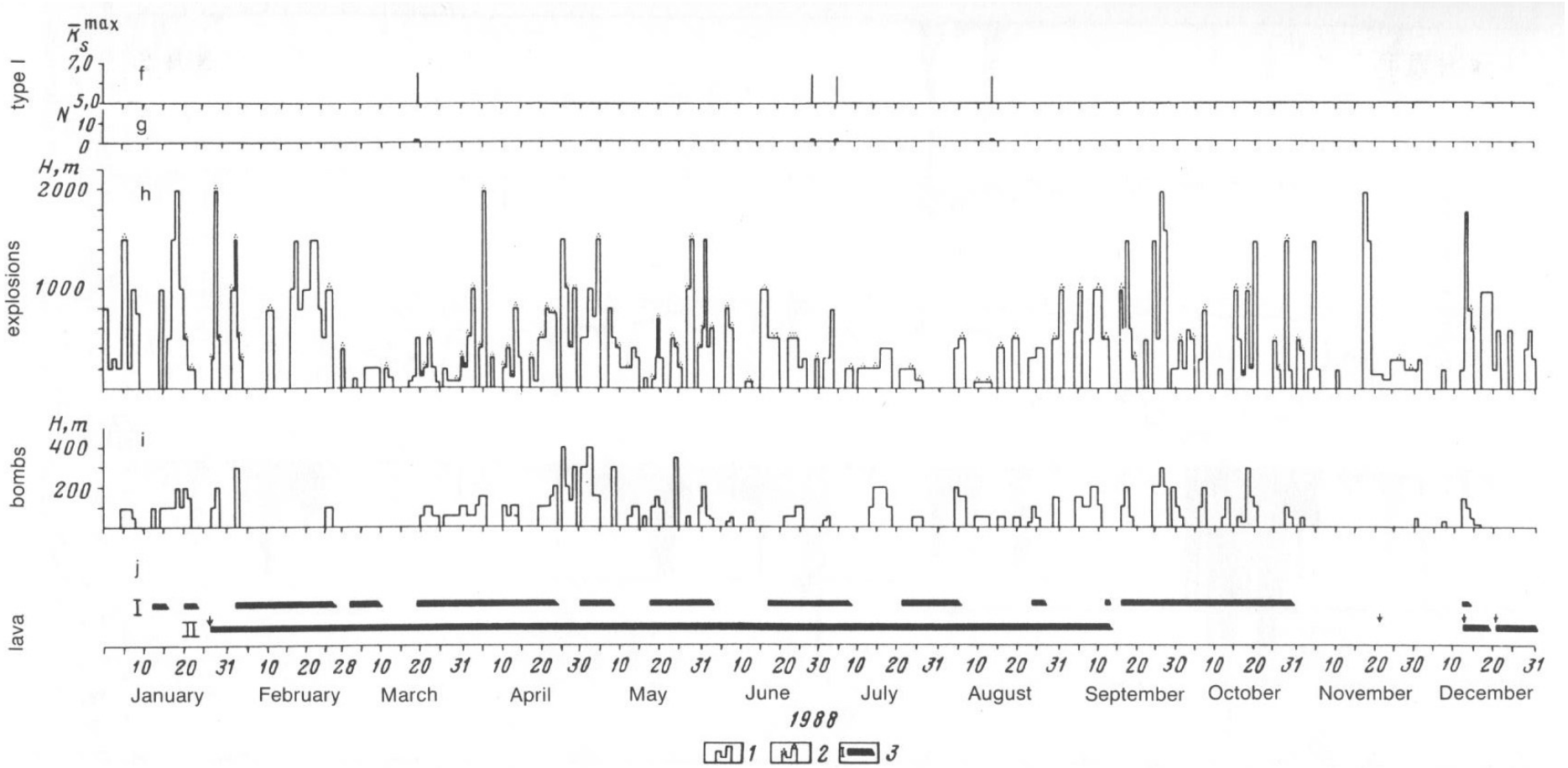
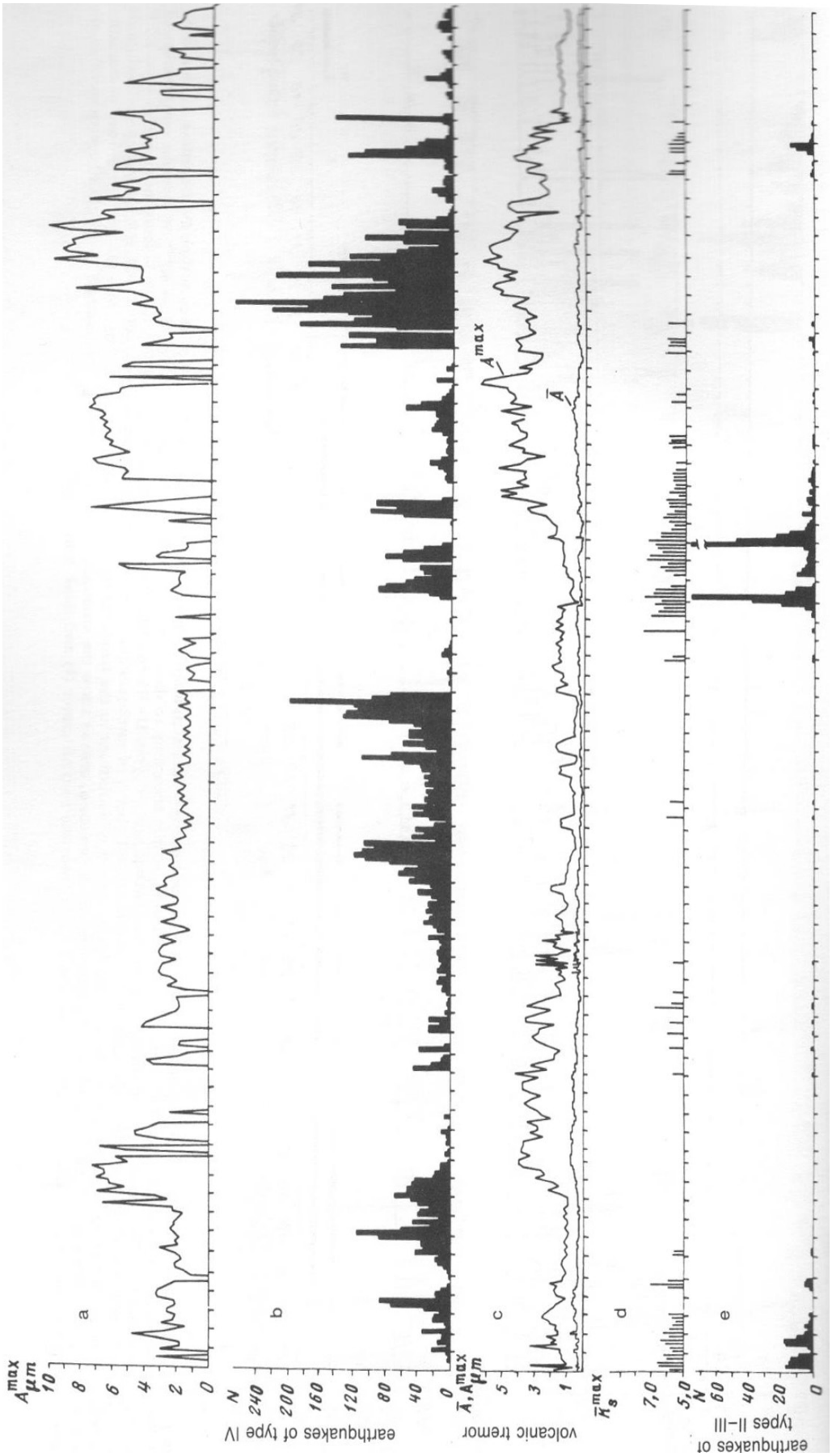


Figure 1 Day-to-day characteristics of the eruptions of Klyuchevskoy in 1988: a—maximum amplitudes; b—number of volcanic earthquakes at type IV according to data from s/st APH; c—maximum (A^{max}) and average ($\bar{A}$) amplitudes of volcanic tremor according to data from s/st APH; d—maximum energy class K_s^{max} of volcanic earthquakes of types II–III from data from the network of stations; e—number of earthquakes of types II–III according to data from s/st APH, PDK, KRS; f—maximum energy class K_s^{max} of earthquakes of type I according to data from the network of stations; g—number N of earthquakes of type I according to data from s/st APH, PD, KRS; h—graph of variations in the height of the ascent of ejections of steam and gas and ash; i—graph of variations in the height of the ejection of volcanic bombs from the summit crater; j—duration of outflow of lava from the summit crater and fissures on the slopes of the volcano, arrows show the moments of the formation of new fissures. 1—height of ejections of steam and gas; 2—height of ejections of ash; 3—periods of outflow of lava from the summit crater (I) and flank fissures (II).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earthquakes of type IV
volcanic tremor
earthquakes of types II–III

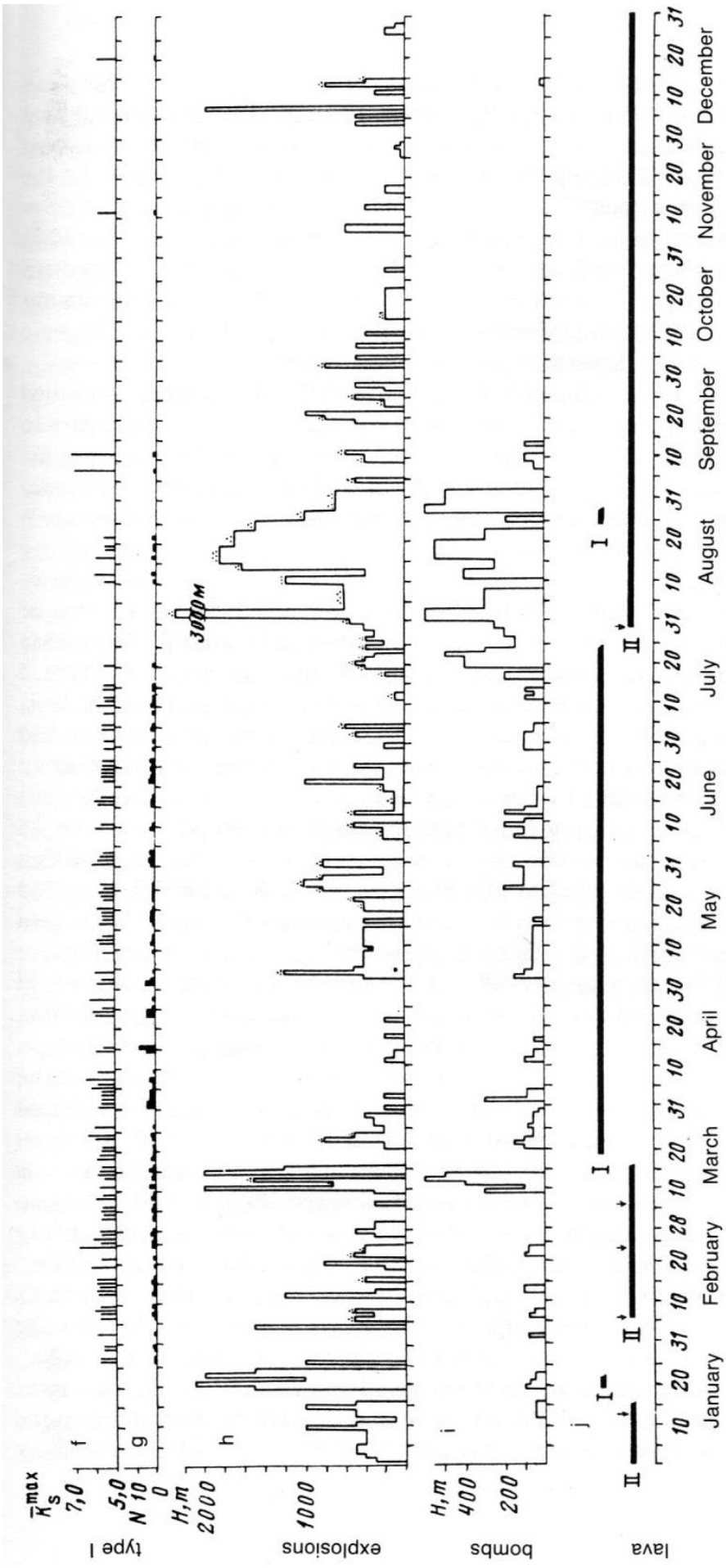

Figure 2 Day-to-day characteristics of the eruptions of Klyuchevskoy in 1989; a–c see Figure 1, but according to data from seismic station PDK; d—see Figure 1 but according to data from s/st ZLN, PDK, KRS. Remaining legend see Figure 1.

The activity of the volcano was resumed on 1 December 1987 with the weak ejection of bombs to a height of 100-200 m. From 14 December lava flowed along the north-western trench. In 1988 lava flowed out of the summit crater almost constantly along one of the trenches, or two or three at once. Breaks in the outpouring of lava lasted from 2-3 to 10-20 days. The most intensive effusive activity of the summit crater in 1988 was observed in October when lava flowed in three directions at the same time: down the western, north-western and northern slopes. By the beginning of November lava had ceased to flow from the summit crater and it was not until 13-14 December that traces of weak effusive activity were noted in the north-western (Krestovsky) trench (see Figure 1).
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1988

A new eruptive centre appeared on **28 January** on a subradial fissure at a height of 4000 m on the south-south-easterly slope, eleven months after a short flank eruption on the same slope in February-March 1987. The flank eruption, which was named after the XXV Anniversary of the Institute of Volcanology (IV), lasted for 230 days, to 14.9.1988, and was mainly effusive. The fissure on which the outbreak had appeared stretched in the form of a coulisse from the eruptive centre at 4000 m up to the rim of the old crater of the Klyuchevskoy volcano. A series of fumarolic vents was formed on this fissure during the initial period of the eruption and on 26 February a gas vent (bocca) was discovered at a height of 4300 m, out of which steam and gas was ejected to a height of 300 m (see Appendix). The initial period of the flank eruption was characterized by the spontaneous outflowing of liquid lava flows with an average speed of 1-3 m/s, the occasional intensification of explosive activity (fountains of lava to a height of 30-40 m), and the formation of a lava field and a small pedestal up to 40 m in height which took the form of a shapeless lava, cinder and block cone with numerous vents. In July the effusive centre of the flam eruption moved 100-150 m further up the fissure, where a cone appeared in the system of branching fissures, which was similar to the previous cone and which also discharged liquid basaltic flows. A depression with a diameter of about 100 m, in which the supply channel could be seen in the form of a dike 2 m thick, subsequently formed on the site of these two effusive centres.

During the flank eruption periods were observed in which only fumarole activity and sublimate-formation were noted on the outbreak. The duration of such ‘pauses’ varied from several hours to 2-3 days, and the frequency and duration of the pauses increased towards the end of the eruption. The width of the lava flow on outbreak varied from 1-2 to 4-5 m, the speed of the lava flow varied from 0.5 to 10 m/s, the flow rate of the lava was between 1 and 4 m^3/s and the greatest height of the ejections in the first half of the eruption was 100-120 m. According to results of an aerial survey, the volume of the products erupted from the flank outbreak was

0.0336 km^3 and the volume of the products erupted from the summit crater was close to 0.012 km^3 (verbal communication from V. N. Dvigalo). The prolonged outflow of lava in the region of the south-south-eastern slope of Klyuchevskoy, which includes the centre of the flank eruption, resulted in the formation of a depression, due to the melting and subsidence of a sheet of ice and pyroclastic material. Mud flows occurring during the eruption extended for a distance of more than 20 km from the site of the eruption along the channel of the river Sukhaya Khapitsa.

As already noted, the flank eruption named after the XXV Anniversary of the IV occurred against the background of the explosive-effusive eruption of the summit crater. At the moment of the beginning of the flank outbreak explosions of gas and ash and the ejection of bombs were observed in the summit crater; there were no outflows of lava on to the slopes of the volcano and these were only resumed several days later on 3 February. From August to the middle of September, the end of the flank eruption, long breaks (up to 20 days, see Figure 1) began to occur in the effusive activity of the summit crater. Immediately after the end of the flank eruption on the 14 September the outflow of lava from the summit crater was resumed with new force, and lava began to flow along three trenches at the same time (see Appendix, Figure l,j).

Despite the prolonged flank and summit eruptions there was no substantial release of pressure in the supply system of the volcano, and from the end of November 1988 the process of Assuring began again on the slopes of the volcano. The formation of a system of radial fissures, accompanied by the movement of a small mud flow, was observed in the height interval 2200-3000 m on the north-eastern slope on **20 November.** The zone of Assuring was not more than 200 m across, the greatest width of the fissures was about 5-6 m, and their apparent depth, about 4 m. No juvenile material passed through the fissures (see Appendix). Steaming stopped after a week.

The fissures and the eruptive centres localised on them formed intensively in December 1988. On **14 December** 1988 lava began to pour out at a height of 2800 m on the north-eastern slope. The lava flow was 600 m long and 5-6 m wide. The movement of the lava over the surface of the glacier caused the rapid melting of the snow and ice and the formation of a mud flow 10-12 km long. The height of the lava fountain at the source was not more than 15-20 m and the speed of the lava flow was about 0.6 m/s. The eruption at 2800 m ended on 19 December. However, a second eruptive centre had been formed two days earlier on **17 December** at a height of 4400 m on the same north-eastern slope on the continuation of the fissure of 14 December, and for a short time lava was extruded and mud flowed from this centre. No movement of lava was detected on 18 December (flight data) but on 19 December fountains of lava were ejected to a height of 300-400 m for 2 h from a gas vent on the outbreak at 4400 m.

On 22 **December** another subradial fissure was formed at a height of 3500 m on the eastern slope and lava began to pour out of it intensively. The eruption was effusive. By the end of the eruption on 15 January 1989 the front of the lava flow had reached a height of 3200m. The mud flows had reached the shrub zone (700 m).

The high level of effusive activity of the summit crater was maintained until the end of July 1989. In 1989 there was a change in the direction of the movement of the main mass of lava pouring out of the crater compared to 1988. It changed from westerly and south-westerly to north-westerly. Periods of intensified Strombolian activity were observed in the summit crater in March-April and July-August, when the lava fountains reached a height of 500-600 m and the frequency of the ejections was 10-12 min^{-1} (see Figure 2, Appendix).

The intensive Assuring on the slopes of the volcano continued in 1989. On 13-15 January a lava flow was extruded at a height of 3800 m on the eastern slope.

An eruptive centre was formed on 6 February at a height of 4400 m on the south-south-eastern slope above the XXV Anniversary of the IV outbreak, and on 16 February a cinder cone up to 5 m high was observed above this centre. A radial fissure was traced for 100 m up the slope from the cone. The lava flow was 1 km long and 1-2 m wide near the source. There were no mud flows. The eruption continued until 22 February. On 23 February an explosive-effusive eruption began from a vent in the north-western base of the intra-crater cinder cone (height 4650 m). The lava fountains reached a height of 500-600 m. The front of the lava flow stopped at a height of 3500 m. The eruption ended on 15 March.

On 26 July 1989 a prolonged flank eruption named the Skuridin outbreak began at a height of 4300-4400 m in the system of radial fissures on the south-eastern slope of the volcano. In the nature of its activity the outbreak was similar to the XXV Anniversary of the IV eruption, but the initial stage in the development of the outbreak was slightly different. The main radial fissure dissected the south-eastern slope of the volcano from the rim of the old crater along the Apakhonchichsky trench to a height of 4000 m. At a height of 4300-4400 m, where lava began to pour out, the fissure was 7-10 m wide in the bedrocks. The total width of the zone of Assuring, including the numerous branching ruptures, was 200-250 m. In the month after the beginning of the eruption the effusive centres shifted downwards every few days with the formation of a chain of small cones along the fissure. The last centre was located at a height of 4000 m and did not alter before the end of the eruption. The width of the lava flow at the source at the beginning of the eruption varied from 1 to 3 m, its thickness varied from 1.5 to 2 m, the speed of the lava flow was between 1 and 3 m/s and the flow rate of the lava was close to 2-5 m^3/s. The eruption lasted for 200 days during which the flow rate varied repeatedly, and this is reflected in the formation of new lava channels. The frontal parts of the lava flows went down to 2500-2800 m. In October the lava fountains reached a height of 50-70 m with a frequency of 15 min^{-1}.

The initial stage in the Skuridin flank eruption developed against the background of intensified Strombolian-Vulcanian activity in the summit crater in July and August.

From September to December 1989 the explosive activity of the summit crater of Klyuchevskoy abated and was manifested mainly as ejections of gas and ash to heights not exceeding 600-800 m. No outflows of lava from the summit crater to

the slopes of the volcano were observed. Effusive activity continued on the flank outbreak at this time and a lava field was formed.

At the end of **January to February** 1990 the powerful activation of the summit Crater was observed, and the explosive-effusive activity of the Skuridin flank outbreak was intensified. On 7-8 February outflows of steam and gas, forming clouds up to 30-40 m high, were noted along the subradial fissure between the summit crater and the effusive vent of the outbreak at 4000 m. At the same time, the main fissure arching round the centre of the flank outbreak extended down the slope to a height of 2500-2700 m. This process was also accompanied by the intensive emission of steam and gas. The intensified explosive-effusive activity of the eruptive centre at 4000 m in January-February 1990 resulted in the formation here of a cinder cone about 30 m high and a lava pedestal with a maximum thickness of 40-50 m. The edges of the lava flows in the vicinity of the source reached a height of 10-15 m. The Skuridin flank eruption ended on 10 February 1990. According to preliminary data the volume of the products erupted is estimated to be -0.03 km^3. On the whole, the flow rate of the products erupted from Klyuchevskoy over the last five years did not exceed the long term average flow rate (~1m^3/s according to Melekestsev) and was close to 0.9 m^3/s.

Seismicity

Data produced by the Klyuchevskoy telemetric network of seismic stations (s/st) [1] and data from the stations in the regional network (s/st. VDP, KZR) were used to estimate seismicity in 1988-1989. Figures 1 and 2 show the day-to-day variations in the main characteristics of the seismic and volcanic activity of Klyuchevskoy for l988-1989. Figure 3 presents layer-by-layer maps of the epicentres of crustal earthquakes in the region of the northern group of volcanoes for the same years. As before [2], in the years in question the seismic activity of Klyuchevskoy was concentrated in the area around the summit crater (Central zone) and was represented by volcanic earthquakes of types I-IV of P. I. Tokarev's classification [4] and volcanic tremor. Within the Central seismically active zone it was possible to identify the coordinates of the foci of the overwhelming majority of earthquakes with an average energy class of $K_S > 6.0$ and also many weaker events. The dimensions of the Central seismically active area were the greatest at depths of <5 km (see Figure 3,a) in 1988-1989. The area was almost isometric with a radius of~7 km and the centre slightly displaced to the east relative to the summit crater. Here groups and swarms of earthquakes of types II—III, associated with the summit and flank eruptions of Klyuchevksoy ($K^{max} = 8.9$), occurred in the upper horizons of the earth's crust and in the volcanic structure. In the depth interval 5-9 km (see Figure 3,b) only a few earthquakes ($K_s^{max} = 7.3$) were noted in 1988-1989. The lower horizons of the earth's crust at depths of 20-30 km were more active. Here weak but numerous earthquakes formed an area stretching for roughly 9 km from north-west to south-east with a width of ~6 km ($K_s^{max} = 6.5$).

The time distribution of the number N and energy K_s^{max} of earthquakes of types I ($H > 5$ km) and II—III ($H < 5$ km) during 1988-1989 is shown in Figures 1 (d-g)

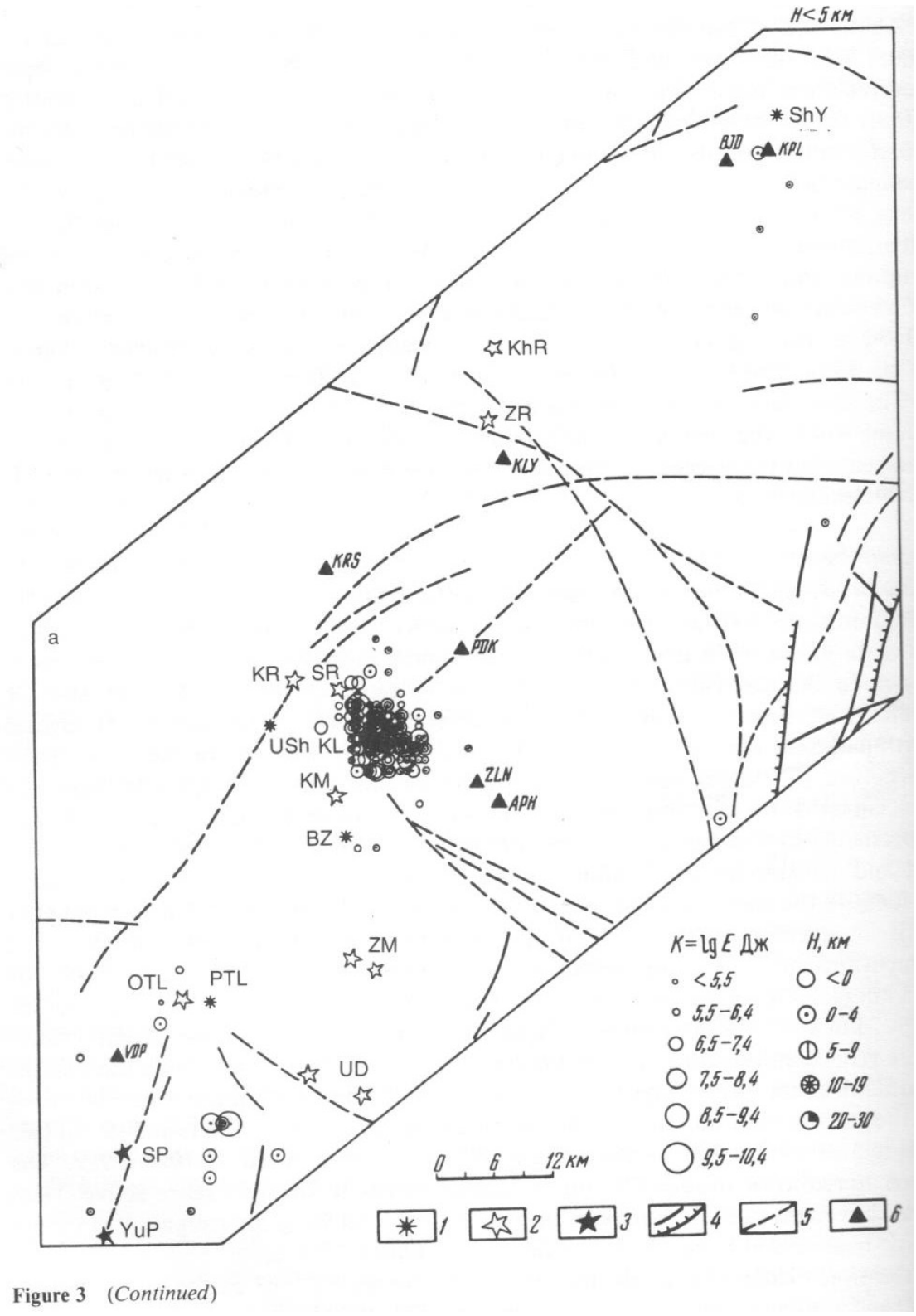
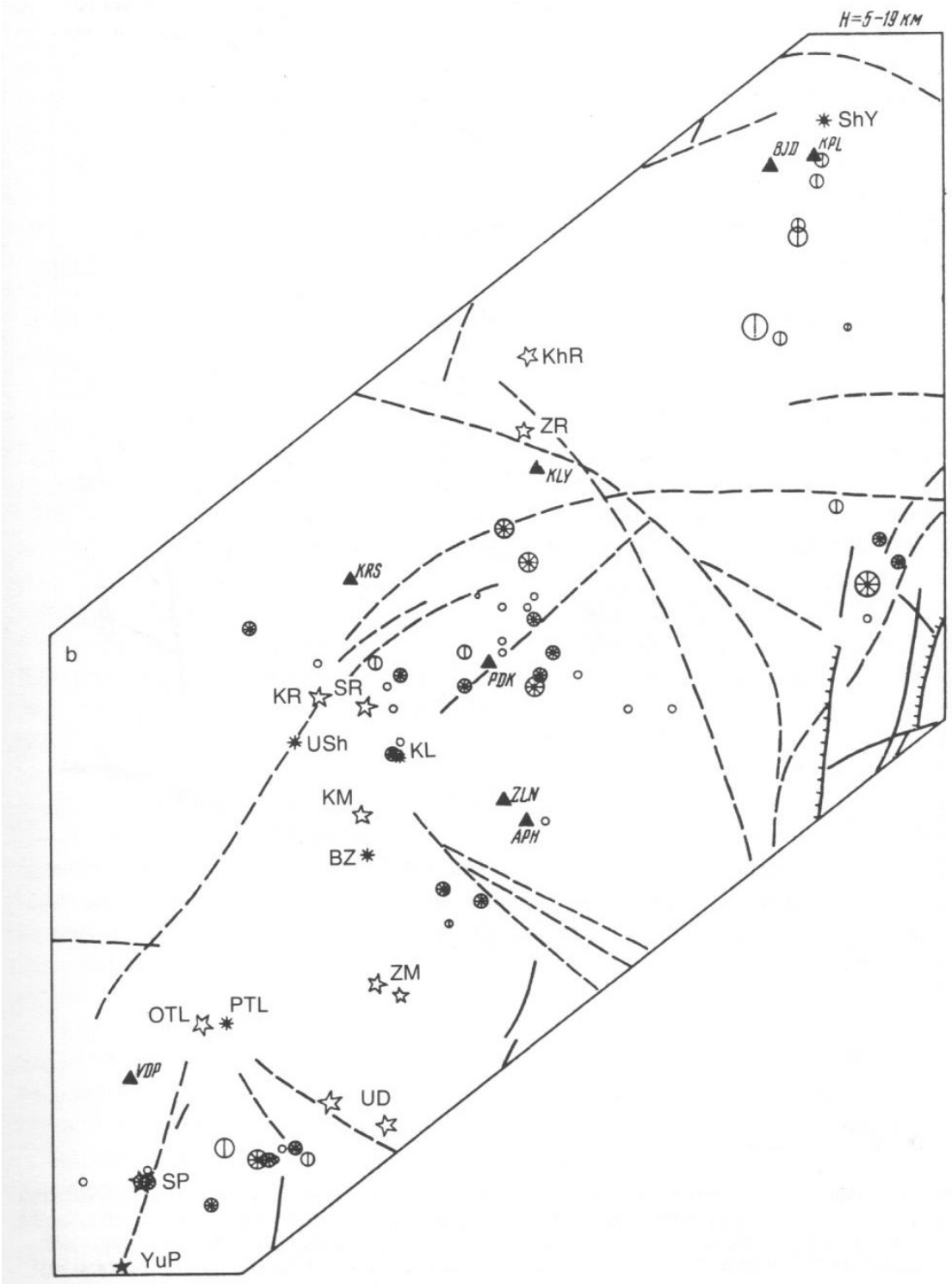


Figure 3 (*Continued*)



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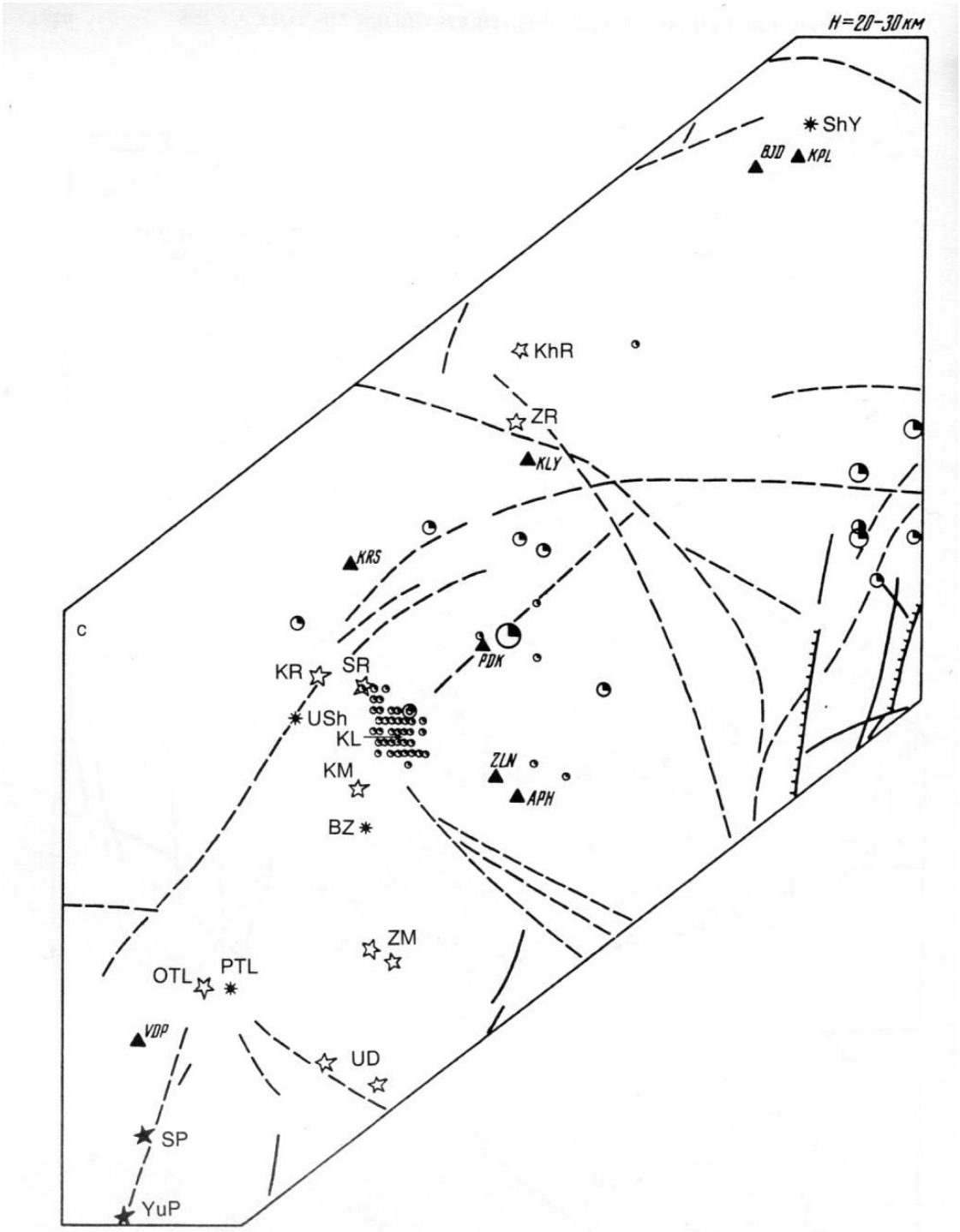

Figure 3 Layer-by-layer maps of the epicentres of crustal earthquakes in the region of the Northern group of volcanoes for 1988–1989, km: A—for depths of <5; B—for depths of 5–19; C—for depths of 20–30. 1—active volcanoes: ShV—Shiveluch; KL—Klyuchevskoy; BZ—Bezymyannyy; USh—Ushkovskiy; PTL—Ploskiy Tolbachik; 2—extinct volcanoes: KhR—Kharchinskiy; ZR—Zarechnyy; SR—Sredniy; KR—Krestovskiy; KM—Kamen'; OTL—Ostryy Tolbachik; ZM—Ziminy sopki; UD—Udiny sopki; 3—Northern (SP) and Southern (YuP) outbreaks of the Great fissure eruption of Tolbachik, flank outbreaks 1988–1989. On slopes of Klyuchevskoy (PR 1988, PR 1989); 4, 5—tectonic disturbances: 4—established, 5—assumed; 6—seismic stations.

and 2 (d-g) respectively. All earthquakes with $K_s > 5.5$, registered by either all or one seismic stations APH, ZLN, PDK and KRS, were taken into account.

Therefore, the number of events on the graphs is significantly greater than the number of events on the maps of the epicentres. The most remarkable feature of the seismic activity of Klyuchevskoy in 1988-1989 was the occurrence of swarms of earthquakes:11 during the 2 years.

Duration of the swarms varied from 2 to 28 days, the number of earthquakes in the swarms from 30 to 480 (including events registered by one or two stations) and the energy class of the most violent events in the swarms varied by several orders of magnitude in the range 6.0 to 8.9. All the swarms occurred around the central crater at a depth of less than 5 km, and only the swarm of 2-30.8.89 featured individual earthquakes with a focal depth of 15-30 km alongside surface earthquakes (see Figure 2,d-g).

The earthquake swarms of 19.1-3.2.88 and 22-30.7.89 anticipated two of the largest flank eruptions in the relevant interval of time: the XXV anniversary of the IV in 1988 and Skuridin in 1989. The maps of the epicentres of these swarms of earthquakes are shown in Figure 4, a-d respectively. In both cases the flank outbreaks occurred at the final stage in the development of the swarms, when the number of earthquakes was decreasing. In both 1988 and 1989 the earthquakes with the maximum energy class in their swarm occurred after the beginning of the outbreak (see Figure 4,b and d). The swarms of 2-30.8.89 and 23-28.11.89 were registered during the Skuridin flank eruption, which occurred against the background of a continuous summit eruption. These swarms consisted of weak and shallow earthquakes and it was impossible to determine the coordinates of them.

The earthquake swarms of 25.10-10.11.88, 13.11-3.12.88, 25-30.12.88 and 1-16.1.89 occurred during a reduction in the effusive-explosive activity of the summit crater and in all probability accompanied the formation of the system of fissures and the subsequent short outflows of lava on the north-eastern slope of the volcano. There is a good spatial coincidence between the epicentral zones of these swarms and the area of fissuring. The connection in time between the occurrence of the earthquakes and the fissures and outbreaks on the surface has not been traced to the exact day in these cases.

The earthquake swarms of 27.12.87-6.1.88, 6-8.4.88 and 7-13.10.88 accompanied an intensification in the explosive activity of the summit crater. A detailed description and analysis of the above earthquake swarms associated with the activity of Klyuchevskoy in 1988-1989 will be given in a separate paper.

Volcanic tremor and earthquakes of type IV accompanying the summit and flank eruptions of Klyuchevskoy were registered almost continuously in 1988-1989 (see Figure l,a-c; 2,a-c) and were associated with the processes occurring in the supply channel and crater of the volcano. Variations in eruptive activity were reflected in the nature of variations in the amplitude of the volcanic tremor. The predominant periods of oscillations lay within the range 0.5-1.0 s.

During the earthquake swarm anticipating the XXV Anniversary of the IV flank outbreak, before the beginning of the eruption, from 19 to 27.1.88 the amplitude

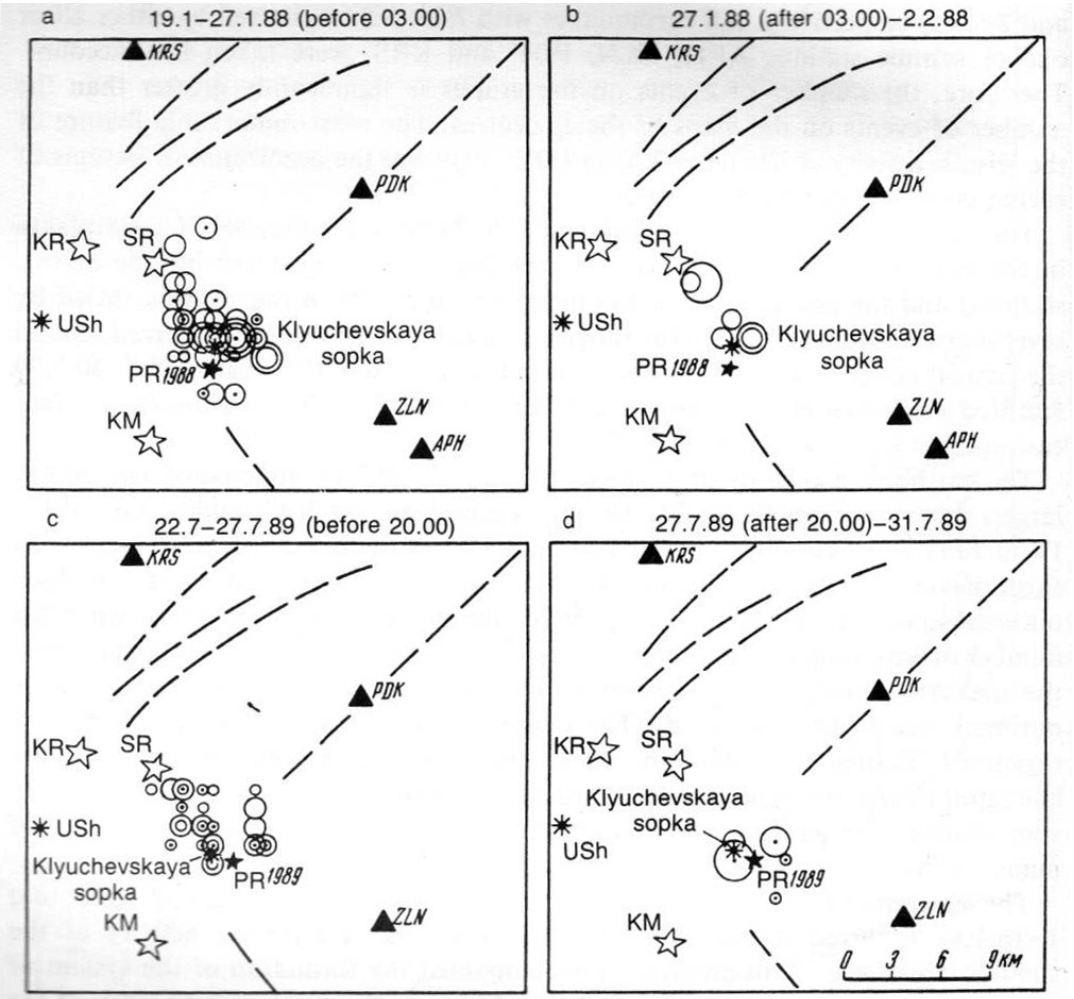

Figure 4 Maps of the epicentres of swarms of earthquakes on Klyuchevskoy 19–31.1.8 (a and b) and 22.7–3.8.89 (c and d) Legend see Figure 3.

of volcanic tremor fell to 0.1-0.2 μm (see Figure l,c). With the beginning of the flank eruption from 28.1 to 3.2.88 volcanic tremor intensified (the earthquake swarm continued to 3.2.88) and pronounced differences were observed in its amplitude, which varied from 0.2 to 2 μm. The 'flare-ups' in the intensity of volcanic tremor lasted from 20 min to 2-3 h. Further appreciable fluctuations in the amplitude of volcanic tremor were observed several times in April-May during the intensification of the explosive activity of the summit crater, from the second half of October to the beginning of November during the cessation of effusive activity in the summit crater, and in the middle of December shortly before and during the formation of the system of fissures and the short flank outbreaks on the north-eastern slope of Klyuchevskoy.

In 1989 the general level of volcanic tremor, according to both average and maximum amplitudes, was higher than in 1988; the value of the maximum

amplitude of volcanic tremor was 4 μm in the first half year and 6 in the second (see Figure 2,c). An increase in the level of volcanic tremor, with a simultaneous sharp change in the periods of increase and reduction in the amplitude of the oscillations, was noted in the first half of January at the final stage of the flank eruption of 22.12.88 -15.1.89, from the second half of February to the end of April and from the middle of August to the end of November 1989, shortly before and during the opening of the fissures on the slope of the volcano and during the intensification of the explosive activity of the summit crater (see Figure 2,c).

Just as before the XXV Anniversary of the IV outbreak, a sharp drop in the intensity of the tremor was observed on the third day after the beginning of the earthquake swarm of 22-30.7.89 anticipating the Skuridin flank outbreak (see Figure 2,c). This is clearly illustrated by Figure 5 which shows the change over time in the root-mean-square value of the rate of the displacement of the ground $X(t)_{rms}$ caused by volcanic tremor. The following combination of apparatus was used to obtain the values of $X(t)_{rms}$: a magnetic recorder with frequency modulated recording, a reproduction magnetograph, a voltmeter measuring the root-mean square value of stress and a recording instrument.

$\dot{X}(t)_{rms} = \sqrt{1/\tau \int_0^{\tau} (t)^2 \, dt}$, where τ is integration interval. When processing the data the value τ is selected on the basis of duration of the interval during which the process can be assumed to be stationary and the admissible value of error in the measurements. In our case the records of volcanic tremor were processed with a value of τ= 6080 s (see Figure 5) ; and seismometric data associated with the activation of the Bezymyanny and Shiveluch volcanoes were processed with τ= 12 s (see below).

The method of processing the seismometric data was suggested and developed by V.A.Gavrilov and A. L. Pudov and used in practice for processing volcanic tremor V.P.Khanzutin.

On the graph in Figure 5 it is shown that volcanic tremor increased gradually for 1,5 months before the flank outbreak and became unstable with a general tendency

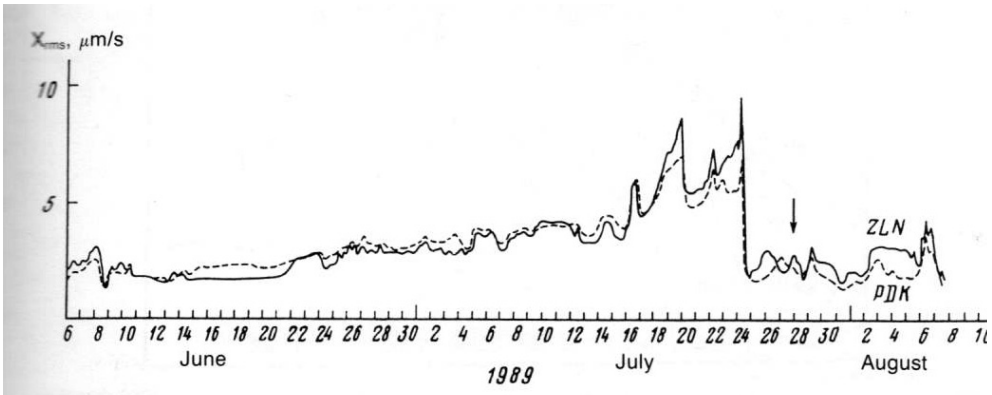

Figure 5 Variations in the level of volcanic tremor on Klyuchevskoy in June–August 1989 (data from seismic stations ZLN and PDK). X_{rms}—root-mean-square value of the rate of displacement of the ground, integration interval—6080 s. Arrow marks the beginning of the flank eruption.

to increase 15 days before the outbreak. On 24 July, during the swarm of earthquakes preceding the flank eruption, there was a sharp drop in volcanic tremor. 28 July, the time of the beginning of the flank eruption, was not marked by any noticeable change in volcanic tremor. This is apparently associated with the fact that processes occurring in the central crater played the main role in volcanic tremor and the contribution from the flank eruption was insignificant in this case.

Thus, the seismic phenomena observed in 1988–1989 on Klyuchevskoy were

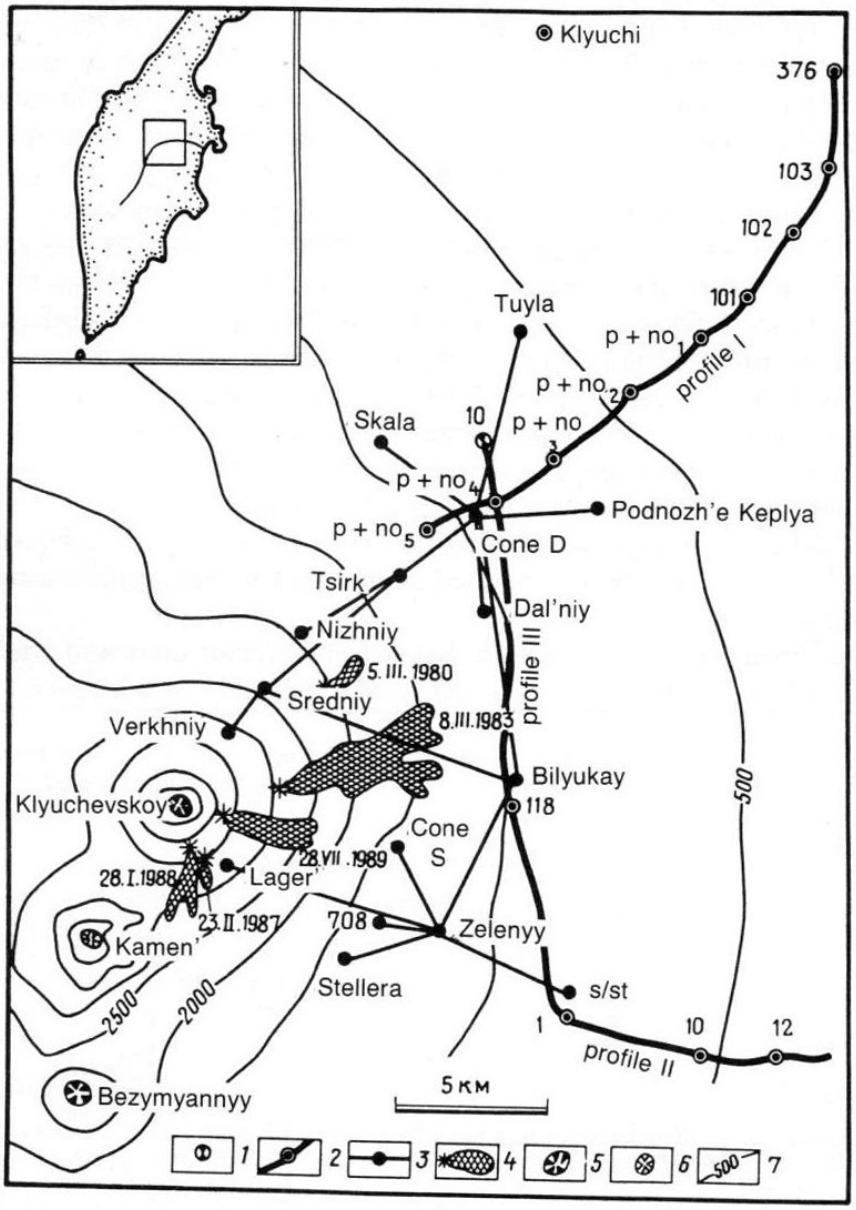

Figure 6 Diagram of the region of the investigation, position of flank eruptions 1980–1989, levelling profiles and lines of trigonometric levelling. 1—rock reference points; 2—ground reference points; 3 – lines of trigonometric levelling; 4—cinder cones and lava flows of flank eruptions; 5—craters of active volcanoes; 6—craters of extinct volcanoes; 7—contour lines.

varied, as was its volcanic activity. The flank outbreaks beginning in 27.1.88 and 28.7.89 were characterized by the occurrence of anticipatory swarms of earthquakes and a sharp reduction in the level of volcanic tremor several days before the beginning of the eruptions, during the development of the swarms. No such regularity was noted in the case of the short-lived flank eruptions (on the northeastern slope of the volcano) in December 1988-February 1989. This is possibly associated with the flow of large batches of magma into the general fissures which opened in January 1988 and July 1989.

Geodesic Observations

Geodesic measurements were carried out in 1988-1989 on Klyuchevskoy to determine the spatial and temporal displacements of the earth's surface. The diagram of the geodesic constructions is presented in Figure 6. Repeated levelling on radial profiles I and II and intersecting profile III was carried out in order to determine the vertical component of the deformations.

Taking into account the results of earlier work [5] and also the fact that from 1983 onwards the flank outbreaks occurred at heights of 3.0 to 4.0 thousand m, radial profiles I and II were extended to heights of 3 and 2.8 thousand m - respectively. It is difficult and inconvenient to carry out differential levelling at such heights, and so the vertical component of the deformations of the earth's surface was determined by bilateral trigonometric levelling [3]. The lengths of the lines were measured at the same time.

The most representative results were obtained for the series of observations carried out along radial profile I (Figure 7,a) and its extension (Figure 7,b). For the period 1987-1989 there was a general tendency for the slope to sink in areas at a distance of 10 to 26 km away from the crater. According to the results of differential levelling, the amplitude of displacement over the 2 years is close to 76 mm in an area

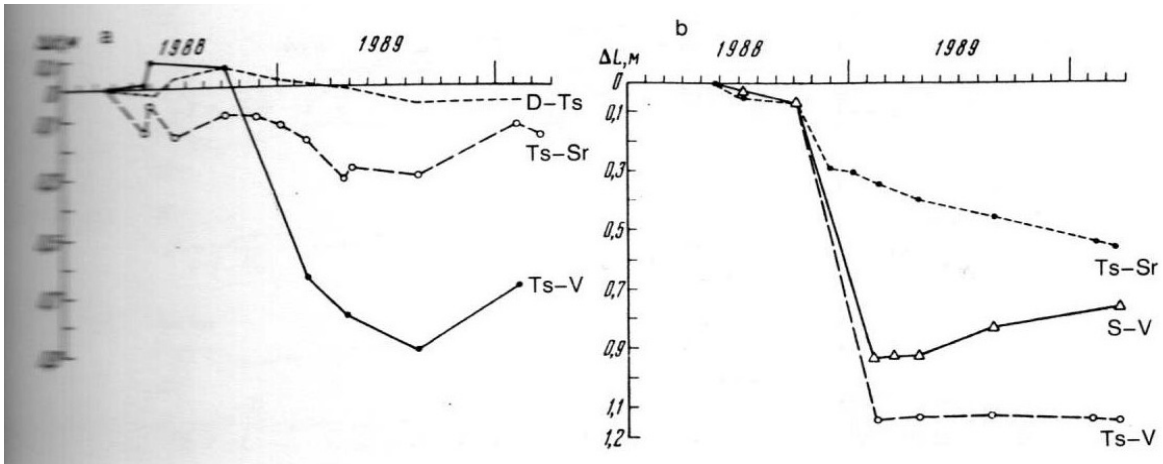

Figure 7 Vertical displacements according to the results of differential (a) and trigonometric (b) levelling along profile I for 1987–1990.

of the profile 16 km long (Figure 7,a). When fissures opened and mud flows formed on the north-eastern slope close to the Sredniy point on 20 November 1988 the Verkhniy point sank 0.7 m relative to the Tzirk point. The sinking continued until the middle of August 1989 (Figure 7,b). A reduction in vertical displacement with increasing distance from the crater is typical (Figure 8,a). The vertical displacements are least between points at the greatest distance from the crater (cone D—Tsirk), they increase to 30 cm between points Tsirk-Sredniy and reach a maximum for the height difference between points Tsirk-Verkhniy. Sign-changing vertical displacements are observed for short intervals of time on the trigonometric profile (cone D—points Tsirk-Sredniy-Verkhniy).

It can be seen from the results of the observations that significant deformations occurred mainly at heights of 2 to 4 thousand m. Considering the deformations to be homogeneous, we carried out an estimate of the change in volume in the sector between profile I (azimuth ~45°) and the direction of fissures with an azimuth of ~90°. The position of the outbreak of 1988 was taken as the centre of the sector, and the lower boundary of the sector passed along the contour line of 2.0 thousand m. The change in volume was close to ~0.0044 km^3.

The rise observed at the end of 1988 was replaced by the sinking of the summit after the opening of the fissures in November and the series of short eruptions in

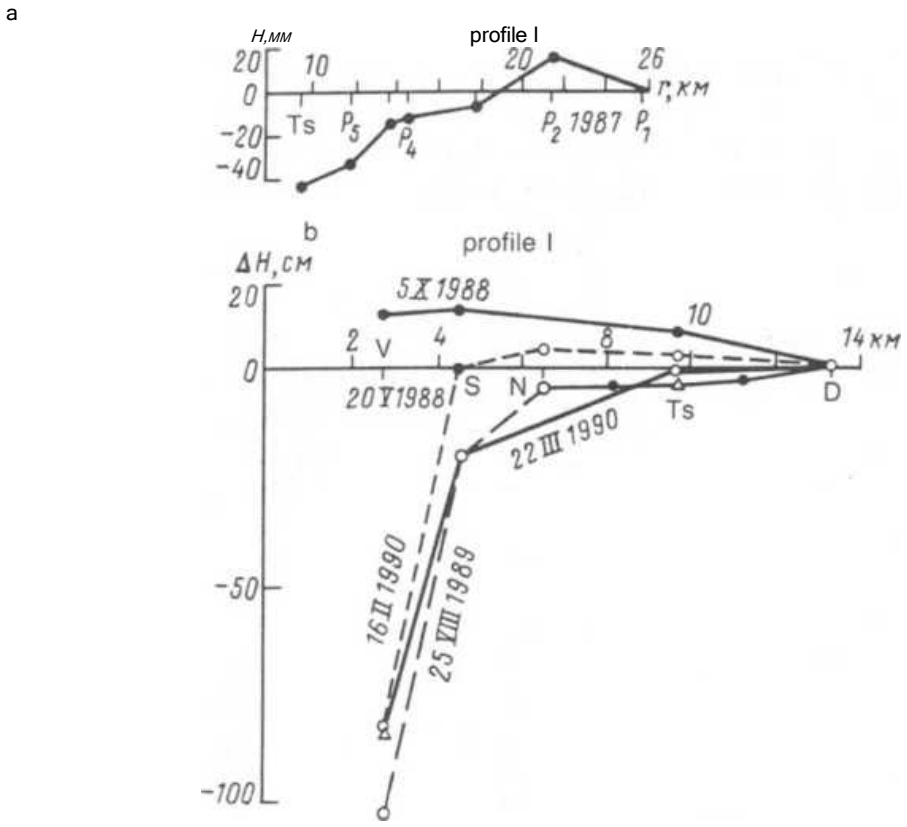

Figure 8 Vertical (a) and horizontal (b) displacements for points of profile I at various distances from the crater of Klyuchevskoy for 1988-1990.

December and the first quarter of 1989 (Figure 8,a). Measurements of the lengths of the lines on trigonometric profile 1 also showed significant horizontal displacements (contraction of up to 1.0 m). The opening of the fissures was accompanied by contraction along the line of the fissures. Further observations showed that the Sredniy point has a tendency to creep along the slope at a rate of 18 mm/month. Creep is indicated by a difference in the signs of horizontal displacements along the lines of the points: extension along the line Sredniy - Verkhniy, and contraction along the line Sredniy-Tsirk (Figure 8,b).

The results of differential levelling along radial profile II (Figure 9,c) for 1987-1988 indicate the insignificant sinking of the slope of the volcano (sinking of the part of the profile at a distance from the volcano or rising in the direction of the summit). The amplitude of displacement is close to ~20 mm with a profile length of ~25 km. A rise in the direction of profile II is also observed along intersecting profile III. Intersecting profile III has a near horizontal position, and with an axiosymmetrical source of pressure under the volcano and a homogeneous medium not disturbed by faults, displacements should not occur on this profile. The most contrasting displacements are registered on two sections from reference points 11 to 13 and between reference points 18 and 20. The amplitude of displacement is close to 20 mm on a base of 20 km (Figure 8,a and b). These contrasting displacements are possibly associated with radial fissures tracing the structure of the volcano. It should be noted that the flank outbreaks of 1980, 1983 and 1987-1989 were confined to fissures with a north-easterly course.

From the analysis of geodesic data it may be concluded that the eruptive activity of Klyuchevskoy was accompanied by deformations of the earth's surface, confined mainly to the flank outbreaks.

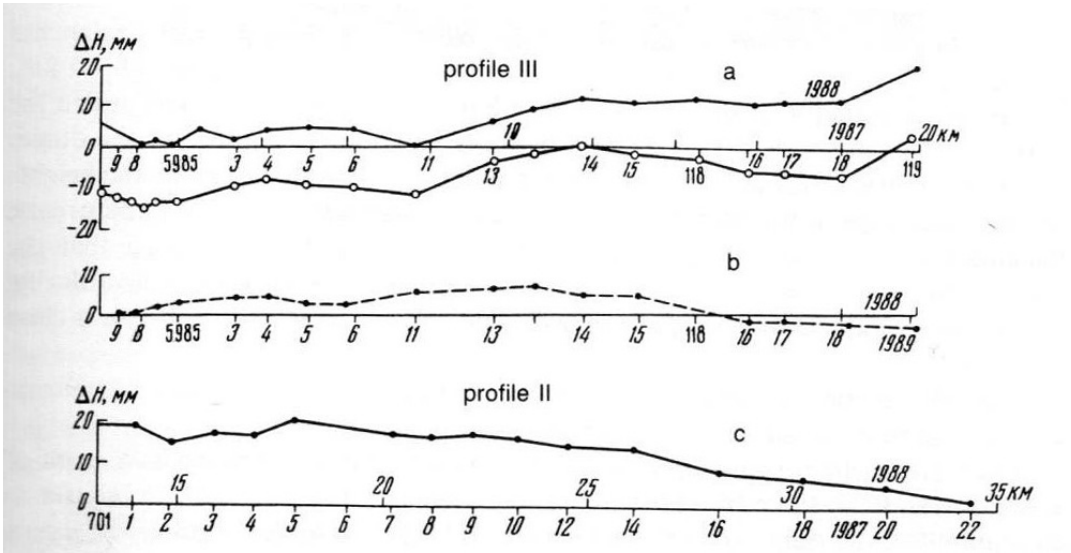

Figure 9 Vertical displacements according to the results of differential levelling along intersecting profile III: for 1987–1988 (a), 1988–1989 (b), along radial profile II for 1987–1988 (c).

BEZYMIANNY VOLCANO

In 1988-1989 Bezymianny was less active than it had been in 1986-1987. The beginning of 1988 saw a continuation of the effusive eruption that had begun in January 1987 [2]. Viscous lava, extruded in the upper part of the dome, had formed a lava flow on its eastern slope which had gradually covered the flows of 1985-1987. The extrusion of lava ceased at the beginning of March. The volcano was in a state of moderate fumarolic activity for ~5 months. At the end of July 1988, according to V. N. Andreyev, a glow was visible at the summit of the dome and there were occasional weak ejections of ash. After this the volcano was in a state of moderate fumarolic activity for exactly a year, until the end of July 1989.

In the night of 1 to 2 August 1989 an explosive-effusive eruption of the volcano began with ejections of ash in the upper part of the dome. The ejections gradually intensified in the morning of 2 August. By 06.35 local time the height of the eruptive cloud had increased to 1.5 km. At times individual ejections merged into the continuous emission of a gas and ash jet, which sometimes lasted more than 10 min and was accompanied by a roaring noise similar to the noise of a jet engine (Figure 10). A crater with a diameter of about 200 m was formed on the summit of the dome by the explosions. Scorching avalanches of rock poured down the slope of the volcano from an area situated slightly to the east of the crater, where the glow of red-hot lava could be seen.

At 10.15 on 2 August the explosive activity weakened and a viscous lava flow began to be extruded from the crater. The explosive activity of the volcano was resumed at about 16.00. After a series of explosions pyroclastic flows began to pour down the eastern slope of the dome. The longest flow, with a length of ~ 5 km, was observed at 16.20. Several more pyroclastic flows were subsequently formed, but none of them was more than 3.5 km long. By 19.00 the intensity of the explosive activity had diminished.

On 3 August ejections of ash issued from the crater, accompanied by avalanches of rock and short pyroclastic flows. The eruptive cloud rose to a height of ~ 1 km. The eruption ended with the extrusion of a batch of viscous lava which sealed the effusive vent and formed three short tongues of lava on the summit of the dome.

Trigonometric levelling from the Zeleny point was used to determine the heights of the upper edge of the lava flow. Measurements were taken on 14.7.89 before the beginning of the eruption and on 18.8.89 after it ended. Considering that the increase in height was due to the extrusion of a new batch of viscous lava during the last eruption, the thickness of the lava flow on the summit of the dome is close to 23 m.

After the end of the eruption, from 4 August to the end of the year, the volcano was in a state of moderate fumarolic activity.

A new trench began to form at the south-eastern foot of the dome as a result of the erosion of the slope by pyroclastic flows. It was orientated radially relative to the summit of the dome and situated roughly 300-400 m to the south of the trench formed during the eruptions of 1984-1986.

The absence of reliable information for April to the beginning of July 1989

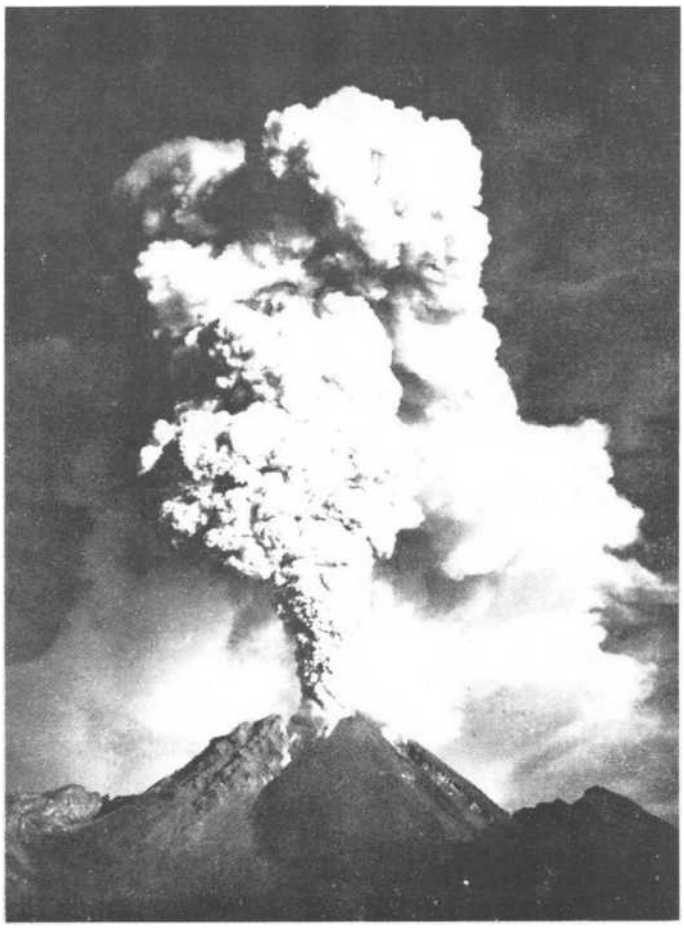

Figure 10. Gas and ash jet above the 'Novyy' extrusive cone of Bezymyannyy on 2.8.89 (07.00 local time). Photo by Yu. V. Demyanchuk.

means that we cannot say anything definite about the period of preparation for the explosive eruption, during which rigid extrusive blocks are usually extruded slowly in the upper part of the dome.

Seismicity

Tie only manifestation of seismic activity on Bezymyanny in 1988 was the registration of spasmodic volcanic tremor for one h (from 23.30 on 3.1.88 to 00.30 on 4.1.88 Greenwich time) in January. According to data from seismic station APH A_{vt}^{max}=0.9 μm, T^{max} = 0.7s, $A\,v_t^{av}$ = 0.3μm, T_{av}= 0.5s. Volcanic tremor accompanied the effusive eruption of the volcano which began in 1987 and lasted until February 1988. No changes in the course of the eruption were noted visually at the moment of the registration of volcanic tremor.

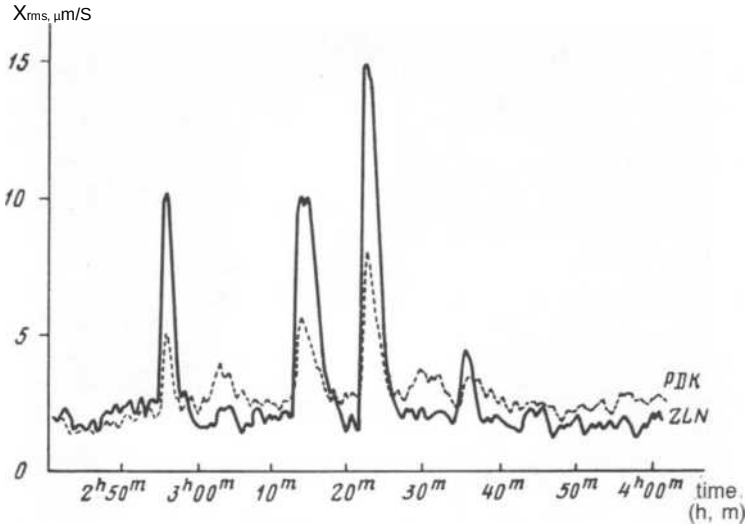

Figure 11 Fragment of the development of the effusive-explosive eruption of Bezymyanny of 2.8.89 according to seismometric data (s/st PDK and ZLN). Integration interval for X_{rms}—12 s.

The explosive-effusive volcanic eruption which began on the evening of 1 August 1989 Greenwich time was accompanied by earthquakes of types II—III and spasmodic tremor. Seismic station 2LN registered several surface earthquakes (K_s < 6.5) for 1 and 2 August, and the coordinates of the foci were determined for two of them (see Figure 3,a). Figure 11 presents the variations in Xrms in the period from 02.50 to 04.00 on 2 August 1989 according to data from seismic stations PDK and ZLN. The peaks on Figure 11 coincide in time with the moments of the formation of the pyroclastic flows.

After the end of the eruption on 5 August seismic station ZLN registered spasmodic volcanic tremor from 14.49 to 15.16 (A^{max} = 2.1 μm, T^{max}= 0.6 s) and from 17.13 to 17.16 (A^{max} = 2.2μm, T^{max} =0.7 s).

SHIVELUCH VOLCANO

During 1988-1989 explosive eruptions occurred on Shiveluch. They took the form of ejections of gas and ash (apparently phreatomagmatic) in the area of the volcanic dome which was extruded in 1980-1981. Individual ejections were observed from Klyuchi, a distance of 40 km away, but the majority were deciphered from the records of radiotelemetric station KPL, situated 2 km from the extrusive dome. In a number of cases additional information was obtained from data produced by visual aerial observations. At 17.35 local time on 3 February 1988 an ejection of gas and ash to a height of 1.5 km from the central part of the dome was observed from Klyuchi. During a flight round the dome on 4 February two double, intensively steaming, deep craters were spotted in its central and western parts.

At 15.15 local time on 7 February 1988 an ejection of gas and ash to a height of 3 km was observed. The ashfall travelled in a southerly direction for a distance of more than 30 km from the volcano. During a flight on 1 March it was established that an explosion had occurred in the central part of the dome where the ejection of 3 February had been observed.

The activity of the volcano increased in 1989, and this is reflected in the number of seismic events registered (see below in the text). Four eruptions were observed visually: on 7 and 18 April and 16 and 26 June.

The series of explosive eruptions in April had a number of special features: a gas and ash jet was emitted from a fissure in the north-eastern wall of the crater of 1964, on the site of fumarolic vents which had been formed and observed in February-March 1987. Mud flows, running down to heights of 1800-1900 m, were observed during the April eruptions, which occurred at heights of 2100-2200 m.

A series of gas and ash ejections occurred, rising to a height of 2-2.5 km at 13.40 local time on 7 April and to a height of 1.5-2.0 km at 14.10 on 18 April. In both cases individual steam and gas jets rose in clouds along the fissures during the eruptions. On 7 April not less then six jets of mixed steam and gas, rising to a height 1.5-2.0 km, were localized along the fissure; on 18 April there were four jets of 'team and gas rising to a height of up to 1 km. The intensive discharge of these jets listed about 1 h after the main ejections of gas and ash. At 23.30 local time on 16 June there was an ejection of gas and ash to a height of 3-4 km above the dome. The glow of red-hot material was observed at the base of the column of ash. The ash cloud reached Klyuchi.

At 17.00 local time on 26 June with poor visibility individual fragments of a gas and ash column were observed rising to a relative height of 4 km and forming a trail which was moving to the south.

The morphology of the dome of Shiveluch changed during the eruptions of 1988-1989. Two of the three craters active during 1987, the central and western craters, merged.

Seismicity

As before, the seismic regime of Shiveluch in 1988-1989 was monitored by two radiotelemetric stations: KPL and BJD. V. I. Gorel'chik [2] has given a classification of the seismic events registered on the volcano. The earthquakes in the Shiveluch region, the coordinates of the foci of which were determined in 1988-1989, are shown on the maps of the epicentres of the earthquakes (see Figure 3). As can be seen from the maps, the earthquakes are situated not more than 5—20 km away from the active dome, mainly to the south, at depths of 0-10 km. The main data about the earthquakes of various types registered by stations KPL and BJD are presented in Tables 1 and 2. According to the data from both seismic stations there was an increase in the seismic activity of Shiveluch in 1989 compared to1988, reflected in all types of earthquakes. This also agrees with the visual observations. The explosive activity of the volcano was accompanied by spasmodic volcanic tremor lasting up to several hours. Figure 12 presents the time variations in the value of *X*rms in connection with the ejections of gas and ash (data from seismic station KPL).

TABLE 1 Basic information about seismic activity on Shiveluch in 1988–89 (according to data from s/st BJD—Baydarnyy)

Year, month	Seismic activity: Earthquakes of type I (S-P < 5.0 s) N	K_s^{max}	Earthquakes of types II–III (S-P < 5.0 s) N	K_s^{max}	High-frequency seismic events ($f \geq 2.5$ Hz) N	A^{max} μm	Low-frequency seismic events ($0.5 \leq f < 2.5$ Hz) N	A^{max} μm	Volcanic tremor with $A^{max} \geq 0.2$ μm N	total duration Δt, h	A^{max} μm	State of volcano according to visual observations
1988: I	2	6.8	2	4.8	—	—	13	0.7	1	0.2	0.7	Ejections of gas and ash: 3.2.88
II	—	—	2	6.0	—	—	11	2.7	3	0.7	1.2	—H = 1.5 km; 27.2.88—H = 5 km,
III	2	5.7	4	5.6	—	—	8	3.9	—	—	—	ashfall for a distance of 30 km.
IV	5	7.8	3	4.8	—	—	3	2.0	—	—	—	Fumarolic activity, H = 200–800 m
V	—	—	5	4.5	—	—	7	1.0	—	—	—	Furmarolic activity. Ejection of
VI	7	7.4	5	7.2	68	4.1	76	1.3	—	—	—	ash 1.6.88—H = 1 km
												Fumarolic activity, H = 800 m
VII	2	5.9	8	6.6	8	0.8	19	1.0	1	0.6	0.4	
VIII	3	6.4	4	5.4	3	0.7	18	1.1	—	—	—	
IX	—	—	2	4.6	3	0.5	12	0.7	1	0.3	0.5	
X	—	—	3	6.7	—	—	2	0.9	—	—	—	
XI	—	—	4	5.7	—	—	3	0.9	1	0.7	0.7	
XII	2	9.2*	3	6.6	—	—	11	1.9	2	1.8	1.8	6–7.12.88 fumarolic activity,
												H = 50 km
1989:												
I	9	7.7*	4	5.1	—	—	13	1.3	—	—	—	
II	17	6.7	7	6.2	1	0.3	29	2.1	1	0.3	0.9	
III	2	6.5	5	5.2	—	—	14	1.3	3	0.8	2.6	
IV	—	—	7	6.1	—	—	13	2.0	5	0.6	1.0	Series of ash ejections
												7.4.89—H = 2–2.5 km,
												18.4.89—H = 1.5–2 km
V	8	6.8	12	6.6	6	2.6	23	2.9	4	2.6	1.5	
VI	12	7.6	9	6.7	23	1.3	86	2.8	5	1.7	2.5	Ejections of gas and ash
VII	19	7.0	3	5.7	—	—	18	1.7	6	1.9	4.8	14, 16.6.89—H = 3–4 km,
												26.6.89—H = 4 km, glow of red-hot
												material. Explosion in crater 30.6.89,
												H = 3–3.5 km
VIII	2	6.1	7	9.0	7	1.3	34	1.8	3	1.2	0.8	
IX	—	—	3	5.7	1	0.2	18	3.2	1	0.3	0.4	
X	1	7.3	4	6.7	7	1.9	21	3.1	1	0.3	0.8	
XI	2	8.0	2	6.2	—	—	48	1.2	1	0.3	1.7	
XII	—	—	6	5.7	—	—	32	4.4	2	1.1	0.4	6, 7.12.89. fumarolic activity,
												H = 50 m

*Average energy class based on network of seismic stations.

Table 2. Basic information about seismic activity on Shiveluch on 1988-1989 (according to data from s/st KPL-Dome (KUPOL))

	Earthquakes of type I (S-P < 5.0 s)		Earthquakes of types II–III (S-P < 5.0 s)		High-frequency seismic events ($f \geqslant 2.5$ Hz)		Low-frequency seismic events ($0.5 \leqslant f < 2.5$ Hz)		Volcanic tremor with $A^{max} \geqslant 0.2\ \mu m$, 1 Hz < f < 2.5 Hz			
Year, month	N	K_S^{max}	N	K_S^{max}	N	A^{max} μm	N	A^{max} μm	N	total duration Δt, h	A^{max} μm	Comments
1988: I	9	7.3	15	6.4	13	0.8	113	5.6	1	2.4	7.4	
II	1	4.2	9	6.0	2	0.2	74	7.5	6	4.0	7.3	Data from visual observations the same as in table 1
III	4	6.5	8	4.5	48	2.7	38	3.3	—	—	—	
IV	2	6.8	3	5.3	29	1.5	5	1.6	—	—	—	
V	No recording from 5.4–5.7.88											
VI	—	—	—	—	—	—	—	—	—	—	—	
No recording from 13.7 to 17.8.88												
VII	—	—	2	4.8	31	1.4	9	2.5	1	0.7	1.1	
No recording from 23.8 to 29.8.88												
VIII	1	5.5	—	—	17	0.8	8	2.0	2	6.8	1.1	
IX	—	—	1	5.0	23	2.3	20	2.9	2	0.7	0.9	
X	—	—	1	6.5	26	0.9	10	6.6	—	—	—	
XI	1	5.4	—	—	18	1.3	31	3.2	2	0.8	1.5	
XII	2	9.2*	1	6.3*	15	1.4	85	6.0	4	3.3	2.7	
1989: I	20	6.3	—	—	27	1.2	60	4.8	—	—	—	
No recording from 29.1 to 13.2.89												
II	3	6.5	3	6.7	47	10.0	46	16.0	2	0.9	1.1	
No recording from 17.3 to 29.3.89												
III	—	—	3	6.2	1	0.5	38	3.0	2	0.6	2.9	
IV	1	6.1	4	5.8	16	1.1	39	3.1	6	3.3	3.0	
V	7	6.7	36	5.8	13	4.7	71	5.5	5	2.4	4.3	
VI	5	6.6	17	6.2	134	3.0	91	4.8	12	11.9	4.0	A higher-frequency component appeared in volcanic tremor ($f \sim 3.5$ Hz)
No recording from 9.7 to 24.7.89												
VII	—	—	3	5.9	68	2.9	49	7.3	7	4.5	4.4	
VIII	2	7.0	11	8.4	218	5.4	65	5.3	7	10.3	4.7	
IX	7	6.8	13	6.8	52	4.3	75	4.9	8	11.7	3.2	
X	3	7.2	12	6.8	8	1.1	63	5.9	9	12.5	5.1	
No recording from 22.11 to 3.12.89												
XI	3	7.9	10	6.3	5	1.2	59	6.4	4	1.1	5.4	
XII	—	—	10	5.7	12	0.8	121	5.6	5	6.1	5.7	

*Average energy class based on network of seismic stations.

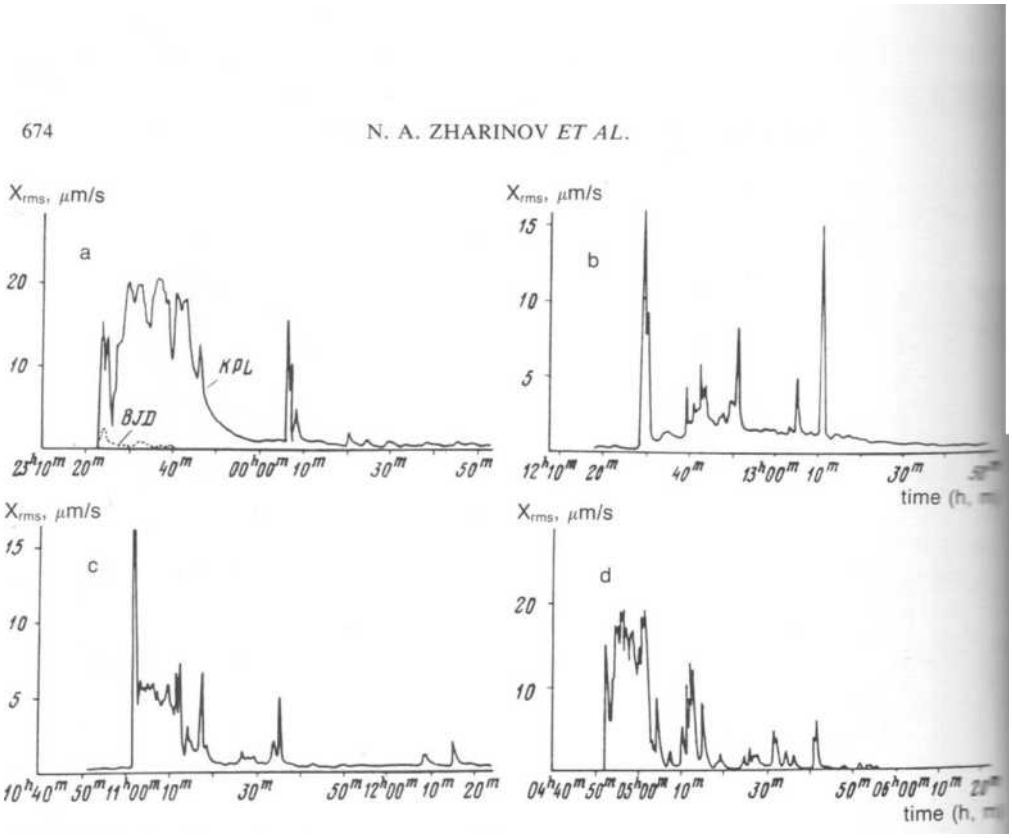

Figure 12 Seismic activity accompanying ejections of gas and ash on Shiveluch according to data from s/st KPL, a—28.5.89; b—13.6.89; c—16.6.89; d—26.6.89. Integration interval for X_{rms}—12 s.

These data indicate the different nature of the development of the explosive process for the examples quoted and the similar maximum values of X_{rms}.

Figure 12,a shows the characteristics of the seismic signal from an ejection of gas and ash on 28 May 1989 registered at stations KPL and BJD. Station BJD is situated 8 km from the active dome of Shiveluch and 5 km from station KPL. As can be seen in the figure, the level of the signal registered at station KPL is significantly higher than the level of the signal at station BJD. This is associated with the shallow depth of the source and the great decay of the seismic waves during their passage through the upper part of the pyroclastic cover.

CONCLUSIONS

Observations of the state of the active volcanoes of the Northern group in 1988-1989 have revealed certain features. A distinctive feature of Klyuchevskoy is the intensive Assuring in the structure of the volcano from a height of 2000 m to the summit, covering the sector lying clockwise between north-east and south-west. Two prolonged flank eruptions occurred at heights close to 4000 m over the period 1988 to 1989 with a volume of erupted material of 0.03 km^3 each. The high explosive- effusive activity of the summit

crater was maintained against the background of the flank eruptions.

An explosive-effusive type of eruptions continues to predominate on Bezymyannyy, accompanied by the growth of a lava dome near the vent of the 'Novy' extrusive dome.

On Shiveluch the number of explosive eruptions is tending to increase and a crater is forming which covers the central and western part of the active dome. On the whole, it can be said that the high level of activity of the volcanoes of the Northern group was maintained in 1988-1989.

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