Seismicity and Source Parameters of Earthquakes in the Region of the Large Tolbachik Fissure Eruption

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ABSTRACT

This study discusses the focal mechanisms of 61 earthquakes and dynamic parameters of 97 earthquakes ($m_b \geq 2.0$ and focal depths 0-20 km) occurring in the region of the large Tolbachik fissure eruption in 1975-1978. Variations of these parameters during the different eruptive stages are examined. Three stages can be distinguished: 1) June 27-July 2, 1975 (from the beginning of the seismic preparation to the large earthquakes of July 2nd with $M = 5.0$); 2) July 2nd-July 6th, 1975 (before the onset of eruption); 3) From July 6th, 1975 to the end of 1976 (during the eruption).

During the second stage the 90° reorientation of the compression stress axes was observed; during the third stage the compression stress system returned to the initial strike. No variation in the orientation of the tension stress axes was noted during all these stages. Simultaneously with the reorientation of the compression stress axes in the volcanic earthquake foci during the second stage, the stress-drop values decreased strongly, whereas during the first stage these values were anomalously high. During the third stage the stress-drop values continued to decrease and approached the average regional values indicative of a calm period. All the estimates of parameters variations were made at 0.1 significance level.

The above-mentioned temporal variations in the volcanic earthquake focal parameters are discussed in connection with the probable model of preparation and course of eruption.

INTRODUCTION

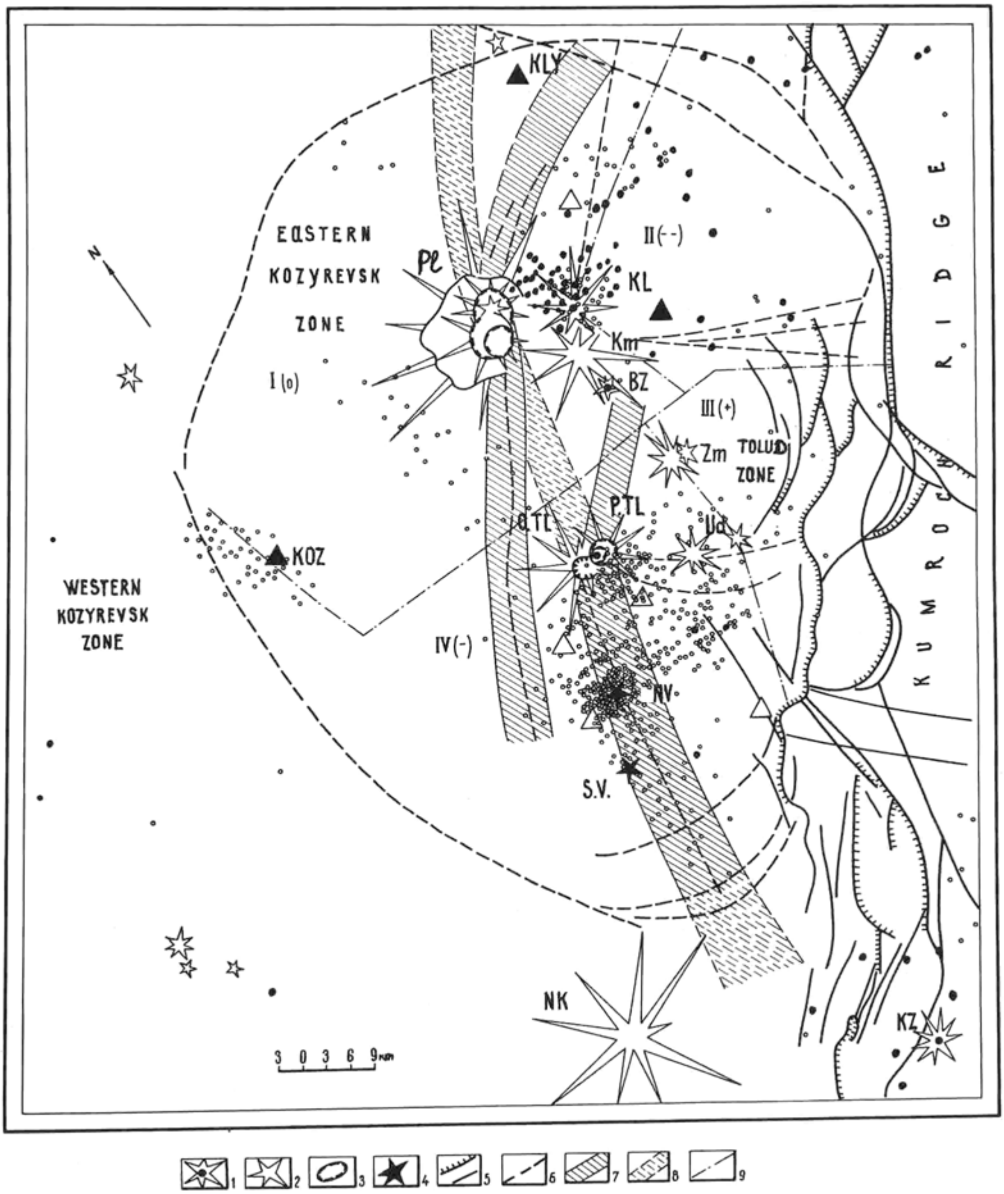
One of the greatest basaltic eruptions of our century - the large Tolbachik fissure eruption, 1975-1976, in Kamchatka - was preceded by an intense seismic activity which commenced on 27 June, 1975. Earthquakes accompanied the eruption throughout all its stages and were observed for a long period after the eruption. The large Tolbachik eruption stimulated a high level of seismicity within the region of the Klyuchevskoy volcanic group during the period 1975-1978. Some results related to studies of seismic activity and source characteristics of the earthquakes associated with the large Tolbachik fissure eruption are published *e.g.* in ZOBIN 1979*a*) and FEDOTOV *et al.* (1980). This paper is a continuation of the above studies presenting refined supplementary data on focal mechanisms and source characteristics of earthquakes in the region of the Klyuchevskoy volcanic group during the Tolbachik eruption. It also discusses the variations in these characteristics during the different eruption stages.

INITIAL DATA AND METHODS OF ANALYSIS

Seismograms of the permanent Kamchatka regional network, as well as of some temporary stations were used as fundamental data. The location of the seismic stations nearest the eruption center is shown in Fig. 1. All seismic channels for these stations had a flat frequency response within the period 0.2-0.9 s. Channel magnification depends on the location of stations and microseismic level, and varies from 75 to 15,000.

The accuracy of hypocenter determinations for the main mass of earthquakes was ± 2-3 km in epicenter and ± 3-5 km in depth.

Focal mechanism solutions are given for earthquakes of magnitude $m_b \geq 3.5$ on the basis of sign distribution of first motions of P- and S-waves obtained from



seismograms of the Kamchatka regional network and from the *Operative Seismological Bulletin of the Institute of the Physics of the Earth*, USSR, and *Earthquake Data Reports*, USA. Constructions were made in the upper hemisphere (Wulff net). Examples of focal mechanism solutions are given in Fig. 2.

Source parameters of earthquakes (seismic moment, radius of circular dislocation, stress drop value) were determined from P-wave spectra of earthquakes according to HANKS and WYSS (1972) technique. The vertical displacement components recorded at the «Klyuchi» (seismograph SVK) and «Petropavlovsk» (seismograph SKD and SKM) seismic stations was used. The procedure for obtaining spectra and spectral characteristics and for the source parameter calculation is described in ZOBIN (1980) and illustrated in Fig. 3. Significance tests were made using the Student criterion (CAULCOTT, 1973). Hypotheses for statistical significance of the difference the average characteristics were tested at 0.1 significance level.

SEISMICITY OF THE LARGE TOLBACHIK FISSURE ERUPTION IN 1975-1978

Figure 1 shown the epicenter distribution of crustal earthquakes of magnitude $m_b \geq 3.0$ for the region of the Klyuchevskoy volcanic group in 1975-1978. This figure also gives the main tectonic lineaments as constructed by MELEKESTSEV *et al.* (1974) on the basis of aerial photograms interpretation. The main band of epicentres extends along the main tectonic structure of the region, *i.e.* the chain of the Klyuchevskoy volcanic group, into several blocks by a net of transverse faults. Apart from this band of epicenters there exists another zone of epicenters to the West elongated along the branches of the Sredinny Ridge near Kozyrevsk village.

Figure 4 shows the temporal variations in the seismic process. On the South of Plosky Tolbachik volcano, an intense swarm of earthquakes which commenced on June 27, 1975, permitted the successful prediction of the location and time of eruption of the volcanoes (TOKAREV, 1978). Earthquake epicentres represented a closed, almost circular plan area of about 100 km^2 inside which all cones of the North vents were subsequently located. The focal depth of earthquakes decreased from 15-20 km to 0 and above sea level. The preceding swarm lasted for 9 days and consisted of two peaks of seismic activity following each other. The firts maximum was recorded on June 28 and the second on July 2 (see Fig. 4). The July earthquakes (07h 10min and 07h 34min) had magnitudes $M_{LH} = 5.0$ ($m_b = 4.7$) and were located at a depth of 10-20 km, almost immediately below the site where cone 1 formed. Other than earthquakes preceding the Sheveluch eruption in 1964 of magnitude $M_{LH} = 5.5$-5.5, those were the largest crustal events recorded in volcanic earthquake swarms in 30 years of instrumental observations in the region of the Klyuchevskoy volcanic group. After

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FIG. 1 — Generalized map of earthquake epicenters within the Klyuchevskoy volcanic group for 1971-1978 ($m_b \geq 3.0$ and focal depth 0-40 km). Legend: Earthquakes are shown by solid circles (1971-June, 1975); and open circles (June, 1975-1978); seismic stations are shown by triangles (solid - permament seismic stations; open - temporary seismic stations); 1 – active volcanoes (KL - Klyuchevskoy; BZ - Bezymianny; P TL - Plosky Tolbachik); 2 – dormant volcanoes (Km - Kamen'; Pl - Plossy; O TL - Ostry Tolbachik; Zm - Ziminy; Ud - Udiny; NK - Nikolka); 3 – calderas; 4 - centres of the large Tolbachik fissure eruption (NV - North vents; SV - South vent); 5-6 – tectonic disturbances (5 - established; 6 - assumed); 7 – largest zones of fissure eruption; 8 – assumed continuation of the zones of fissure eruption; 9 – boundary of physiographical blocks with different nature of Recent movements (I - relatively stable segments; II - segments subsidence; III - segments of slight rises; IV - segments of slight subsidence).

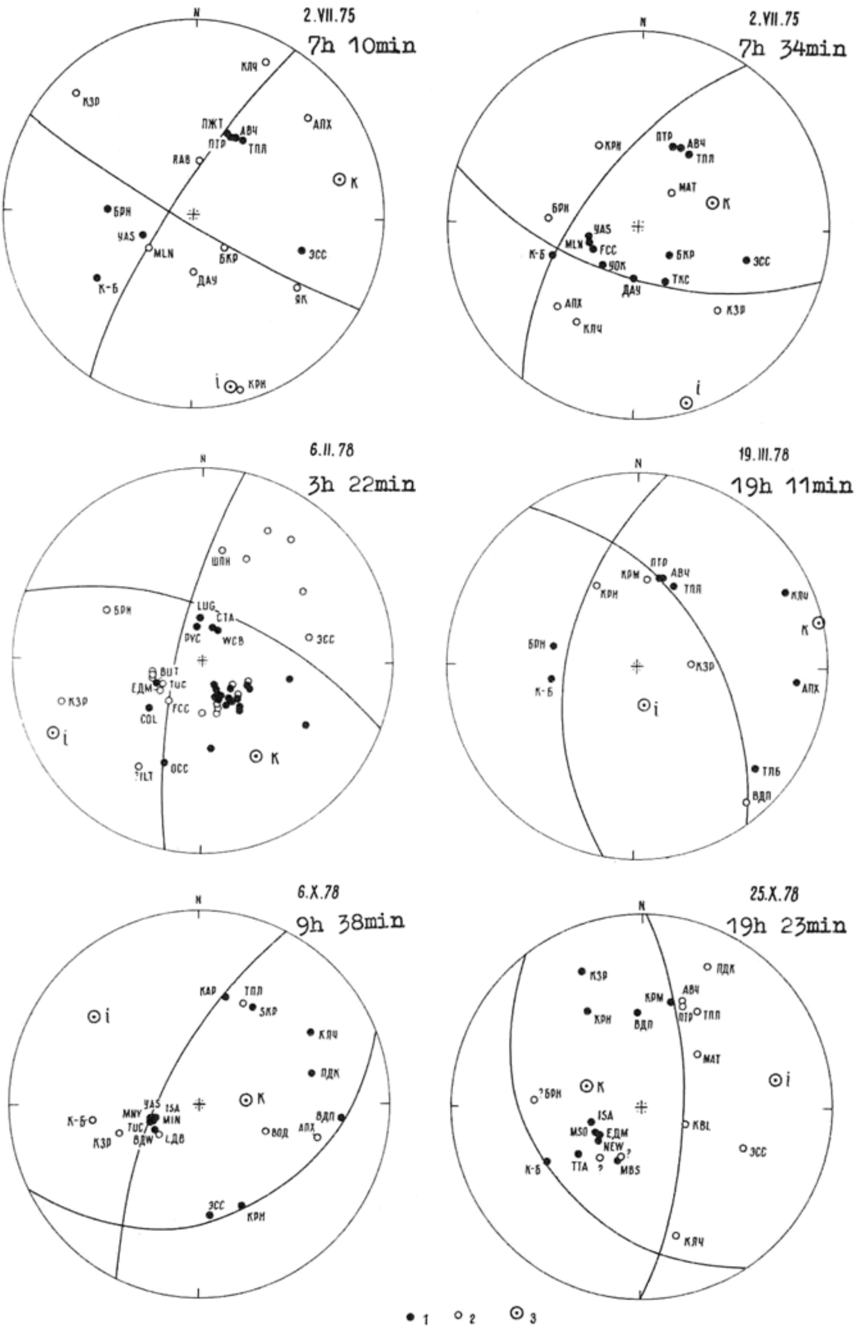


FIG. 2 — Focal mechanism of earthquakes with $m_b \geq 4.5$. Legend: 1 – compression; 2 – dilatation; 3 – projection of compression stress (i) and tension stress (K) axes.

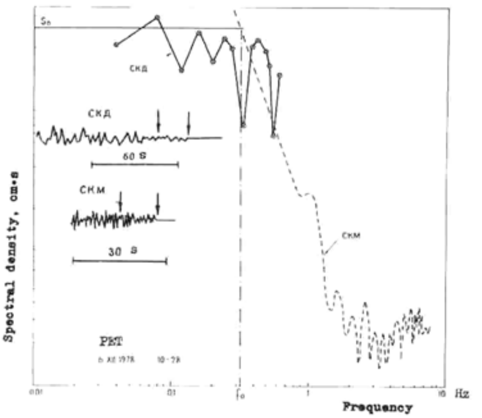


FIG. 3 — Example of P-wave spectral characteristics. Arrow indicate the sample length.

the July 2 earthquakes, the quantity and size of earthquakes in the swarm began do decrease rapidly. Cone 1 eruption commenced at 21h 45min (GMT) on July 5 during only slight seismic activity. In the period July 6-26 a violent continuous explosive activity was observed at cone 1. Earthquakes in that period were very few, and had focal depth of 0-10 km. The second earthquake swarm (August 2-17, 1975) (see Fig. 4) marked the cessation of the activity of cone 1 on August 8 and preceded the birth of cones 2nd (August 9) and 3rd (August 17). In comparison to the first swarm (June 27-July 5), the epicentral zone of the second swarm enlarged conspicuously. Two contiguous regions were singled out: the region of the North vents where the largest earthquake foci ($m_b = 4.0$) were located and a reasonably large territory (about 400 km^2) between the eruption centres and Plosky Tolbachik crater and to the East, South and Southeast. The quantity of earthquakes that occurred within this territory (called by us the Tolud epicentral zone) exceeded by 5-10 times the number of earthquakes that occurred in the eruption region. The eruption of the North vents ceased on September 15, 1975, and two days later, on September 17, a new fissure opened and a new eruption vent (10 km south of the zone of scoria cones, Cone 8th) began to grow; it was active up to the end of 1976 issuing flows of basalt composition. The eruption of this cone was preceded by an earthquake swarm which commenced on September 16 immediately after the end of eruption at the North vents (see Fig. 4). Earthquake foci of the swarm extended to the southwest of the North vents.

From September, 17, 1975 up to the end of 1976, only sporadic small earthquakes occurred in the eruption region near the North vents. The main seismic activity spread to the north and northeast of the new volcanoes, encompassing practically the whole region of the Klyuchevskoy volcanic group. In addition to the Tolud epicentral zone, two more zones east and west Kozyrevsk village (KOZ) (see Fig. 1), as well as the region of Klyuchevsky volcano were the most seismic within this territory.

Both zones around Kozyrevsk, just as the Tolud zone, were practically aseismic before the large Tolbachik fissure eruption. They formed mainly during and after it. As can be seen from Fig. 4, the seismic activity in the eruption region and in the Tolud epicentral zone developed in connection with the Tolbachik eruption, reflecting the main stages in its development.

SOURCE CHARACTERISTICS OF EARTHQUAKES IN THE REGION OF THE KLYUCHESVKOY VOLCANIC GROUP IN 1975-1978

The study of source characteristics of earthquakes such as focal mechanisms, seismic moments and stress drops allows us to consider a space-time picture of elastic stress release in the eruption region, and compare it with the course of the eruption development.

Focal mechanism were studied for 61 earthquakes of magnitude higher than 3.5, *i.e.* for 67% of all earthquakes of this magnitude. Focal mechanism solutions were made both for the volcanic earthquakes of the large Tolbachik fissure eruption and for all other epicentral zones of the regions described earlier, except for the Tolud zone where the magnitude of

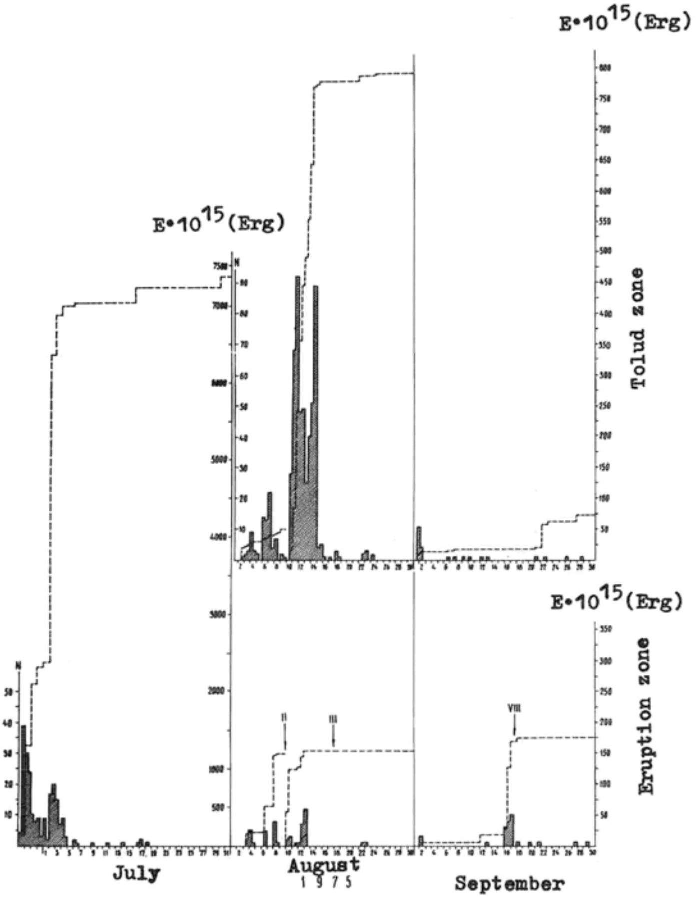


FIG. 4 — Temporal seismic activity in the eruption zone and in the Tolud epicentral zone in the period 27 June-30 Sept., 1975; I, II, III and IV – cones in the region of the North and South vents (eruption zone).

earthquakes proved to be too low for confident focal mechanism constructions. Two epicenters inside this zone were considered in common with earthquakes of the Eastern Kozyrevsk zone.

Arrows in Fig. 5 illustrate the inferred crustal stresses in the region of the Klyuchevskoy volcanic group in 1975-1978. They show the generalized distribution of compression and tension stress axes in earthquake foci, as well as faulting orientation.

A relative predominance of strike-slip faults over dip-slip faults is indicative of the earthquakes in the region under study. However, the sign of the dip component varies significantly in space. This is well illustrated in Fig. 5 which shows the distribution of foci with thrust or normal components of faulting.

The Region beyond the Eruption (Eastern and Western Kozyrevsk Zone).

Figure 5 gives detailed information on the peculiarities of the stress state of the region. In the center (on the western slope

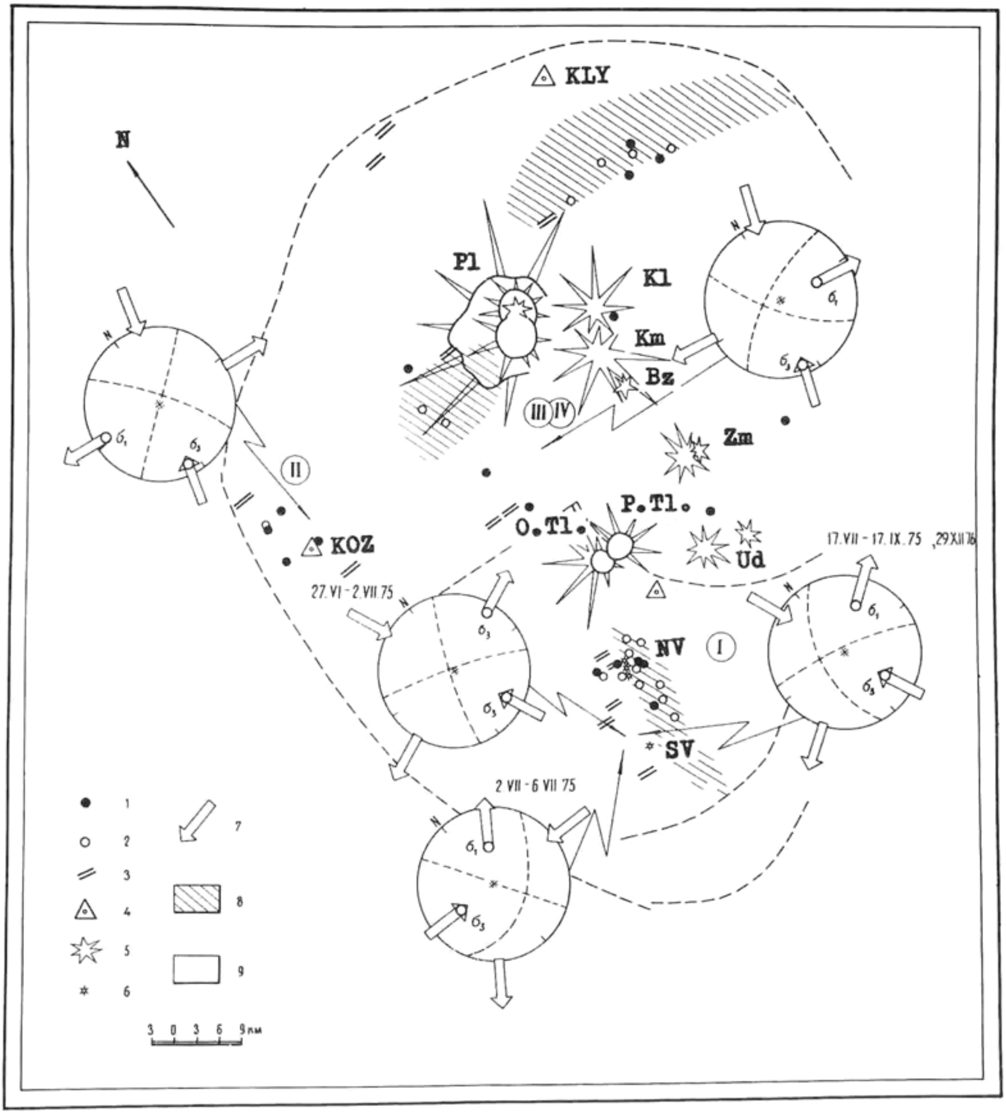


FIG. 5 — Scheme of the stress state of the region of the Klyuchevskoy volcanic group in 1975-1978. Types of faulting in earthquake foci: 1 - strike-slip faults with normal component; 2 - strike-slip faults with thrust component; 3 - strike-slip type; 4 - seismic stations; 5 - volcanoes; 6 - cones of the large Tolbachik fissure eruption; 7 - average vectors of the local stress system; 8 - zones of strike-slip of faulting with thrust component of faulting; 9 - zones of strike-slip type of faulting with normal component of faulting; projection of compression stress (10) and tension stress (11); 12 - average axes location.

of Plosky volcano) a small area of predominant thrust type of faulting like a peculiar column can be recognized. It is surrounded by a wide band of foci with the predominant normal type of faulting. From the north and south the boundary of the region is fixed by strike-slip type of faulting. In the northeastern extremity of the region between Klyuchevskoy volcano and the town of Klyuchi the area of contrasting movements is noted. Here a boundary can be drawn on the change of sign of dip component, *i.e.* normal type of faulting and thrust type of faulting. It is noteworthy that from 1975 to February 1978 thrust type of faulting was noted in this area, and in June-October 1978 normal type of faulting began to appear.

Figure 6 shows the orientation of compression and tension stress axes separately for the Eastern and Western Kozyrevsk zones. Focal mechanism solutions of 7 earthquakes were determined for the western zone. Inferred compression and tension stress axes for these earthquakes are oriented rather orderly; their range is within a quadrant. The average locations of compression and tension stresses suggest, rather reliably, the existence of near-horizontal sublatitudinal tension although the range of inclination values to the horizon is greater. The location of the average compression stress axis on the stereographical projection is near-horizontal. However this estimate should subsequently be refined.

The generalized stereogram of compression and tension stress axes for 22 earthquakes of the Eastern Kozyrevsk zone including practically the entire region of the Klyuchevskoy volcanic group north of Tolbachik volcano is constrained more reliably, although stress axes for these earthquakes (Nos. 40, 41, 18) were beyond the limits of their respective quadrant. These three earthquakes lie within the volcanic edifices and, perhaps, their deviation from the general zonal regularities is nonrandom and is caused by microtectonics of the volcanic edifices.

The average position of local stress axes suggests that, just as in the western cone, the tension stress orientation is close to the latitudinal, although with less inclina-

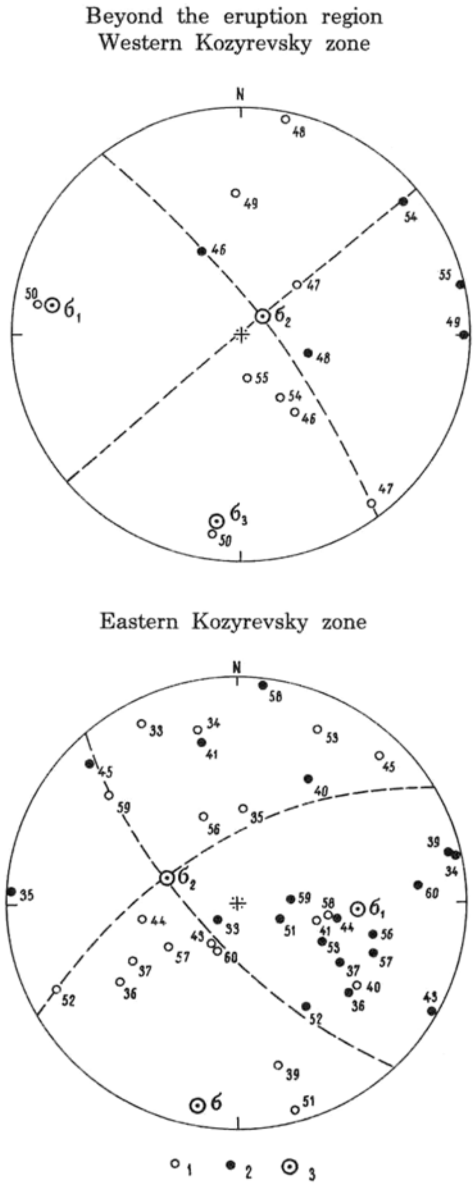


FIG. 6 — Generalized stereograms of the distribution of stress axes in earthquake foci beyond the eruption region. Legend: Projection of compression stress (1) and tension stress (2) axes; 3 – projections of averaged local compression stress (σ_3), tension stress (σ_1) and intermediate (σ_2) axes. Numerals correspond to the temporal sequence of earthquake initiation.

TABLE 1 — Average characteristics of local stress system.

Zones	Observational periods	Number of observations	Average azimuth values of stress axes					
			compression			tension		
			$\overline{Az}$	σ	E	$\overline{Az}$	σ	E
Western and Eastern Kozyrevsk		29	187	44	8	101	39	7
Tolbachik (eruption region)	27.6 - 2.7.75	16	168	31	8	74	25	6
	2.7 - 6.7.75	7	105	38	14	58	49	18
	6.7.75 - 12.1978	9	152	45	15	62	59	20

σ - standard deviation

E -standard error

tion to the horizon (~ 35°). The position of the average compression stress is similar of the western zone: close to the meridional and close to horizontal. Inasmuch as the stress states of both zones of the region of the Klyuchevskoy volcanic group where the eruption did not occur were similar, the arithmetic compression and tension mean values were calculated for both zones jointly. These values along with standard deviation and standard error values are listed in Table 1.

The eruption region is characterized by more developed thrust type of faulting, *i.e.* on the whole, in comparison to the northern passive zone, the zone of the large Tolbachik fissure eruption upheaved. This zone can be sudbivided into two subzones, the boundary between which is fixed by a chain of cones formed in the course of the eruption. The eastern subzone is characterized by the predominance of thrust faults, and the western subzone of strike-slip faults. The difference in the type of faulting in these two zones becomes significant for earthquakes of magnitude m_b higher than 3.5. It is noteworthy that a similar pattern was observed in focal mechanisms of volcanic earthquakes associated with the lateral eruption of Klyuchevskoy volcano in 1974 (ZOBIN 1979 *b*).

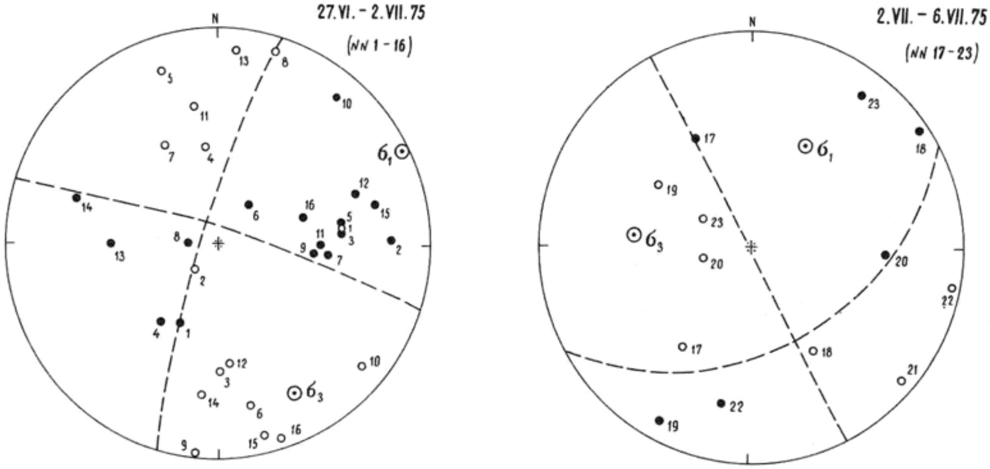
The stress system in the eruption region was unstable during the different eruption stages. Figure 7 shows the generalized stereograms of the distribution of compression and tension axes in earthquake foci in the different stages, and Figure 8 shows the variations of the average stress orientation values based on data from Table 1. During the first stage (June 27-July 2, 1975), at the end of which two large earthquakes of magnitude $M_{LH} = 5.0$ occurred, the stress system was close to the regional, which is characteristics of the northern zone that is calm from the point of view of volcanic avtivity. In the stage which began after the July 2 earthquakes and continued up to the beginning of eruptive activity the stress system was essentially reoriented. The orientation of the average compression stress value changed almost by 90°. At the same time, the orientation of the average tension stress valued did not change. In the eruptive stage the orientation of both compression stress and tension stress differs insignificantly from that in the first stage. Thus, in comparison to the tension stress the compression stress responded far stronger to the change of conditions in the zone in connection with the approaching eruption. The orientation of tension stress did not change appreciably during all the stage of seismic and volcanic activity in the eruption region (see Fig. 8).

Source parameters of earthquakes (seismic moment, stress drop) were determined for 61 earthquakes of magnitude higher than 3.5 (for the two-third of the recorded earthquakes) and for 36 earthquakes of lower magnitude. The dependence of seismic moment upon the energy class ($K_{S1,2}^{F68}$) (1), upon corner frequency

(1) $K_{S1,2}^{F68} = 2.0\ m_b + 2.1$

Region of eruption

Before euption



During eruption

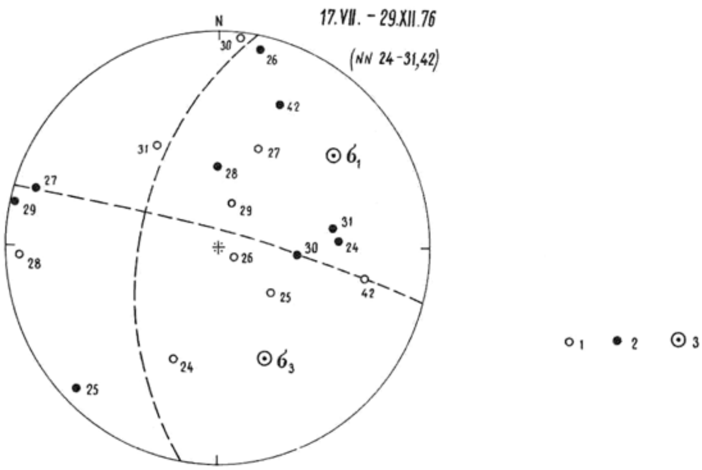


FIG. 7 — Generalized stereograms of the distribution of stress axes in earthquake foci in the region of eruption. Symbols are the same as in Fig. 6.

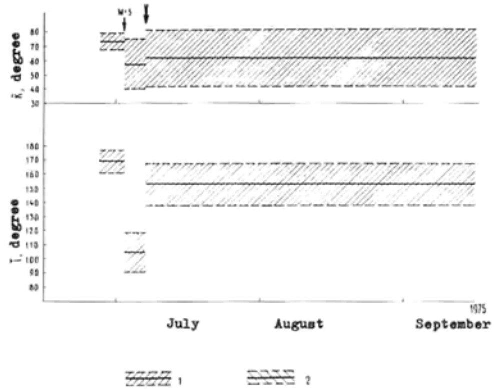


FIG. 8 — Variations in azimuth of compression stress (i) and tension stress (K) axes in earthquake foci during different eruption stages: 1 – in the region of eruption; 2 – beyond the eruption region. Heavy arrow marks the onset of the large Tolbachik fissure eruption.

of P-wave spectrum f_0, and upon stress drop value $\Delta\sigma$ is shown in Fig. 9. The equations or orthogonal regression lines under the condition of an equally precise determination of studied characteristics were also calculated.

$$\lg M_0 = 0.67\,K^{F68}_{S1.2} + 15.86 \qquad (\sigma = 0.44) \qquad (1)$$

$$\lg M_0 = -7.61 \lg f_0 + 23.06 \qquad (\sigma = 1.59) \qquad (2)$$

$$\lg \Delta\sigma = 1.23 \lg M_0 - 26.70 \qquad (\sigma = 0.70) \qquad (3)$$

where σ is the rms deviation from the regression line.

Equation (1) is the most reliable. The $\lg M_0$ *vs* $K^{F68}_{S1.2}$ correlation coefficient is equal to 0.61 and is significant at the 0.01 level. The rms deviation value is reasonably small. Unfortunately, equations (2) and (3) have mainly a formal sense. In fact, the high rms deviation value and small correlation coefficients (0.28 and 0.38, respectively) make it impossible to use these equations successfully.

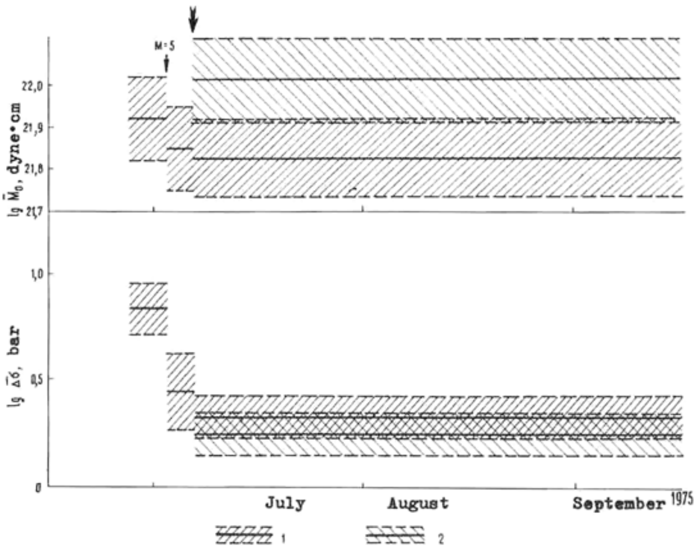


FIG. 9 — Correlation of dynamic parameters of earthquake foci and energy classes. a) M_0 versus $K^{F68}_{S1.2}$; b) lg $\Delta\sigma$ versus lg M_0; c) M_0 versus f_0. 1-3 – the region of eruption (1 – from 26 June to 2 July 1975; 2 – from 2 July to 6 July 1975; 3 – during the period of eruption); 4 – Tolud zone; 5 – Eastern Kozyrevsk zone; 6 – Western Kozyrevsk zone.

Regional Variation of M_0 versus $K_{S1.2}^{F68}$

A field of $\lg M_0 = f\,(K_{S1.2}^{F68})$ is shown in Fig. 9*a*. As one can see, the dependence between these two characteristics is rather strong. Using equation (1), we normalize the seismic moment values to one energy class level and then compare the average seismic moment values for different zones and eruption periods. These average reduced values ($\overline{\lg M_0^{red}}$ with fixed $K_{S1.2}^{F68} = 9.0$) are shown in Table 2. The maximum values ($\overline{\lg M_0^{red}} = 22.20$) are characteristic of the western Kozyrevsk zone, smaller values (22.01) are characteristic of the Tolud zone and significantly smaller values (21.54) are indicative of the eastern Kozyrevsk zone. In all appearance, the average $\lg M_0$ values depend significantly upon local conditions. At the same time, the average $\lg M_0$ values for the western Kozyrevsk, Tolud and eruption zones (before the onset of eruption) differ insignificantly, whereas a small $\lg M_0$ value for the eastern Kozyrevsk zone seems to be a peculiar regional anomaly.

Of interest are the variations in the average seismic moment values observed in the eruption region (Fig. 10). In the first stage of swarm development (before the July 2, 1975 strong earthquakes) the average values $\overline{\lg M_0^{red}} = 21.91$ differed insignificantly from the regional ones. In the second stage (July 2-6), before the onset of eruption, a small decrease in the seismic moment values (21.85) at a fixed energy class was observed. In the third stage, during the eruption, the decrease in the average seismic moment value (about 21.82) becomes significant at the 0.05 level. Similar differences between the average $\lg M_0$ values at a fixed energy class permit the delineation of the region where the change in physical properties and in stress state of the medium has occurred.

Variations of Stress Drop Values

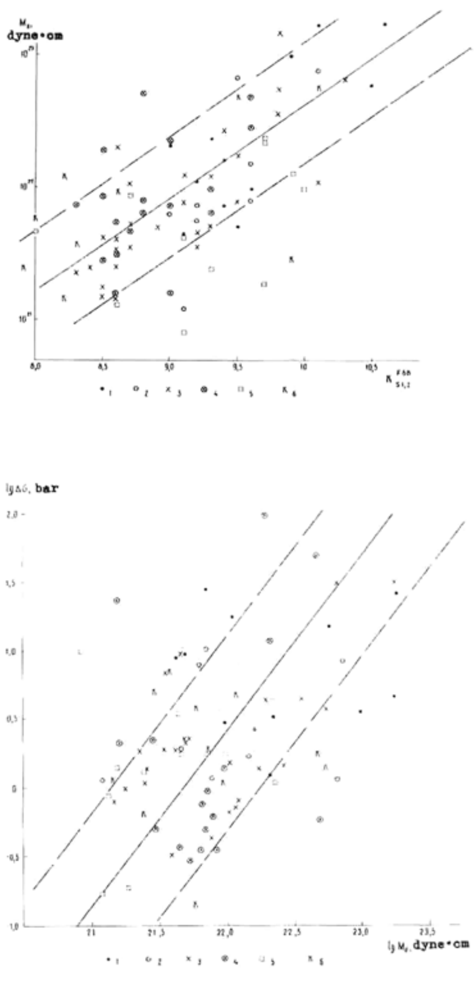
Figure 9*b* shown the field of points of stress drop values $\Delta\sigma$ versus the seismic moment. A line of orthogonal regression is given. However, the correlation between these two values, as it was reported above, is very slight. One can see in Fig. 9 that the $\Delta\sigma$ values of the earthquakes sources in the different zones are distributed practically independently of the seismic moment value. The range of deviations from the average stress drop value for an aindividual zone is half that of deviations from the orthogonal regression line. Therefore, we shall analyse the average $\Delta\sigma$ values for the single zones considering them as independent of M_0 value. Data of Table 2 suggest close mean stress drop value for both the Kozyrevsk and Tolud zones. It varies from the zone to another $\overline{\lg \Delta\sigma} = 0.21$ to $\overline{\lg \Delta\sigma} = 0.27$ and for the region of the Klyuchevskoy volcanic group is equal, on the average to 0.24 ± 0.10. Anomalously large of $\Delta\sigma$ were observed in the region of the forthcoming eruption ($\overline{\lg \Delta\sigma} = 0.84$ that is three times the mean regional estimate). This value changed during the different stages of the eruption preparation and during the eruption itself (see

TABLE 2 — Average source parameters of earthquakes.

Zone	Observational periods	Number of observations	$\overline{\lg M_0^{red}}$ (dyne·cm)	σ	E	$\overline{\lg \Delta\sigma}$, bar	σ	E
Western Kozyrevsk		11	22.20	0.55	0.17	0.23	0.50	0.15
Tolud		18	22.01	0.41	0.10	0.27	0.80	0.19
Eastern Kozyrevsk		12	21.54	0.48	0.14	0.21	0.54	0.15
Tolbachik (eruption region)	27.6-2.7.75	12	21.92	0.31	0.10	0.84	0.43	0.12
	2.7-6.7.75	8	21.85	0.31	0.11	0.45	0.52	0.18
	6.7.75-12.78	28	21.83	0.47	0.09	0.32	0.51	0.10

Fig. 10). After the strong earthquakes of July 2, 1975 it decreased from 0.84 to 0.45 and during the eruption it was 0.33, differing insignificantly from this value in the neighbouring Tolud zone (0.27).

In conclusion, we shall dwell upon the estimates of source characteristics of six large earthquakes recorded in the period 1975-1978 ($m_b \geq 4.5$). The focal mechanism solutions of these earthquakes are shown in Fig. 2. The first two earthquakes occurred on July 2, 1975, marking the turning-point in the development of a swarm preceding the eruption of cone 1. After these earthquakes, a reorientation of the stress system in the earthquakes foci and an abrupt decrease of the stress drop value were observed. Both earthquakes are characterized by a strike-slip type of faulting with minor thrust component; one of the two possible nodal planes for these earthquakes is close to the trend of the eruptive fissure where the active eruption cones formed. The length of rupture during these earthquakes, according to estimate made from P-wave spectra, for dephts of 10-20 km, is 10-15 km. This transcends the length of the eruptive



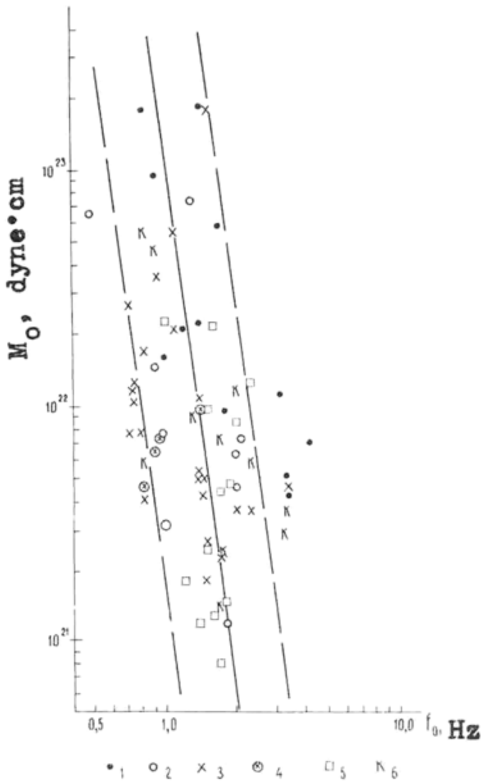


FIG. 10 — Variations of seismic moment M_0 and stress drop $\Delta\sigma$ in earthquake foci during the different eruption stages. 1 - in the region of eruption; 2 - beyond the eruption region. The arrow marks the onset of the large Tolbachik fissure eruption.

fissure at the surface (3 km). Stress drop values for these earthquakes were the largest of any earthquakes of the sequence 1975-1978 (635 bar). One may propose that the rupture zone of these earthquakes formed the conduit up which the magma rose to the surface. Later on, earthquakes of such magnitude were noted within this region only in the final stage of the seismic activity in the two years after the cessation of the eruption in 1978. During that period earthquakes occurred in the periphery of the active zone, in the extreme north the town of Klyuchi and Klyuchevskoy volcano (Feb. 6, 1978) and in the extreme south of the zone, south of the South Vent cone (Oct. 25, 1978), as well as at the eastern boundary of the western Kozyrevsk zone (March 19, 1978) and on the western slope of Plosky volcano (Oct. 6, 1978).

The focal mechanisms of three out of these earthquakes were characterized by the presence of thrust dislocations. Normal faulting was characteristic of the smallest earthquake of this sequence (March 19, 1978). This suggests that after the end of the eruption the periphery of the seismically active zone upheaved, or synonymously, that the area of the active volcanoes subsides. Stress drop values for the four earthquakes were not more than 3-5 bar, *i.e.*, were similar to those of earthquakes of smaller magnitude.

DISCUSSION

The obtained results as well as data reported in GORELCHIK *et al.* (1981) allow ut to consider the peculiarites of seismic processes in the eruption region.

During the period of seismic preparation for the cone I eruption (the fisrt swarm), variations were noted in statistical characteristics of the seismic regime and in source characteristics of earthquake foci. Two stages can be distinguished in the development of the swarm of volcanic earthquakes (June 27-July 5, 1975): the stage before the two strong earthquakes ($M_{LH} = 5$) of July 2 and the subsequent stage up to the onset of eruption. Before the strong earthquakes of July 2 a decrease of the slope of the recurrence graph γ and a simultaneous decrease of the average daily number of earthquake (GORELCHIK *et al.*, 1981) were noted in the region. After the occurrence of the strongest earthquakes, a reorientation of the stress system and a decrease of stress drop values were observed. On the basis of laboratory data and field investigations on different destructive processes (rock destruction, rock impacts, large earthquakes), the decrease in the slope of the recurrence graph during the period before July 2 may be interpreted as the increase of surplus stresses in the region of the future eruption caused by magma and (or) gases moving to the surface. The initiation of the strongest earthquakes on July 2 seems to be associated directly with the formation of the eruptive fissure. This process leads to a gradual accumulated strain release which is accompanied by the increase of coefficient γ, against the background of which the eruption occurs. A decrease in stress drop values indicated by the increase of predominant periods of seismic wave radiation, showed that the medium inside which earthquake foci were concentrated, became more heterogeneous with lower effective elastic moduli.

The predominat tension stress orientation changed little in time, whereas the predominant compression stress orientation changed significantly. A steady tension stress orientation, in our opinion, suggests that the magma intrusion occurred within one fissure (or single fissure system) which, wedging apart by the supplying magma was affected practically by one-trend tension. At the same time, the conspicuous compression stress reorientation may indicate that the direction of magma intrusion changed with its approach to the surface. In all appearance, the magma intruded first vertically, then, after the formation of the main rupture during the July 2 strong earthquakes, the magma began to intrude in an inclined fashion (or horizontally) filling the feathering fissures that led to the change in compression stress orientation. After the onset of eruption the magma supply to the surface occurred predominantly vertically, just as in the first stage of seismic preparation. This has led to the restoration of the initial stress system.

One can see in Fig. 10, that the stress drop values for earthquakes in the eruption region during the eruption preparation were relatively large, but after the onset of eruption they became comparable to those of earthquakes beyond the eruption region. A study of variations in stress drop values in small earthquakes before the initiation of large earthquakes (ZOBIN 1980), reveals that 1.5 or 2 years before the large earthquake of magnitude $M = 7.7$, the increase in stress drop values is observed for small foreshocks and after the occurrence of the large earthquake, the stress drop values decrease again to normal. Apparently, the preparation processes for the large earthquake and for the volcanic eruption are similar in many respects.

CONCLUSIONS

1. The large Tolbachik fissure eruption, 1975-1976, was preceded and accompanied by intense seismic activity. The eruption has triggered an abrupt increase in seismicity throughout the region of the Klyuchevskoy volcanic group.

2. During the development of a swarm of volcanic earthquakes the cone I eruption, and after the large July 2, 1975, earthquakes, a stress system reorientation occurred. Simultaneously, stress drop values for earthquakes in this zone decreased strongly from previously high values. In the course of the eruption these characteristics became similar to mean regional values.

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Ms. received Jan. 1982; sent to review Jan. 1982. Revised and accepted March 1982.