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Seismic Events Associated with the 1996 Volcanic Eruptions in the Karymsky Volcanic Center

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A study of the seismicity that preceded and accompanied eruptions in the Karymsky volcanic center revealed a relationship between the seismic processes caused by local tectonic movements and volcanic eruptions at Karymsky Volcano and in the Akademii Nauk caldera. The Karymsky eruption triggered the large (magnitude 7.0) Karymsky earthquake of January 1, 1996. This crustal tectonic earthquake reactivated a fault, through which magma began to rise and this magma was erupted in the Akademii Nauk caldera in the northern part of Lake Karymskoe. The distribution of hypocenters showed that there was an anomalous volume of rock beneath Karymsky Volcano, whose properties indicated that it was a magma chamber. The top of the chamber was at a depth of 4-5 km.

INTRODUCTION

Detailed studies of Kamchatka and Komandorskie Islands seismicity started in 1962, when a regional network of seismographic stations was established. The resulting earthquake catalog contains over 50,000 events which have occurred since 1962, making it possible to determine many of the spatial and temporal features of seismic processes that are

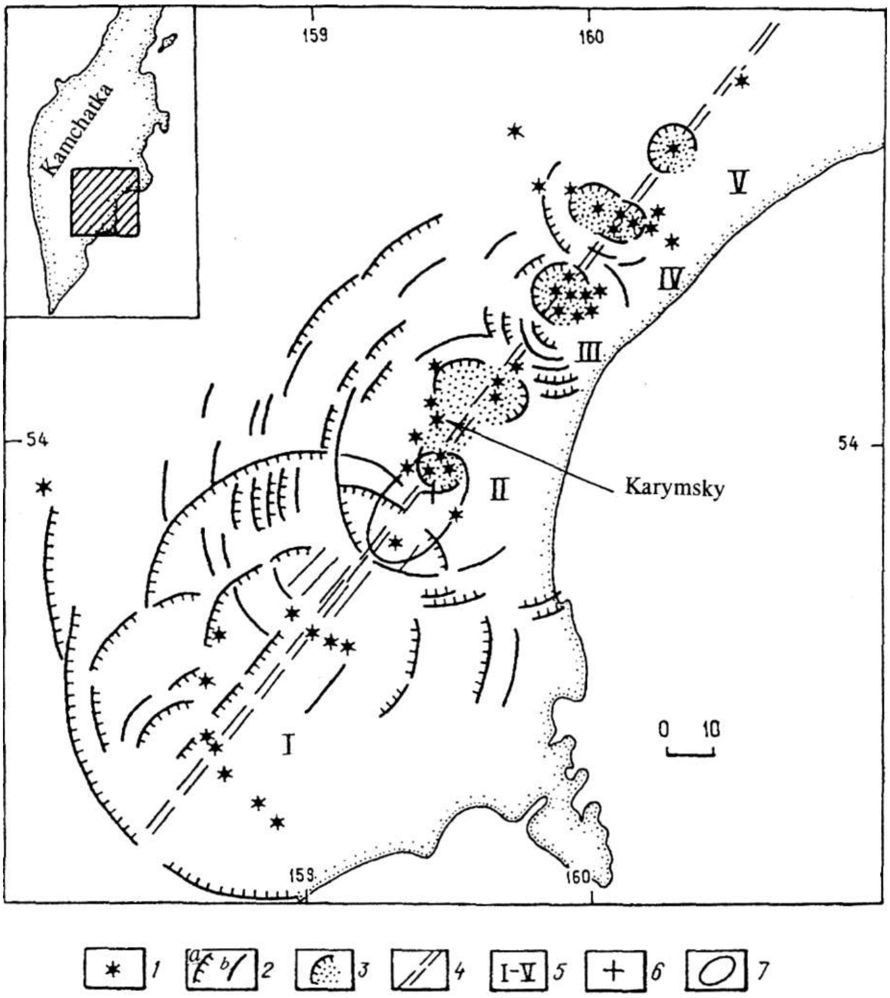

Figure 1 Schematic tectonic map of the central segment of the East Volcanic Belt, after V. L. Leonov: *1* - Quaternary volcanoes; 2 - faults (*a* - vertical slip, *b* - fissures); *3* - late Quaternary calderas; *4* - axis of a deep-seated magma-channeling fault; J - volcanic centers (I - Nalachevo, Π - Karymsky, in - Bolshoi Semyachik, IV - Uzon-Geiser, V - Krasheninnikov); ***6*** **-** location of the instrumental epicenter for the January 1, 1996, earthquake; 7 - source zone of the latter.

occurring in the subduction zone and in continental Kamchatka. The spatial geometry and fine structure of the subduction zone were improved using the distribution of hypocenters [14], [15], [22]. Most of the earthquakes occur in the Benioff zone, with the deepest hypocenters being at 650 km. Earthquakes also occur in continental Kamchatka, but they

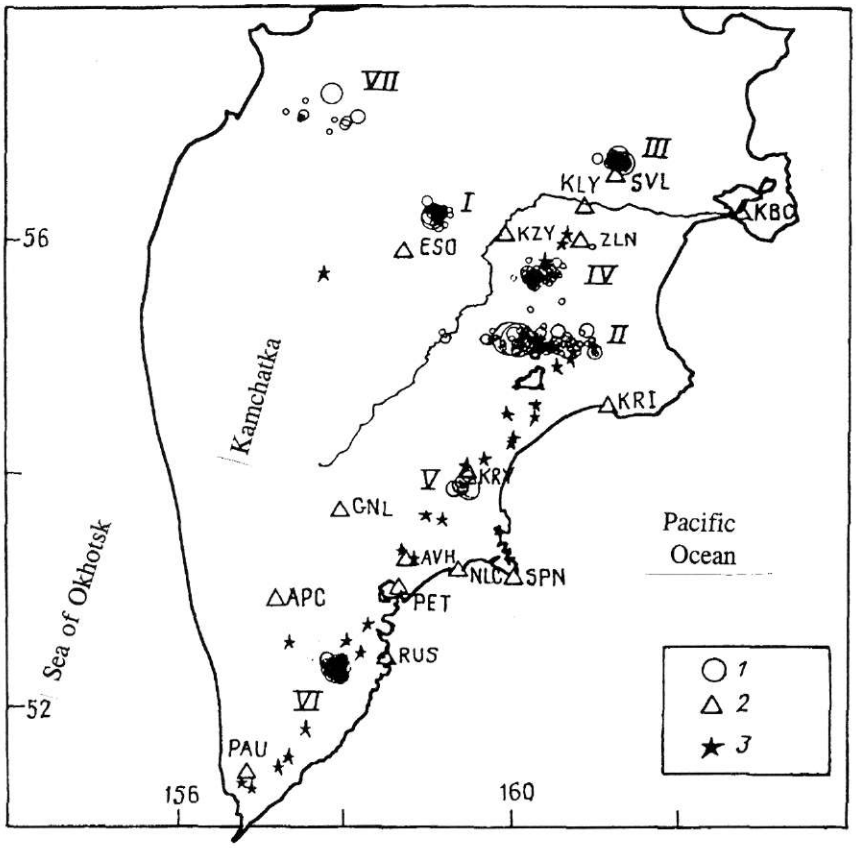

Figure 2 Epicenter map for earthquake swarms in continental Kamchatka: *1* – epicenter; *2* – seismic stations: ESO – Esso, SVL – Shiveluch, KLY – Klyuchi, KZY – Kozyrevsk, ZLN – Zelenaya, KRY – Karymsky, SPN – Shipunsky, NLC – Nalychevo, AVH – Avacha, PET – Petropavlovsk, GNL – Ganaly, APC – Apacha, RUS – Russkaya, PAU – Pauzhetka, KBG – Krutoberegovo, KRI – Kronoki; *3* – volcanoes. Earthquake energy classes are as indicated in Fig. 3.

are much fewer than in the Benioff zone, and are mostly associated with volcanic activity. Almost all of the large eruptions are accompanied by swarms of numerous volcanotectonic earthquakes. In contrast to the subduction zone, where the earthquake magnitudes may be as high as 8.5-8.6 (the largest possible worldwide), generated volcanotectonic earthquakes in continental Kamchatka have magnitudes less than or equal to 6.0 and are confined to the upper 50 km of the crust. Viewed in this context, the magnitude 7.0 earthquake that occurred on January 1, 1996, in the Karymsky volcanic center, and simultaneous eruptions at Karymsky Volcano and in the Akademii Nauk (Academy of Sciences) caldera, were unusual and rare events.

Table 1 Parameters of earthquake swarms in continental Kamchatka.

Swarm no.	*Date*	*Coordinates, deg* град		*Number of events*		*Maximum*		*Area*
		N lat	E long	K ≥ 8,5	K ≥ 10,5	*class*	*magnitude*	
I	20.11.1962– 18.02.1963	56,0–57,0	158,8–160,0	27	5	12,4	4,8	Esso Vil.
II	02.04.1963– 14.09.1963	55,0–55,5	159,0–161,0	108	8	14,4	6,0	Shchapina R.
III	02.11.1964– 11.11.1964	56,5–57,0	161,0–162,0	64	13	12,3	5,5	Shiveluch Vol.
IV	27.06.1975– 05.07.1975	55,3–56,0	160,0–161,0	73	6	11,0	4,7	Tolbachik Vol.
V	25.01.1978– 23.02.1978	53,5–54,2	158,9–159,8	15	5	12,7	5,4	Karymsky Vol.
VI	07.03.1983– 08.04.1983	52,0–52,5	157,0–158,0	212	13	11,8	4,6	Asacha Vol.
VII	10.06.1990– 14.06.1990	56,5–57,5	157,0–159,0	11	2	11,6	4,9	Tigil Vil.
VIII	01.01.1996– 20.02.1996	53,5–54,2	158,9–159,8	459	34	14,3	7,0	Karymsky Vol.

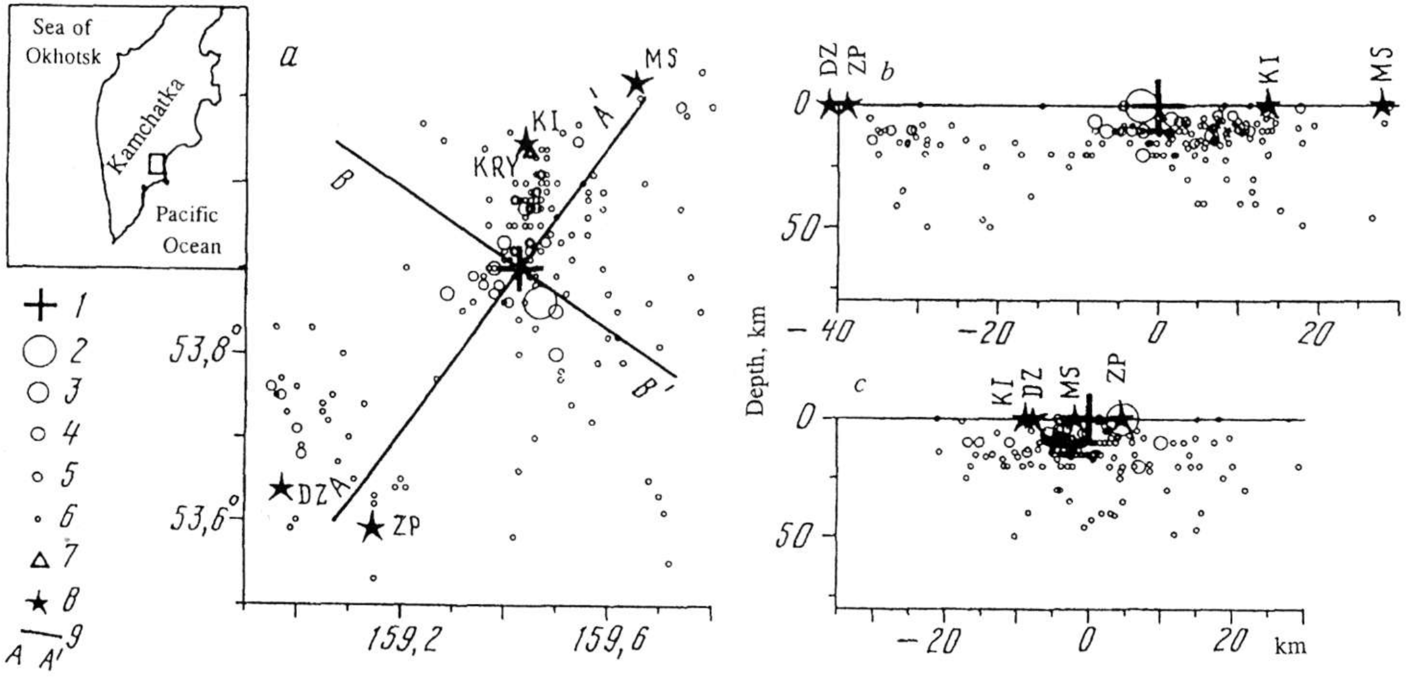

Figure 3 Epicenter map (*a*) and vertical cross-sections along lines A–A′ (*b*) and B–B′ (*c*) for the area of Karymsky Volcano, 1962–1994 (K≥7.5): *1* – epicenter of January 1, 1996, earthquake; 2–6 – earthquake epicenters (values of classes: *2* – 13, *3* – 12, *4* – 11, *5* – 10, *6* – 8 and 9); *7* – seismic stations; *8* – volcanoes (MS – Malyi Semyachik, KI – Karymsky, DZ – Dzenzur, ZP – Zhupanovsky); *9* – lines of vertical cross-sections which coincide with the directions of the longer and shorter axes of the January 1, 1996, source zone.

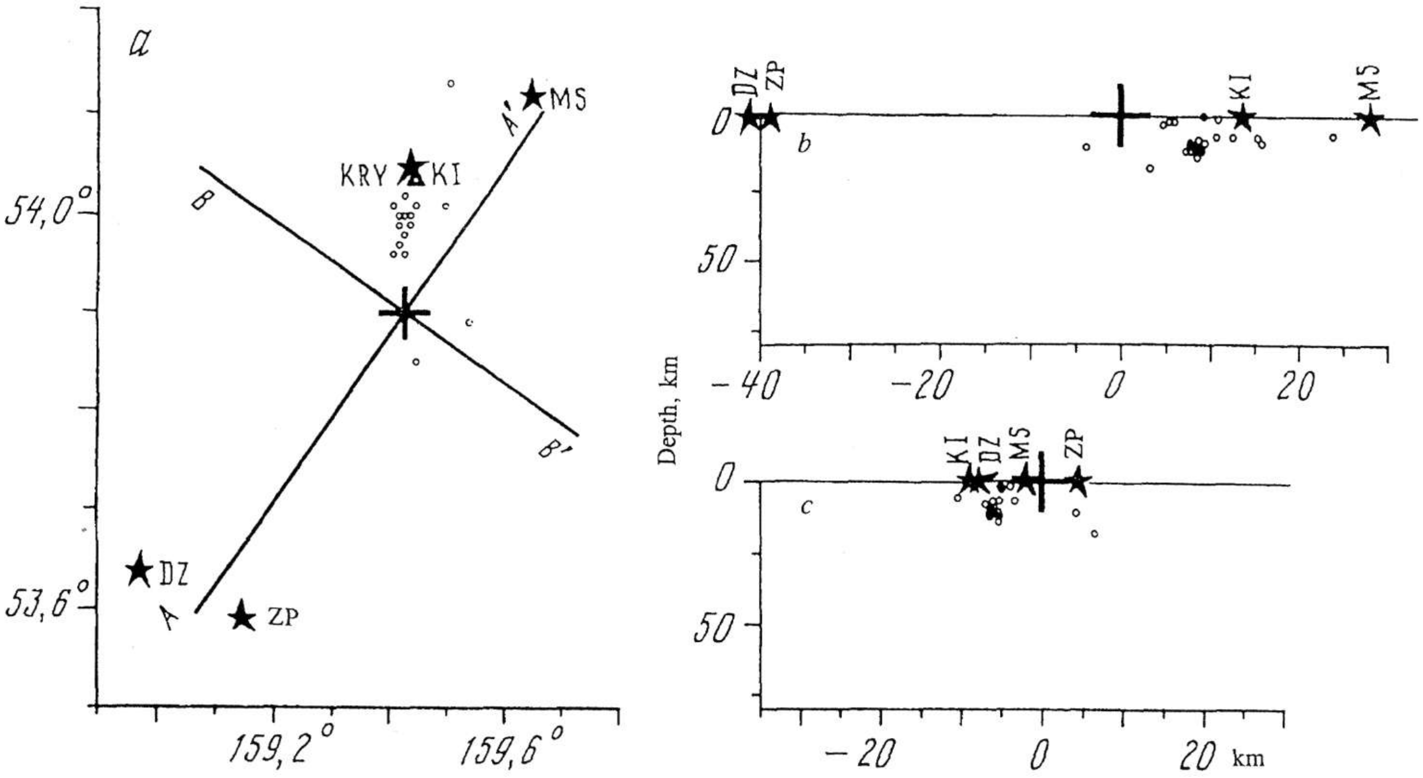

Figure 4 Epicenter map (*a*) and vertical cross-sections (*b* and *c*) for earthquakes that occurred in the Karymsky area during 1995 (K ≥ 7.5). The notation is as in Fig. 3.

Seismicity has been studied in the Karymsky area since 1962, when the Kamchatka regional seismic network was set up. A seismic station was set up in the Karymsky area during the last major eruption (1969-1972), and the volcano's seismicity has been monitored since that time [11], [12], [18], [20]. At present all of the hypocenters are located in the Karymsky area, starting from energy class eight (on the Fedotov scale [13]).

The present paper reports a study of spatio-temporal characteristics of the seismicity that preceded and accompanied eruptions at Karymsky Volcano and in the Akademii Nauk caldera based on data from routine recordings by the regional seismic network and on observations of temporary seismograph networks carried out in August 1996 with the aim of promoting Russian-Japanese cooperation in the geosciences.

TECTONIC SETTING OF THE KARYMSKY AREA

Karymsky Volcano, one of the most active in Kamchatka, is situated in the central segment of the Eastern Volcanic Belt. This segment of the belt has several features that distinguish it from the other volcanic areas of Kamchatka. Its Quaternary volcanoes are situated within a major depression (also known as a graben-syncline, after Erlikh [21]) and are confined to the central parts of dome-ring structures (volcanic centers) that partially overlap one another forming a chain trending northeast (see Fig. 1) [4], [7]. In a north-easterly direction, the dome-ring structures steadily decrease in diameter and become closer to one another. These structures are replaced by ordinary volcanic edifices at the north-eastern end of the chain. A deep-seated fault passes along the axis of the chain. This fault was defined by many workers as a magma conduit [7], [8], [19]. In the south-west of the area the fault is expressed at the surface as an elongate graben which controls the positions of numerous thermal springs. The graben was named "Thermal Rift" by Masurenkov *et al.* [7], [8], [9]. The surface expression of the fault over all of its length is a dense network of recent minor faults and fissures. It resembles an extensional fault [3], [17], and contains several late Quaternary calderas which also too form a north-east-striking chain (see Fig. 1). The faults and calderas become progressively younger from south-west to north-east. There are also some transverse faults, which complicate the structure of the area. The faults can be followed at the surface as transverse chains of volcanoes. Most of these faults strike north-west, whereas the direction of the Karymsky faults is north-south.

GENERAL CHARACTERISTICS OF SEISMICITY OBSERVED IN CONTINENTAL KAMCHATKA

The seismicity of continental Kamchatka is characterized by swarms of earthquakes generally confined to the areas of active volcanoes. Figure 2 shows an epicenter map for

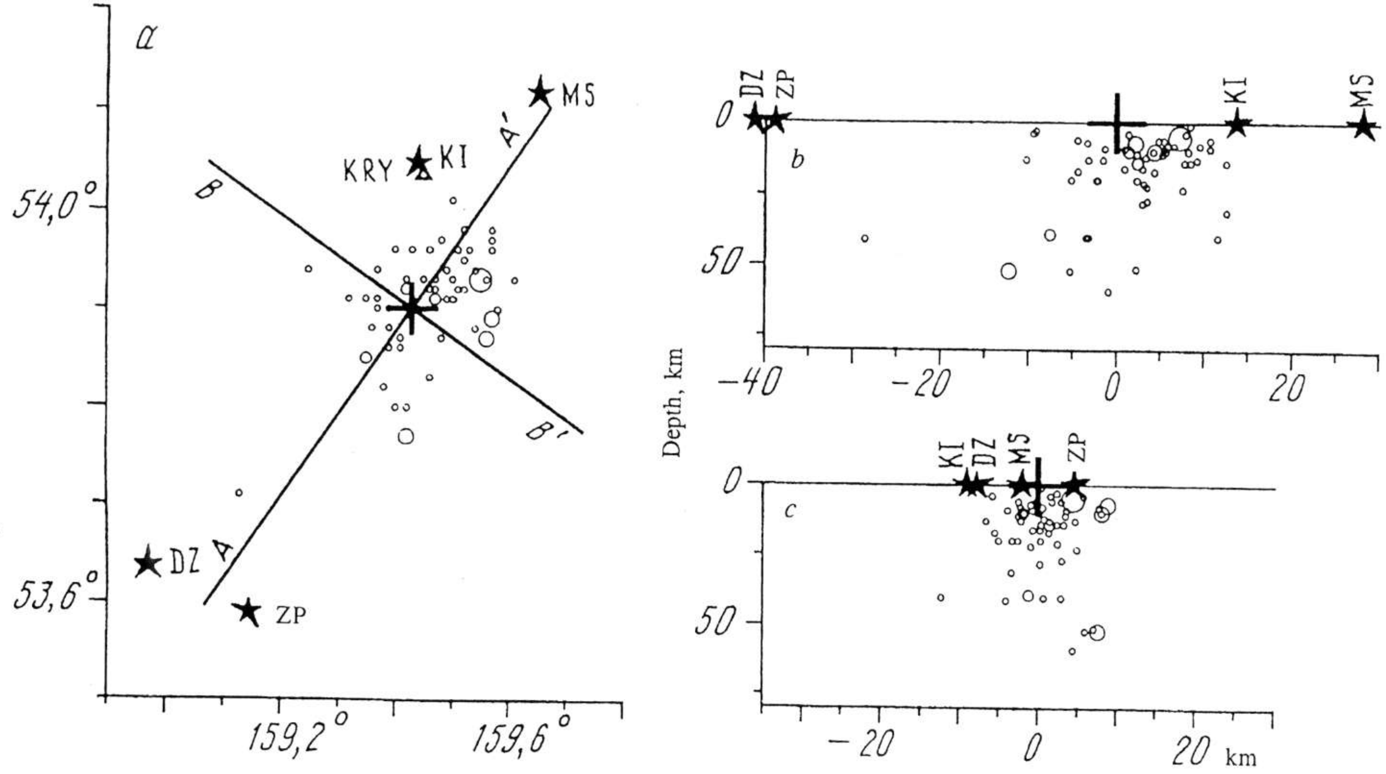

Figure 5 Epicenter map of foreshocks (*a*) and vertical cross-sections (*b* and *c*) for January 1, 1996 (K ≥ 7.5). The notation is as in Fig. 3.

major (K_{max}>11.0) earthquake swarms in continental Kamchatka for the 1962-1995 observation period. Table 1 lists comparative parameters of the swarms shown in Fig. 2. Swarms I, II and VII took place far from active volcanoes; all earthquakes in these swarms occurred within the crust and were caused by local tectonic processes. The largest event (M=6.0) belonged to swarm II (see Fig. 2 and Table 1).

Swarms III-V were related to volcanic activity. Swarm III preceded the 1964 catastrophic eruption at Shiveluch Volcano. Swarm IV both preceded and accompanied the great Tolbachik fissure eruption of 1975-1976. Swarm V occurred during the active phase of the 1978 effusive-explosive eruption at Karymsky Volcano. A swarm of this kind usually lasts a long time, grows in intensity before the eruption, and contains many large events of nearly the same size. The origin of these earthquakes, which are usually called volcanotectonic, is related to tectonic processes beneath active volcanoes due to magma injection. The largest event in such a swarm usually does not exceed magnitude 5.5. An earthquake of this magnitude occurred in a swarm that preceded the catastrophic Shiveluch eruption (see Table 1). The only swarm (VI) of volcanotectonic earthquakes that was not followed by any volcanic activity took place in the area of Asacha Volcano (see Fig. 2 and Table 1).

The observed features of the swarms of tectonic and volcanotectonic earthquakes, which were recorded in continental Kamchatka during a period of detailed seismological observation, suggest that the earthquakes that began in the area of Karymsky Volcano on January 1, 1996, and are still continuing to occur, are unique events (Table 1, swarm VIII). First, the largest earthquake in this sequence had a magnitude of 7.0 and was the largest event ever recorded in continental Kamchatka during the period of instrumental seismological observation. Secondly, the events occurred as a foreshock-aftershock sequence with the following typical features: the main shock was preceded by a series of foreshocks, the largest subsequent events were smaller by more than one magnitude unit (the largest aftershocks had magnitudes of 5.5), the exponent in the Omori law ($N = N_0T^a$) was close to the average value for Kamchatka as a whole (a = 1.03), and most of the aftershocks occurred during the first three days.

The seismicity of the Karymsky volcanic center during the preceding period of 1962 to 1994 consisted of both discrete events and swarms (Fig. 3), the largest swarm occurring in January-February 1978 (see Table 1) [2], [6], [18]. The epicenters of the earthquakes that occurred in the area of Karymsky Volcano during that period were located 10-15 km south of the volcano and followed the pattern of the regional fault system (see Fig. 1). The seismicity in the Karymsky area over the year prior to the January 1, 1996, earthquake was low; the earthquakes were concentrated south of the volcano at depths greater than 18 km, actually beneath Lake Karymskoe (Fig. 4). Some small groups of energy class 8-9 earthquakes occurred in March, May, and July. In 1995 the Karymsky station (KRY) which is the closest to the volcano (1.4 km from the summit) recorded a considerable number of volcanotectonic earthquakes with *S-P* times between 1.0 and 1.5 s.

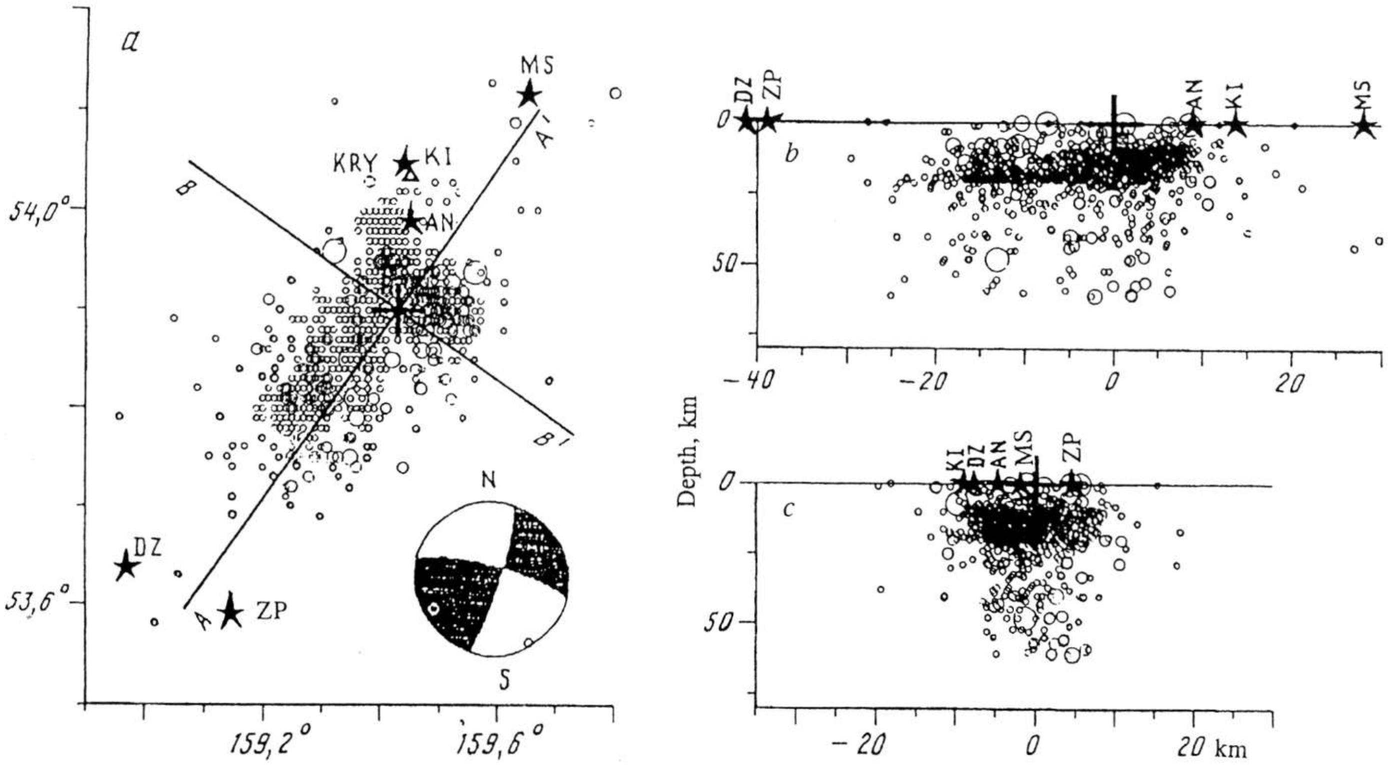

Figure 6 Epicenter map of aftershocks (*a*) and vertical cross-sections (*b* and *c*) for the period of January 1 to February 20, 1996 (K ≥ 7.5). The notation is as in Fig. 3. AN indicates the eruption in the Akademii Nauk caldera. The diagram shows the focal mechanism of the January 1, 1996, earthquake.

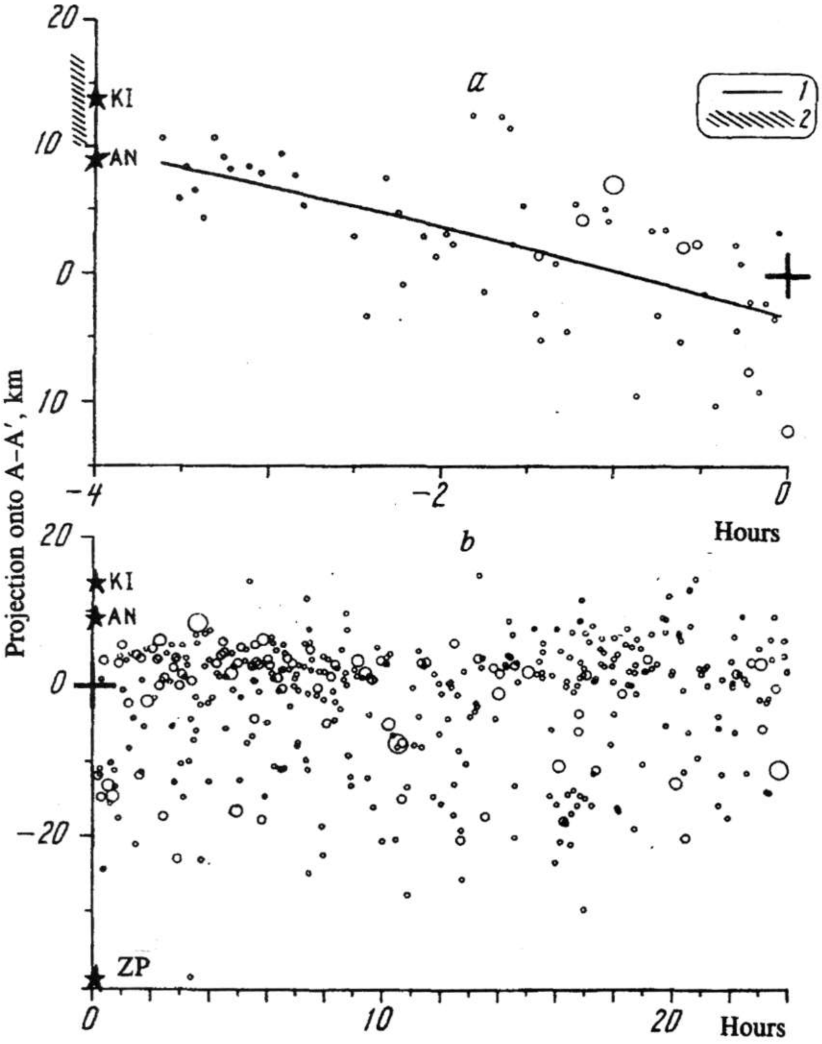

Figure 7 Variation of earthquake projections on to the A–A′ line over time: *a* – January 1, 1996, from 6 hr to the time of the large earthquake; *b* – over the 24 hr after the earthquake occurred (K≥7.5). The notation is as in Fig. 3. AN indicates the projection of the eruption in the Akademii Nauk caldera; *1* – regression line; *2* – projection of micro-earthquakes recorded at KRY from 4 hr to 6 hr of January 1, 1996 (GMT).

FORESHOCKS AND AFTERSHOCKS OF JANUARY 1. 1996. EARTHQUAKE

The area of where the earthquake was to occur began to be active a few hours before the main shock. Earthquakes as large as energy class 12 occurred almost over the entire source zone of the future main shock (Fig. 5). Four earthquakes larger than energy class 11 (M >4.5), which were foreshocks of the main event, occurred during the last hour before the main event. The maximum foreshock magnitude was 5.2 (see Fig. 5). Because of the high level of seismic signals at the closest seismic station (KRY), the records of this station could not be used to locate the earthquake. This reduced the reliability of earthquake recording in the area and gave rise to large errors in hypocenter depths. For example, Fig. 5 shows some events at depths of about 50 km, which probably resulted from hypocenter location errors. Similar errors in hypocenter depths were observed in the aftershock location, when the KRY data were not used because of the high seismicity level there (Fig. 6).

The foreshock process was evolving in time, as shown in Fig. 7, a. The movement of epicenters is displayed as a projection on to the AA' line (see Fig. 5) from 6 hr of January 1 till the instant of the main shock which occurred at 9 hr 57 min (Greenwich mean time here and below, Kamchatkan time being 12 hr more). It can be seen in Fig. 7, *a* that the foreshock process started at the northern edge of the source zone, the epicenters then gradually moving southward in the direction of the instrumental main-shock epicenter. The aftershocks of the first few hours following the main shock filled almost all of the source zone (Fig. 7, *b).*

To sum up, the Karymsky earthquake occurred at 9 hr 57 min 45.6 s on January 1, 1996. The instrumental epicenter was at 53.90°N, 159.43°E, the focal depth, as determined from data from the Kamchatkan regional seismographic network was 0 km. The S-wave energy class was K = 14.3 on the Fedotov scale [13], the magnitude was $M_s = 7.0$ (as listed in the catalog of the Experimental Seismological Expedition, Joint Institute of Physics of the Earth, Russian Academy of Sciences). The location uncertainty was 3 km for the epicenter position and 2 km for the focal depth.

Figure 6 shows a map of aftershocks and cross-sections for hypocenters projected onto the AA' and BB' lines for the January 1-February 20, 1996, for earthquakes of energy class greater than 7.5. In all, 459 earthquakes of energy class higher than 8.5 occurred from January 1 to February 20, 1996 in the source zone; 323 of these events took place on January 1-2. The total number of events with energy class greater than 7.5 was 1000 (see Table 1). The aftershock process as a whole had terminated by January 20; some single earthquakes of energy class <= 10 occurred in the source zone during the next 12 months. Figure 8 shows the plots of the total number of events and the energy released in the source zone, both for the entire period of detailed seismological observation (a) and for January 1, 1996 (b). One can see that the foreshock-aftershock process developed in a regular way over time, as reflected in the accumulated number of events.

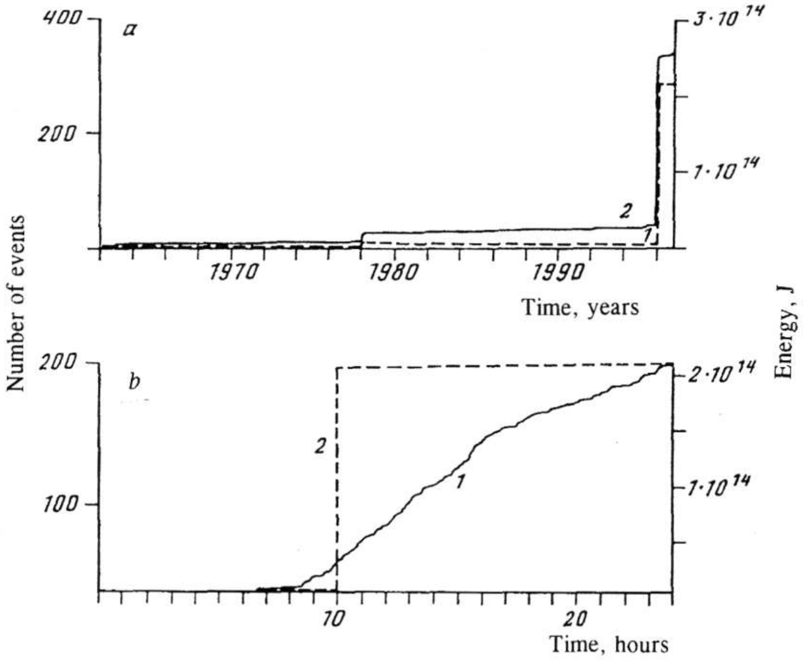

Figure 8 Cumulative plots of the number of earthquakes (*1*) and the energy released in the main-shock zone (*2*): *a* – for the period 1962–1996, *b* – for January 1, 1996 (K≥9.0).

The first-day aftershocks were used to delineate the source zone. This was an ellipse elongated in a NE-SW direction, with axes of 30 km and 15 km, located 10-15 km south of Karymsky Volcano (see Figs 1 and 6). The main shock epicenter is displaced north-east away from the center of the ellipse. To determine the vertical size of the source volume more reliably we used only those hypocenters whose locations were based on KRY data. Figure 9, *b* and c shows cross-sections for these aftershocks. It can be seen that most of the aftershocks occurred at <=20 km depth. To sum up, the source volume of the January 1, 1996, Karymsky earthquake had a size of 30 x 15 x 20 km, which is consistent with the average source dimensions of crustal tectonic earthquakes with magnitudes around 7.0. The aftershock area of the January 1, 1996, earthquake coincided with the source area of the earthquakes that had occurred there over the last 33 years (see Figs 2 and 3), and were associated with tectonic movements.

The mainshock focal mechanism inferred from the distribution of P-wave first motions as recorded by the Kamchatkan regional network, as well as by stations of the world network, is shown in Fig. 6. The construction was done on the lower hemisphere. The

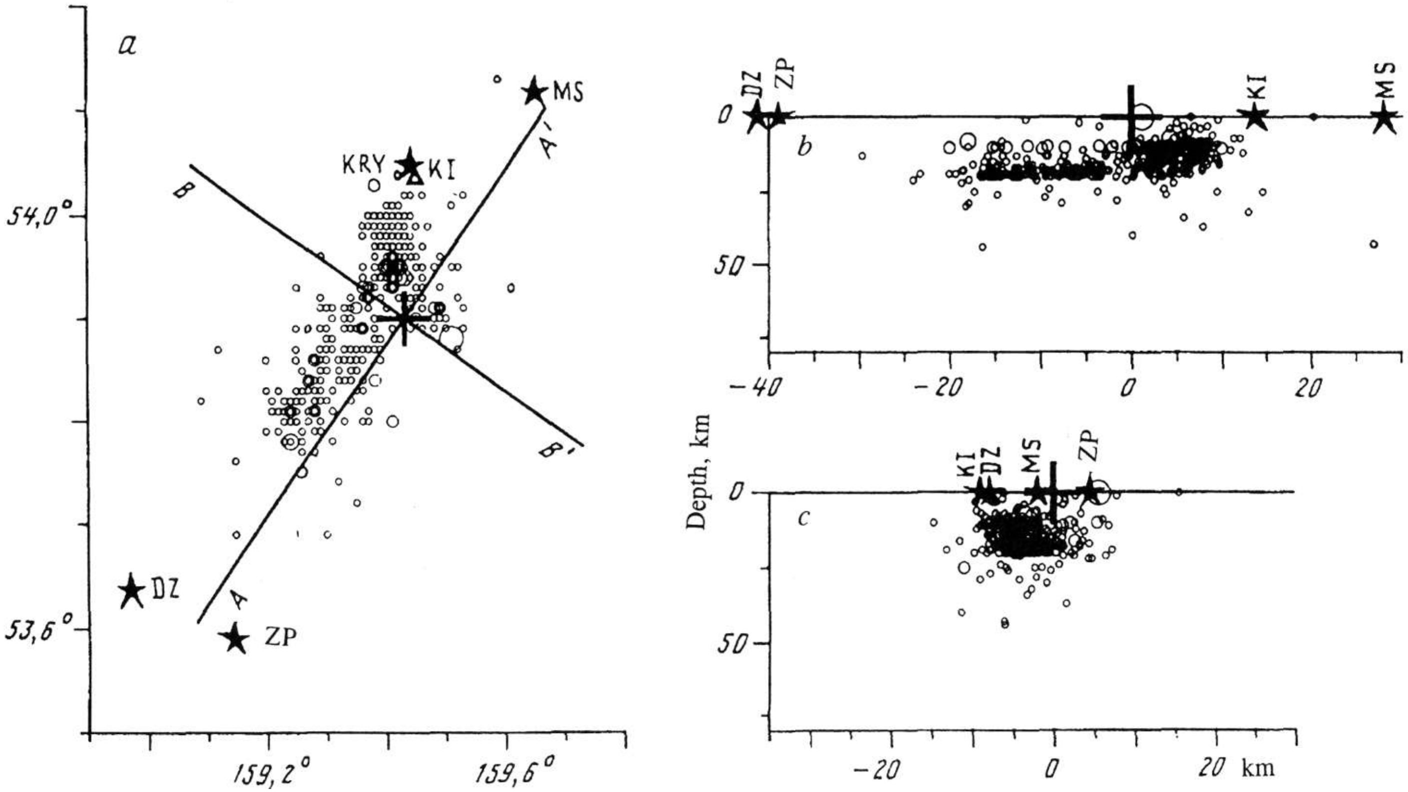

Figure 9 Epicenter map (a) and vertical cross-sections *(b* and c) for earthquakes whose location involved KRY data (K>=7.5). The notation is as in Fig. 3.

source parameters are listed in Table 2. The extension and compression axes were nearly horizontal. The movement was strike-slip with some reverse component. The nodal plane, which strikes north-east, has been chosen as the rupture plane. The associated movement was left-lateral strike slip. The trends of the ruptures and fissures that are located in the area where a new crater was formed in the Akademii Nauk caldera, were in overall satisfactory agreement with the rupture plane, based on the focal mechanism. A detailed description of ground-surface deformation between the Karymsky and Akademii Nauk calderas is given in [5].

Table 2 Mechanism of January 1, 1996 earthquake.

Principal stress axes	*PL*	*AZM*	*Nodal plane*	I	II
T	16	238	STRIKE	282	14
P	4	147	DIP	76	81
N	74	45	SLIP	171	14

Note. I and II are nodal plane numbers.

FORESHOCK SEISMICITY AND DEVELOPMENT OF VOLCANIC ERUPTIONS

Nearly simultaneously with the January 1, 1996, earthquake, volcanic eruptions took place in the central crater of Karymsky Volcano and in the northern part of Lake Karymskoe near the source of the Karymskaya River. A spatial difference between the main-shock source zone and the positions of Karymsky Volcano and the new crater in the Akademii Nauk caldera (Fig. 6), suggests that this tectonic earthquake and the volcanic eruptions were separate events. At the same time, the fact that these events followed one another indicates that they must be related in a more complex manner than a direct relationship. Of particular interest is the commencement of these processes, especially the foreshock. As has been shown (see Figs 5 and 7), quite a number of earthquakes occurred in the source area of the main shock about 4 hours before it, the largest of these events having energy class of about 12. At the same time, observations at KRY, the closest seismic station, revealed that micro-earthquakes had started 8 hours before the main shock in the area of Karymsky Volcano with typical *P* and *S* time differences of around 1 s. The rate of these micro-earthquakes gradually increased until they formed a continuous seismic background, so that the KRY data became unusable (Fig. 10). The micro-earthquake hypocenters were located using the distribution of *S-P* times and the polarization of P-wave first motions. For this purpose we chose micro-earthquakes that were recorded at KRY, for which we could determine the arrival times of compressional and shear waves. The average difference between the *P* and *S* arrival times was 0.95 s, the standard

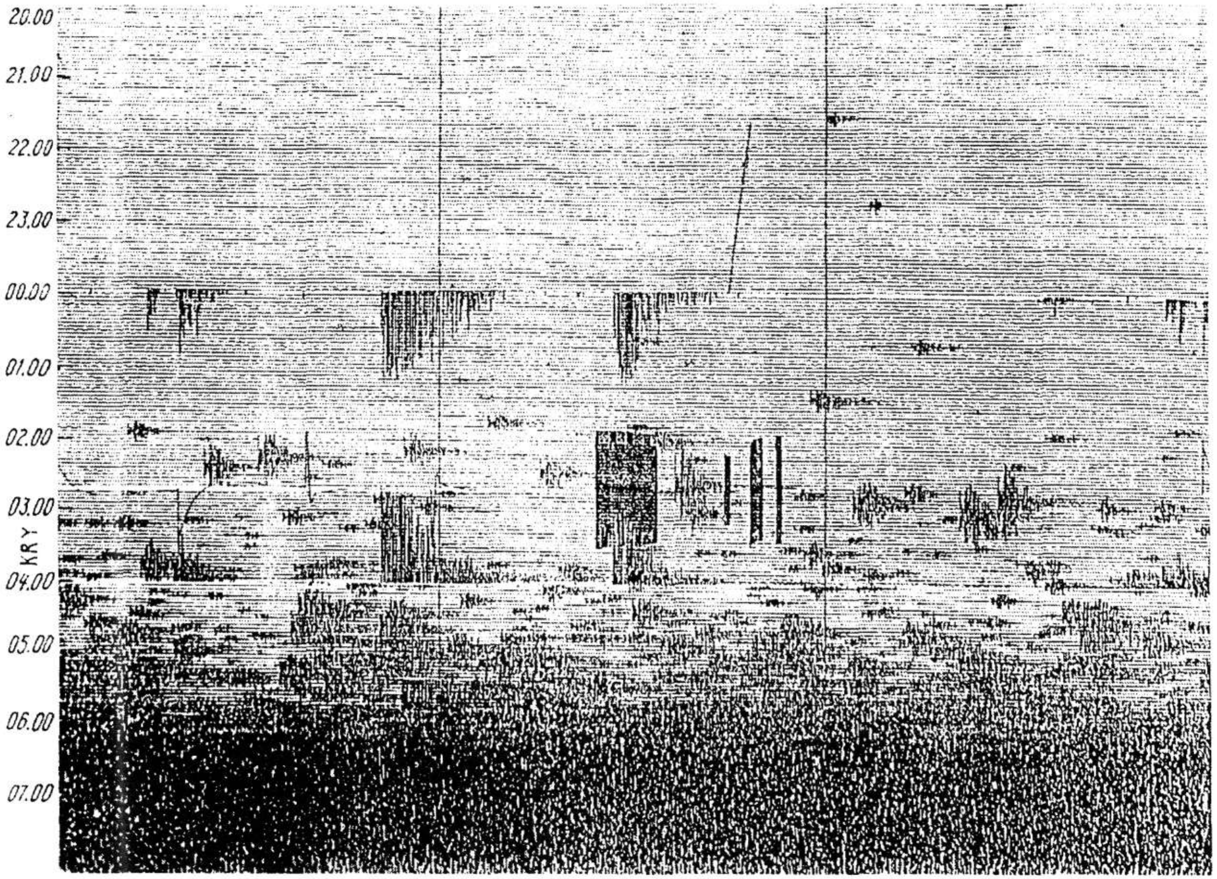

Figure 10 Seismogram recorded at station KRY (Z-component) during the time from 20 hr of December 31, 1995, to 8 hr of January 1, 1996.

deviation being within <= 0.1 s. This stable value may mean that all of the micro-earthquakes were derived from the same location. We had to assume a value of compressional wave velocity and the ratio between compressional and shear wave velocities to be able to locate the hypocenters. According to numerous estimates, the compressional wave velocity in the shallow subsurface of the Earth's crust, for areas of present-day volcanism is not likely to exceed 3 km/s [1], the common assumption for the velocity ratio being 1.73. Using these values, the maximum distance at which the micro-earthquake hypocenters might be situated was estimated to be about 4 km, while its scatter due to possible variations in the time difference between the arrival times of compressional and shear waves was within 400 m. Hypocenter locations could be determined more accurately using the polarization of P-wave first motions. Figure 11, a shows an example of three components of a typical micro-earthquake recorded at the KRY station a few hours before the main shock. The nearly vertical direction of P-wave first motion, indicates that the event occurred almost beneath the station. Figure 12, *a* presents a map of micro-earthquake epicenters which were located from the polarization of compressional first motions, assuming the compressional wave velocity to be 3 km/s and the ratio of compressional to shear wave velocity to be equal to 1.73. Figure 12, *b* and *c* shows the distribution of micro-earthquake hypocenters with depth, as projected on to the AA' and BB' lines. The hypocenters are situated as a compact cluster at a depth of about 3 km under the south-eastern slope of Karymsky Volcano.

It can thus be concluded that the micro-earthquakes began to occur almost 8 hours before the main shock. The fact that the events had their hypocenters beneath Karymsky Volcano may indicate that they were initiated by magma injection. The spectra of the micro-earthquakes are typical of volcanotectonic earthquakes, i.e. they have a dominant frequency at about 10 Hz (see Fig. 11, *b).*

The subsequent evolution of the volcanic processes is unfortunately based on conjectural reconstructions and rather uncertain evidence on the outbreak of eruptions at Karymsky and in the Akademii Nauk caldera. Because the main shock at 9 hr 57 min completely overwhelmed the KRY seismic station, we could not determine the exact time of the inception of the Karymsky eruption; this could have been found from the arrival of the characteristic low-frequency seismic signals which always accompany crater explosions. Eye-witness evidence from persons who were a few tens of kilometers from Karymsky Volcano indicated the evening of January 1 as the start of the summit eruption. The eruption in the Akademii Nauk caldera was reckoned by eye-witnesses to have begun on January 2, between 11 and 14 hr local time [10], [16].

The sequence of events thus seems to be as follows: firstly the beginning and development of micro-earthquakes beneath Karymsky Volcano at a depth of about 3 km, which was caused by magma intrusion into the conduits of the volcano; secondly, premonitory seismicity in the source zone of the main shock; eruption of Karymsky Volcano and the main magnitude 7.0 tectonic earthquake; and thirdly, an eruption in the Akademii Nauk caldera.

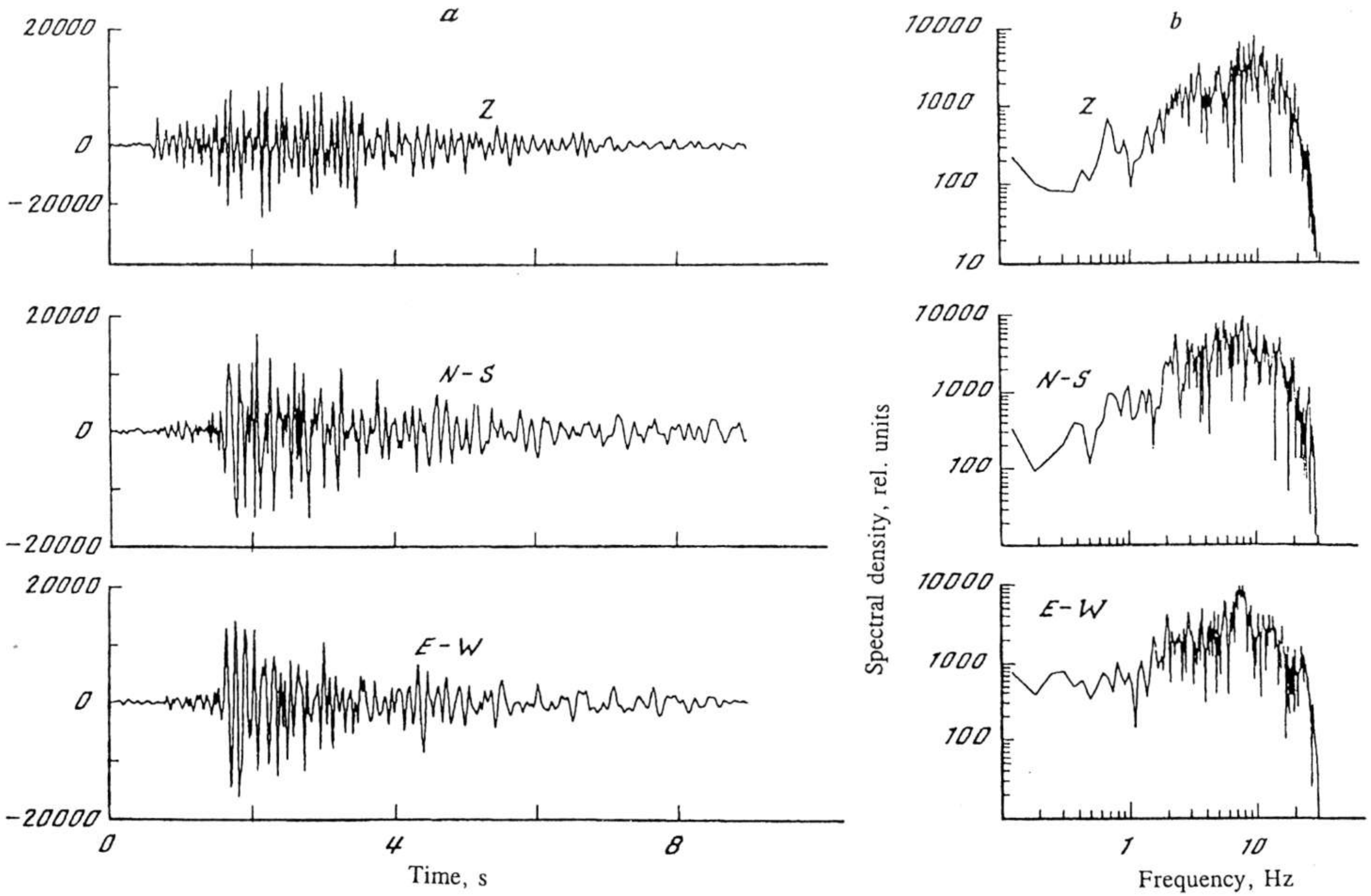

Figure 11 Sample records at KRY (*a*) of a typical micro-earthquake on Karymsky Volcano and the associated spectra (*b*).

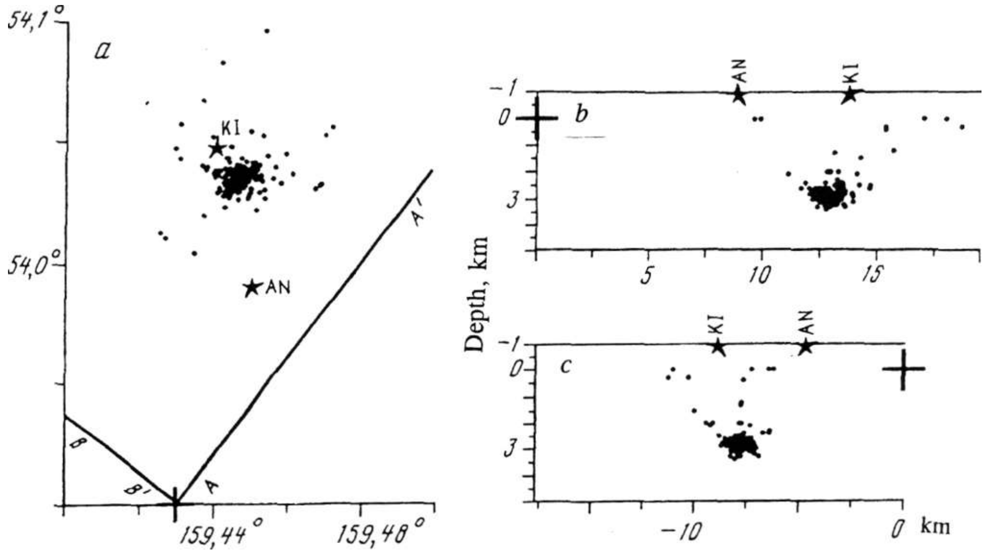

Figure 12 Epicenter map for micro-earthquakes on Karymsky Volcano (a) and vertical cross-sections of hypocenters: *b* - for A-A'; *c* - for B-B'.

RELATIONSHIP BETWEEN VOLCANIC AND TECTONIC PROCESSES

For the purpose of the exact location of the main-shock source zone and the estimation of the seismicity associated with the Karymsky eruption, we carried out observations using a dense network of seismographic stations installed at eight sites, with a maximum distance between them of about 10 km. Figure 13, a shows the network and the epicenters of the earthquakes recorded in August 1996. The cross-sections of hypocenter distributions with depth (Fig. 13, *b* and c) are in good agreement with the location of the magnitude 7.0 main-shock source zone (see Fig. 6, *a).* This agreement confirmed that the earthquake location, based on data from the Kamchatka regional seismograph network, was reliable. The more accurate location of earthquakes based on data from August 1996 new local network revealed some particular features of the source zone of the Karymsky earthquake. First, there was no seismic activity beneath Karymsky Volcano except for a small cluster of earthquakes at 3-4 km depth (see Fig. 13, *b);* this cluster seems to have been related to magma movement, because lava was still flowing from the Karymsky summit crater in August 1996. (Low seismicity beneath Karymsky Volcano was observed during the entire 1962-1994 period of detailed seismological observation (see Figs 3 and 4).) Secondly, the hypocenters became deeper southwards, away from Karymsky Volcano and toward the main-shock epicenter (see Fig. 13, b); this also follows from distance-depth

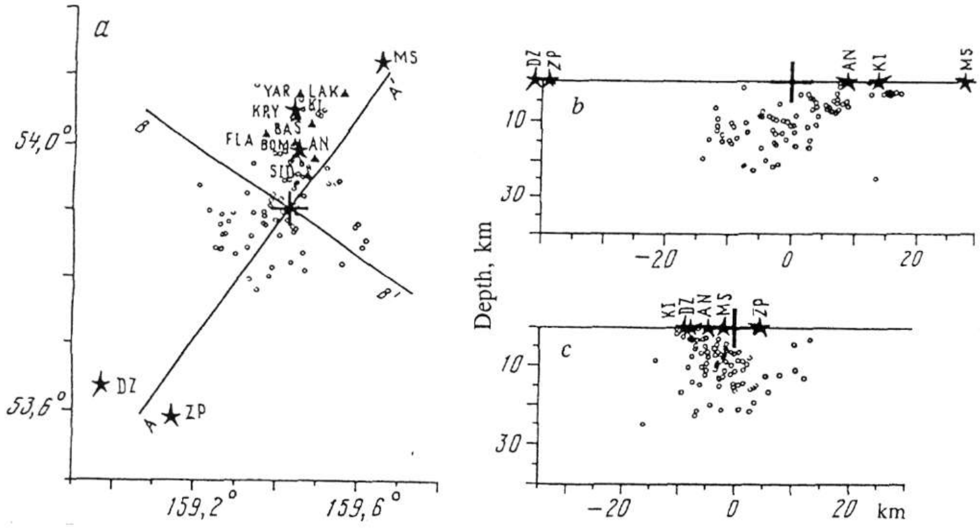

Figure 13 Epicenter map (*a*) and vertical cross-sections (*b* and *c*) for earthquakes recorded in August 1996. The notation is as in Fig. 3.

plots of the aftershocks, whose location was based on data from the regional seismograph network (this was always supplemented with KRY data: see Fig. 9). It can be hypothesized from the estimated location of the source volume (see Figs 9 and 13) that the main-shock hypocenter based on the regional network data must in all probability be erroneous, due to a lack of KRY data. A more likely location would be at about 10 km depth. The supporting evidence is the fact that no ground-surface deformation was discovered in the epicenter area, whereas some must have been produced by a magnitude 7.0 earthquake occurring at zero depth.

The overall hypocenter distribution of the earthquakes recorded during August 1996 points to the existence of an active fault zone dipping southwards from Karymsky Volcano and emerging at the ground surface in the northern part of Lake Karymskoe. Field observations conducted by V. L. Leonov during the summer of 1996 revealed numerous surface fractures and fissures between the Karymsky caldera and the Akademii Nauk calderas, these were as long as 1 km and wide as 2.5 m [5].

The direction of the longer axis of the main-shock source zone and the attitude of the rupture plane as inferred from the main-shock mechanism are in good agreement with the general trend of the fault zone (see Figs 1 and 6). It can thus be supposed that the Karymsky earthquake of January 1, 1996, reactivated the fault which emerged at the surface in the northern part of Lake Karymskoe. The development of the fault southwards away from Karymsky Volcano was probably related to a considerable volume of viscous material beneath Karymsky Volcano, which relaxed the stresses, the fact which explains the absence of seismicity beneath Karymsky Volcano. The upper boundary of this viscous material can be estimated from the hypocenters of earthquakes recorded in August 1996. There was a cluster of earthquakes at 4-5 km depth, which probably defined the upper surface of the anomalous volume beneath Karymsky Volcano (see Fig. 13, *b)*. It is likely that the micro-earthquakes that were recorded a few hours before the main earthquake occurred at that boundary and were generated by the beginning of magma intrusion into the conduits of Karymsky Volcano. Magma intrusion was caused by increasing pressure within the magma chamber. This pressure gave rise to extra stresses in the surrounding rocks, resulting in higher seismicity and the occurrence of the main earthquake, which had been prepared by tectonic processes. The excess magma pressure served as the mechanism that finally triggered the large earthquake. The fault that was reactivated by the earthquake created favorable conditions for the intrusion of magma, which rose to the surface through this fault and initiated the Akademii Nauk caldera eruption. This concurrence of unique geological conditions took place mainly via the build-up of local tectonic stresses released by the large earthquake; a repeat of these specific conditions may only occur once every few hundred, or even every few thousand years, while Karymsky erupts every 10-15 years. Viewed in this light, the main reason why the processes coincided in time was that Karymsky Volcano was ready for its next eruption; this event (the emplacement of magma into the conduits) was the first to begin and was marked by an increase in the micro-earthquake seismicity. Thereafter the excess magma pressure triggered foreshock seismicity in the source zone, which moved progressively from Karymsky Volcano to the main-shock epicenter (see Fig. 7). This was caused by the propagation of stresses due to the excess magma pressure. The magnitude 7.0 earthquake relieved much of the tectonic stress in the area and produced a fault through which magma could rise to be erupted in the Akademii Nauk caldera. All of these processes were thus interrelated, and their development reflected the volcanotectonic situation in the area of Karymsky Volcano.

CONCLUSIONS

The eruptions at Karymsky Volcano and in the Akademii Nauk caldera, as well as the magnitude 7.0 earthquake which occurred at the same time, were unique natural phenomena. The relations between them provide a better understanding of the volcanotectonic processes that are going on in the area. In spite of the limited seismic data, owing to an episodic lack of observation at KRY, the closest seismic station, there are indications of a probable sequence of volcanic and tectonic events. Based on the distribution of earthquake hypocenters in the area of Karymsky Volcano during the entire period of detailed seismological observation (about 33 years), the source zone of the large earthquake under discussion was invariably active, while virtually no seismicity occurred beneath Karymsky Volcano.

Detailed observations by the local seismic network in August 1996 suggest the presence of a considerable volume of viscous material beneath Karymsky Volcano, which controls its activity. The Karymsky eruption was started by the intrusion of magma into the conduits, which resulted in numerous micro-earthquakes. The excess pressure of magma served to trigger earthquakes in the fault zone. The magnitude 7.0 earthquake activated the fault, through which magma rose toward the surface to produce an eruption in the Akademii Nauk caldera. A special study needs to be carried out to determine a 3-D velocity structure to more accurately locate magma chambers beneath Karymsky Volcano.

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REFERENCES

1. S. T. Balesta, A. A. Kargopoltsev, and G. B. Grigorian, in: *Geologicheskie i geofizicheskie dannye o Bolshom treshchinnom Tolbachinskom izverzhenii 1975-1976 gg.* (Geological and Geophysical Data on the Great Tolbachik Fissure Eruption of 1975-1976)(Moscow: Nauka, 1978): 225–233.
2. V. M. Zobin, P. P. Firstov, and E. I. Ivanova, *Volcanol. Seismol.* **3**, N5 (1983)(cover-to-cover translation of the Russian journal *Vulkanol. Seismol.* N5, 1983).
3. V. A. Legler and L. M. Parfenov, in: *Tektonicheskoe raionirovanie i strukturno-veshchestvennaya evolyutsiya severo-vostoka Azii* (Tectonic Zonation and Lithostructural Evolution of Northeast Asia)(Moscow: Nauka, 1979): 134–155.
4. V. L. Leonov, *Volcanol. Seismol.* **13**, N2 (1991)(cover-to-cover translation of the Russian journal *Vulkanol. Seismol.* N2, 1991).
5. V. L. Leonov, *Volcanol. Seismol.* N5: 655–674 (1998)(cover-to-cover translation of the Russian journal *Vulkanol. Seismol.* N5, 1997).
6. V. L. Leonov and V. V. Ivanov, *Volcanol. Seismol.* **16**, N2: 115–131 (1994)(cover-to-cover translation of the Russian journal *Vulkanol. Seismol.* N2, 1994).
7. Yu. P. Masurenkov, in: *Vulkanicheskiy tsentr: stroenie, dinamika, veshchestvo (Karymskaya struktura)*(A Karymsky Volcanic Center: Structure, Dynamics, and Composition)(Moscow: Nauka, 1980): 111–116.
8. Yu. P. Masurenkov, in: *Deistvuyushchie vulkany Kamchatki* (Active Kamchatkan Volcanoes), vol. 2 (Moscow: Nauka, 1991): 8–13.
9. Yu. P. Masurenkov and L. A. Komkova, *Geodinamika i rudoobrazovanie v kupolno-koltsevoi strukture vulkanicheskogo poyasa* (Geodynamics and Mineralization in a Dome-Ring Structure of a Volcanic Belt)(Moscow: Nauka, 1978).
10. Ya. D. Muraviev, S. A. Fedotov, V. A. Budnikov, *et al.*, *Volcanol. Seismol.* N5: 567–604

(1998)(cover-to-cover translation of the Russian journal *Vulkanol. Seismol.* N5, 1997).

11. P. I. Tokarev, *Volcanol. Seismol.* **11**, N2 (1989)(cover-to-cover translation of the Russian journal *Vulkanol. Seismol.* N2, 1989).
12. P. I. Tokarev and P. P. Firstov, *Byul. Vulkanol. Stantsiy* N43: 9–22 (1967).
13. S. A. Fedotov, *Energeticheskaya klassifikatsiya Kurilo-Kamchatskikh zemletryaseniy i problema magnitud* (The Energy Classification of Kurile-Kamchatka Earthquakes and the Magnitude Problem)(Moscow: Nauka, 1972).
14. S. A. Fedotov, A. A. Gusev, G. V. Chernysheva, and L. S. Shumilina, *Volcanol. Seismol.* **7**, N4 (1985)(cover-to-cover translation of the Russian journal *Vulkanol. Seismol.* N4, 1985).
15. S. A. Fedotov, L. S. Shumilina, and G. V. Chernysheva, *Volcanol. Seismol.* **9**, N6 (1987)(cover-to-cover translation of the Russian journal *Vulkanol. Seismol.* N6, 1987).
16. P. P. Firstov and Yu. A. Filippov, *Volcanol. Seismol.* **19**, N2: 167–182 (1997)(cover-to-cover translation of the Russian journal *Vulkanol. Seismol.* N2, 1997).
17. I. V. Florenskiy and V. G. Trifonov, *Geotektonika* N4: 78–87 (1985).
18. A. P. Khrenov, Yu. M. Dubik, B. V. Ivanov, *et al., Vulkanol. Seismol.* N4: 29–48 (1982).
19. A. E. Shantser, *Byul. Vulkanol. Stantsii* N57: 53–65 (1979).
20. V. A. Shirokov, V. V. Ivanov, and V. V. Stepanov, *Volcanol. Seismol.* **10**, N3 (1988)(cover-to-cover translation of the Russian journal *Vulkanol. Seismol.* N3, 1988).
21. E. K. Erlikh, *Geotektonika* N1: 93–105 (1965).
22. A. Gorbatov, G. Suarez, V. Kostoglodov, and E. Gordeev, *Geophys. Res. Lett.* **21**, N16: 1675–1678 (1994).