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RESEARCH ARTICLE

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Seismicity and crustal deformation preceding the January 1996 eruptions at Karymsky Volcanic Center, Kamchatka

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Abstract Two explosive eruptions occurred on 2 January 1996 at Karymsky Volcanic Center (KVC) in Kamchatka, Russia: the first, dacitic, from the central vent of Karymsky volcano, and the second, several hours later, from Karymskoye lake in the caldera of Akademia Nauk volcano. The main significance of the 1996 volcanic events in KVC was the phreatomagmatic eruption in Karymskoye lake, which was the first eruption in this lake in historical time, and was a basaltic eruption at the acidic volcanic center. The volcanic events were associated with the 1 January Ms 6.7 (Mw 7.1) earthquake that occurred at a distance of about 9–17 km southeast from the volcanoes just before the eruptions. We study the long-term (1972–1995) and short-term (1–2 January 1996) characteristics of crustal deformations and seismicity before the double eruptive event in KVC. The 1972–1995 crustal deformation was homogeneous and characterized by a gradual extension with a steady velocity. The seismic activity in 1972–1995 developed at the depth interval from 0 to 20 km below the Akademia Nauk volcano and spread to the southeast along a regional fault. The seismic activity in January 1996 began with a short sequence of very shallow microearthquakes (M ~0) beneath Karymsky volcano. Then seismic events sharply increased in magnitude (up to mb 4.9) and moved along the regional fault to the southeast, culminating in the Ms 6.7 earthquake. Its aftershocks were located to the southeast and northwest from the main shock, filling the space between the two active volcanoes and the ancient basaltic volcano of Zhupanovsky Vostryaki. The eruption in Karymskoye lake began during the aftershock sequence. We consider that the Ms 6.7 earthquake opened the passageway for basic magma located below Zhupanovsky Vostryaki volcano that fed the eruption in Karymskoye lake.

Keywords Kamchatka · Karymsky Volcanic Center · Seismicity · Deformations · 1996 eruptions

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Introduction

The 50-km-long Karymsky Volcanic Center (KVC) is a part of the Kurile-Kamchatka volcanic chain and consists of 21 volcanic cones and 6 calderas. Two volcanoes, Karymsky and Maly Semyachik (Fig. 1), were active during historical time (Fedotov 1998). Karymsky is the only dacitic active volcano of the Kurile-Kamchatka zone (Khrenov et al. 1982). Six kilometers to the southeast, the Pleistocene–Holocene Akademia Nauk volcano was characterized by the basaltic lavas at the initial stage of activity which changed to the rhyodacitic lavas during its last eruptions 48,000–28,000 years ago (Fedotov 1998). Together they form the only center of acid volcanism in Kamchatka.

Two explosive eruptions occurred on 2 January 1996 in KVC (Fedotov 1998): the summit eruption of andesitic-dacitic magma at Karymsky volcano, and, several hours later, the phreatomagmatic basaltic eruption from Karymskoye lake at Akademia Nauk volcano (Fig. 1B). The eruption of Karymsky volcano was not uncommon for this very active volcano. In contrast, the explosive eruption in Karymskoye lake from the New Eruptive Center (NEC) was the first historic eruption after 28,000 years of dormancy. The total duration of the eruption of NEC was only about 20 h. By the end of the eruption, the pyroclastic deposits, represented mainly by juvenile basalt, formed a new peninsula in the northern part of the lake (Fedotov 1998).

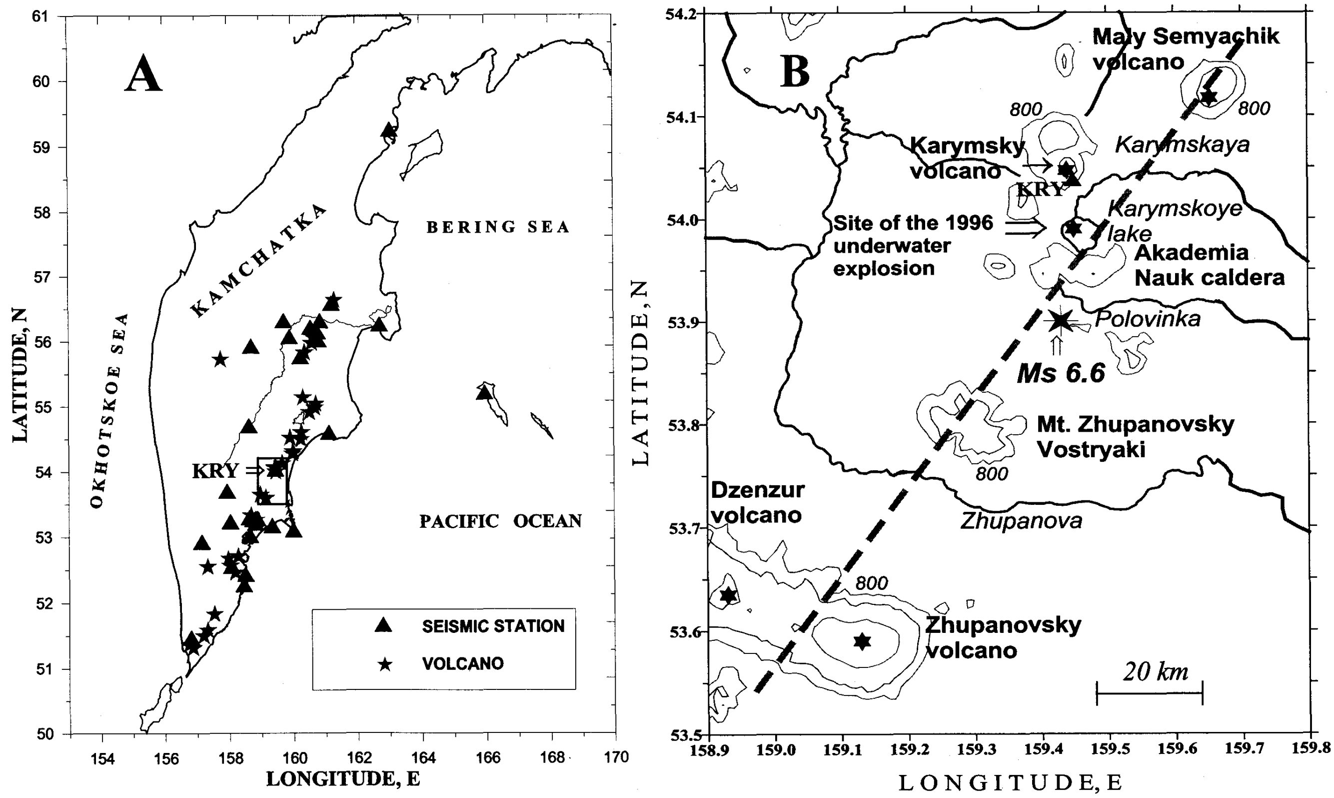

Fig. 1 Regional seismic network of Kamchatka (**A**) and index map of the region of study (**B**). **A** The region of study is shown by a *quadrangle*. *Arrow* shows the position of seismic station KRY near Karymsky volcano. **B** Active volcanoes are shown by *black stars*; epicentre of the Ms 6.7 earthquake of 1 January 1996 is shown by *four-pointed star*; volcanic structures are shown by *relief contours* beginning at 800 m, with intervals of 400 m. The fault that serves to channel magma to the surface fault according to Masurenkov (1991) is shown by the *dashed line*

Karymskoye lake fills the northern part of Akademia Nauk caldera (Fig. 1B). The caldera is crossed by a major NNE regional fault that follows the volcanic chain and is considered to be a deep-seated magma outlet of this volcanic chain (Masurenkov 1991). This fault connects Karymskoye lake (or Akademia Nauk caldera) with the basaltic and basaltic-andesite volcanoes: Maly Semyachik volcano to the north and Mt. Zhupanovsky Vostryaki and Dzenzur and Zhupanovsky volcanoes to the south (Fig. 1).

The double eruptive event of 2 January 1996 at KVC was associated with crustal deformation and seismic activity (Gordeev et al. 1998; Maguskin et al. 1998; Zobin and Levina 1998). A large earthquake of magnitude Ms 6.7 (Mw 7.1) occurred on 1 January, 17 km to the south of Karymsky volcano and 9 km to the south of Karymskoye lake, at 21:57 (local time) at a depth of about 10 km. It was preceded by a 4-h foreshock sequence and was followed by intensive aftershock activity (Fig. 2).

The deformation of the earth's surface during this volcano-tectonic crisis was the maximum value recorded for Kamchatkan volcanoes for the last 35 years. The maximum horizontal and vertical displacements were recorded at geodetic sites located near the NEC and in the area of surface rupture between Karymsky volcano and Karymskoye lake. The submeridional zone of subsidence (width of 1.5–2.0 km, amplitude up to 0.8 m) borders the uplift zones to the east (up to 23 cm) and to the west (up to 66 cm) of the subsidence zone. The horizontal deformations across the zone of open faults and crater of NEC were about 10^{-5} (Maguskin et al. 1998).

This paper discusses the long-term and short-term crustal deformation and seismic activity that were observed before and during the January 1996 volcanic events. Seismic investigations near Karymsky volcano began in 1965 (Tokarev and Firstov 1967); later, a permanent seismic station was installed there in 1970 (Firstov et al. 1977). Joint seismic and geodetic investigations at KVC began in 1972 (Maguskin et al. 1982), allowing us to study the 24-year sequence of seismic events and trends in local deformations.

Seismic and geodetic monitoring system

Seismic activity of KVC was monitored by the regional seismic network (Fig. 1A) equipped with three-component, short-period seismometers. The nearest seismic station, KRY, which was installed in 1970, is situated between the Karymsky volcano and Karymskoye lake at a distance of 1–20 km from the local epicenters (see Fig. 1). This seismic network locates all earthquakes of magni-

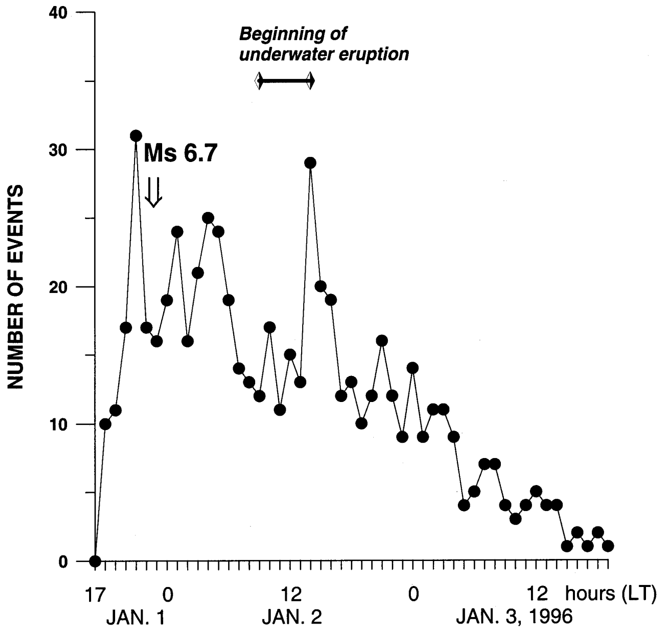

Fig. 2 Temporal variations of hourly earthquake numbers (M >2) during the first 50 h of activity. The time of the Ms 6.7 earthquake is shown by the *arrow*. The probable time interval for the beginning of the NEC eruption is noted

tude M >2 with mean error of epicenter about ±3 km and of depth ±4 km within the KVC. Between 1972 and 1995, 116 events of magnitude Ms 2–5.5 were located, and about 600 events of magnitude Ms 2–6.7 were located in January 1996. The magnitude estimations used in this paper were made by the International Seismological Centre (ISC) and were taken from the *Bulletin of ISC*.

Geodetic monitoring (Fig. 3) was carried out using annual levelling and triangulation measurements within KVC (Maguskin et al. 1998). For measure of vertical displacements, two sites, 7 and 20, situated to the SSE of the Karymsky volcanic crater (Fig. 2) were used. The values of vertical displacements represent the comparative vertical movements of a site that was situated about 1.5 km from the crater (site 20) relative to the benchmark that was situated about 5 km from the crater (site 7). These values have a mean error of ±0.5 cm.

The average horizontal displacements for the 1972–1982 period were estimated as the mean value of the line change for 18 sites situated at distances of 1–4.5 km around Karymsky volcano (mean error ±2 cm). For the period 1986–1996, the average horizontal displacements were estimated as the mean value of line change for a local network of 10 sites situated at distances of 1.3–4.0 km to the SSE of the summit of Karymsky volcano (between Karymsky volcano and Karymskoye lake), and with the use of more precise equipment the error decreased (mean error ±0.5 cm).

Long-term observations of seismic activity and deformations (1972–1995)

Seismic activity

Figures 4A and 5A show the epicenters and hypocenters of earthquakes of magnitude >2 that were located within KVC in 1972–1995 with a depth interval of 0–60 km. Ninety four out of 116 events occurred in swarms; the main swarms were recorded in 1978, 1992 and 1995 and are shown by special symbols in Figs. 4A and 5A.

The epicenters of seismic events were distributed between the Karymsky, Dzenzur and Zhupanovsky volcanoes (Fig. 4A). The majority of events occurred to the southeast of Karymsky volcano along the regional fault within an area of about 25 km of length and 20 km of width, mainly beneath the Karymskoye lake. The dense band of epicentres stopped before the Pleistocene volcano; a few events were located between Mt. Zhupanovsky Vostryaki and volcanoes Dzenzur and Zhupanovsky.

Three main swarms of earthquakes were located within a 15×20 km^2 area near Karymskoye lake. The 1978 swarm is characterized by a large epicentral zone; a magnitude Ms 5.5 event, which occurred on 29 January 1978 between Karymsky volcano and Karymskoye lake, was the largest event recorded between 1972 and 1995 (Zobin et al. 1983). The 1992 and 1995 swarms formed more compact groups around Karymskoye lake. The events occurred at depths of 0–22 km, with the majority at depths of 5–15 km (Fig. 5A).

Crustal deformations

Figure 6 shows the variations in horizontal and vertical displacements for the KVC. The horizontal displacements reflect the gradual extension of KVC with a strain velocity of about 3×10^{-6}/year. This extension was observed against the background of the overall sinking of the KVC region with a velocity of about 2–3 mm/year. Displacements of more than 70 mm were accumulated over 24 years.

Annual measurements are not able to resolve the detailed variations of deformations with the 1970–1973 and 1976–1982 eruptions of Karymsky volcano, nor the influence of earthquake swarms in 1978, 1992 and 1995 on the deformation process. The occurrence of the Ms 6.7 earthquake and the subsequent eruptions at KVC produced instantaneous vertical and horizontal displacements of about 140–150 mm, but the subsequent 1996–1999 measurements showed that the sign and velocity of the regional deformation process in KVC did not change after the eruption (Fig. 6).

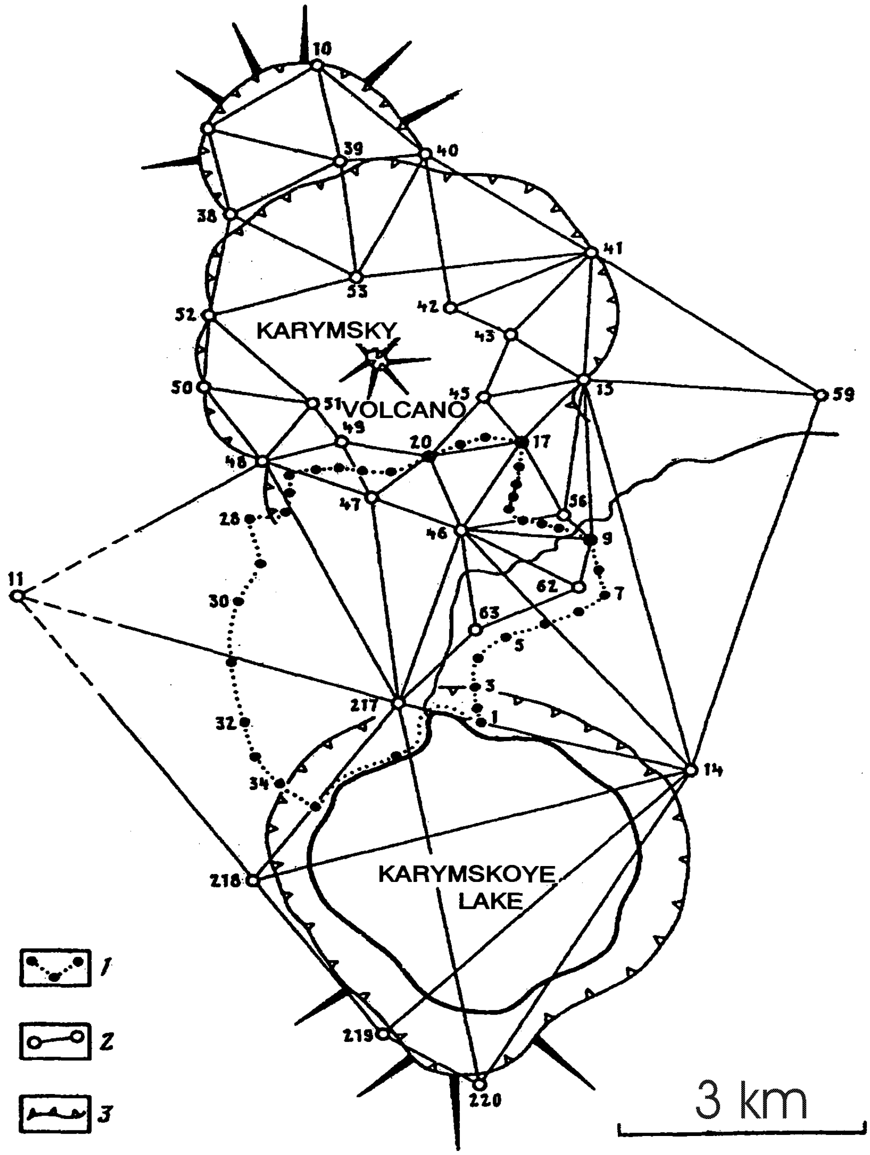

Fig. 3 Geodetic network at KVC. *1* Route of first-order levelling; *2* triangulation benchmarks; *3* caldera outline

Short-term observations of seismic activity (1–2 January 1996)

Seismic activity began on 1 January at about 16 h with a 2-h sequence of numerous, very small (magnitude about 0) earthquakes below Karymsky volcano (Fig. 4B). The average difference between P and S arrival times for these events was stable and equal to 0.95 s at the nearest station KRY. Gordeev et al. (1998) used the three-component records of seismic station KRY to estimate the position of the majority of the hypocenters as being at a depth of about 3 km beneath the southeastern slope of Karymsky volcano. They were typical volcano-tectonic microearthquakes with well-defined P and S onsets.

A sharp increase in seismic activity began at 18 h (Fig. 2). During the first 4 h, the number and magnitude of events drastically increased; the largest events were of magnitude mb 4.8 and 4.9. The main Ms 6.7 earthquake occurred at 21:57. During the next 16 h the frequency of earthquakes significantly decreased. However, four earthquakes of magnitude Ms 5.0–5.3 were observed. A new peak in number of events was observed at 15:00 on 2 January; after this peak, the activity gradually decreased over 15 h down to a level of 3–5 events hourly. The low-level seismic activity continued for about a month (Zobin and Levina 1998). The main release in seismic energy was observed during the first 36 h of activity on 1 and 2 January; this time interval is the subject of this study.

Figure 4B shows the epicentral distribution of the 1–2 January events. We divided the events into three groups: the microearthquakes that occurred mainly beneath Karymsky volcano (first sequence); the foreshocks of the Ms 6.7 event (second sequence); and the aftershocks of the Ms 6.7 event (third sequence). The epicenters of the second sequence form a dense cluster along the regional fault between Karymskoye lake and Mt. Zhupanovsky Vostryaki. This seismic sequence included 58 events of magnitude greater than 2 that were recorded at depths

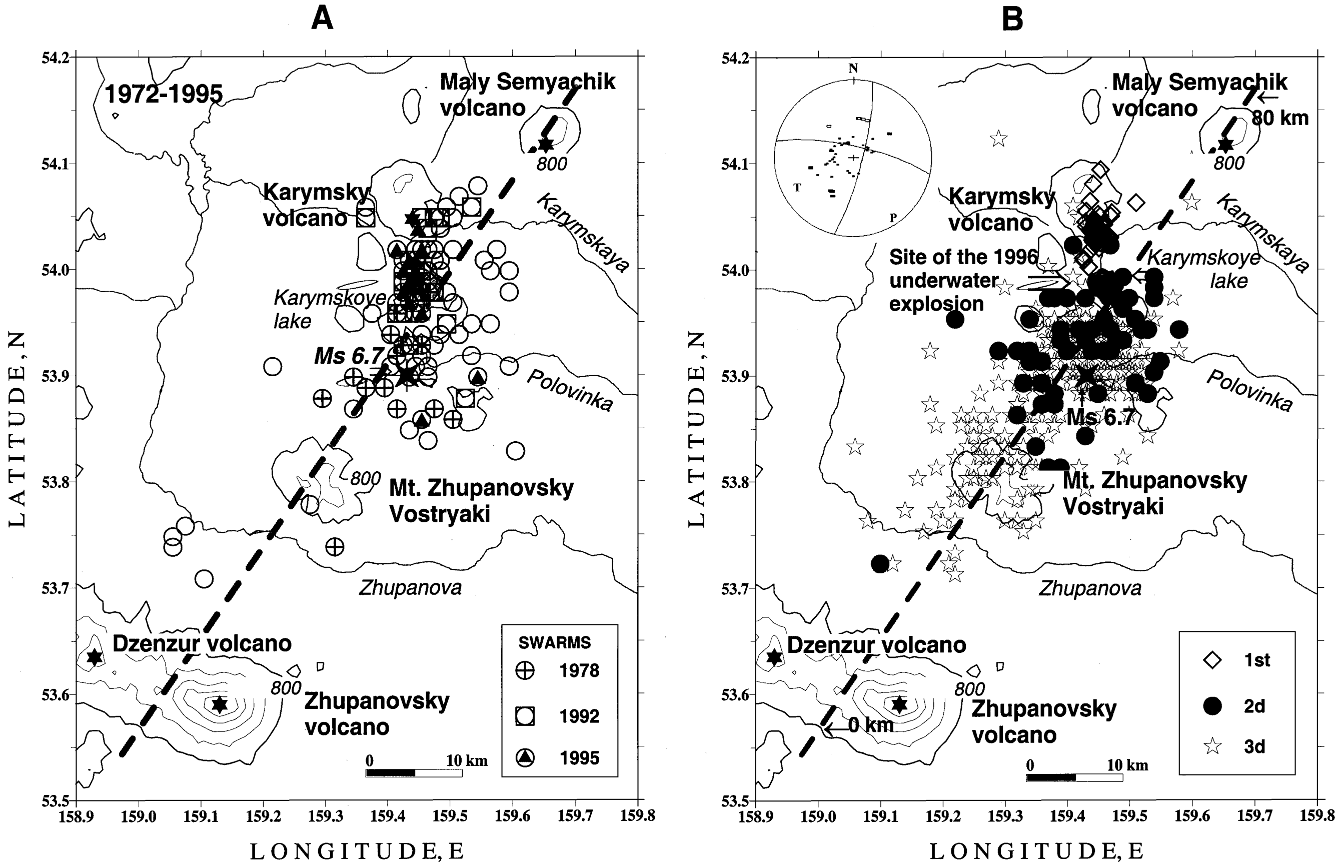

Fig. 4 Epicenters of earthquakes (M >2) located at KVC in 1972–1995 (**A**) and in January 1996 before the eruption in Karymskoye lake (**B**). **A** *Open circles* show the epicenters of the earthquakes. Epicenters of the three main swarms of 1978, 1992 and 1995 are noted by *special symbols* as shown. Volcanoes are shown by *black stars*; epicenter of the Ms 6.7 event is shown by the *four-pointed star*. Regional fault is shown by a *dashed line*. **B** *1st*, *2nd* and *3rd* are the epicenters of the three earthquake sequences. *Arrows* with indexes of *0 km* and *80 km* on the regional fault show beginning and end of cross section along the fault of Fig. 7B. Focal mechanism of the Ms 6.7 event [taken from Zobin and Levina (1998)] is shown in *top left corner*. The remaining legend is the same as in Fig. 1B

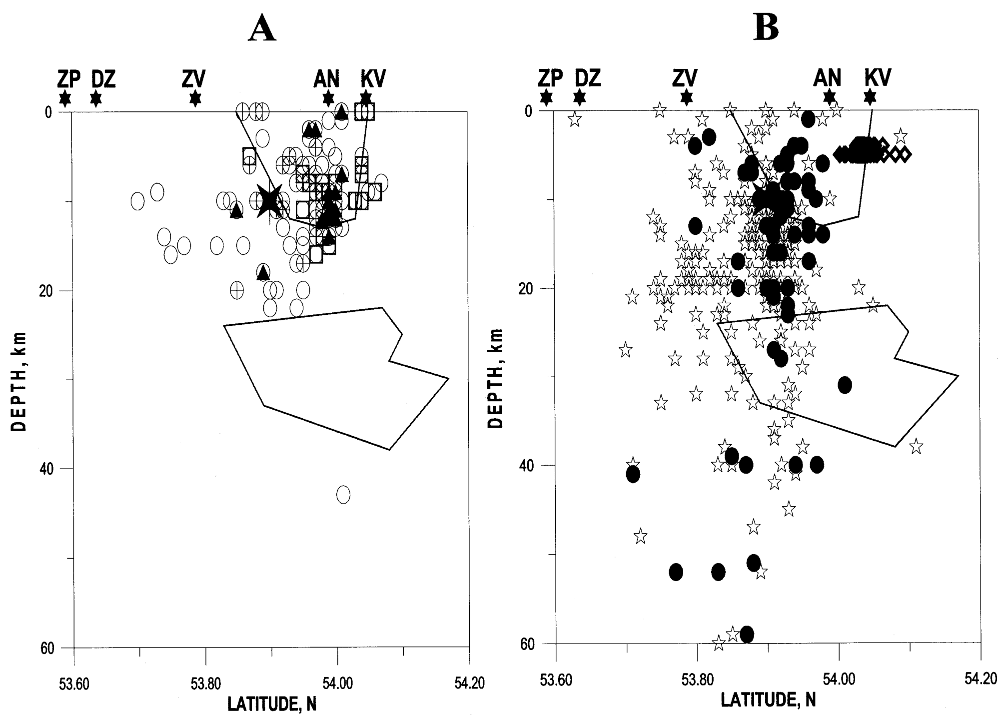

Fig. 5 Hypocenters of earthquakes (M >2) located at KVC (**A**) in 1972–1995 and (**B**) in January 1996 before the eruption in Karymskoye lake. Asperities that were destroyed during the Ms 6.7 earthquake are shown by *lines* (from Zobin and Levina 1998). All other *symbols* are the same as for Fig. 4

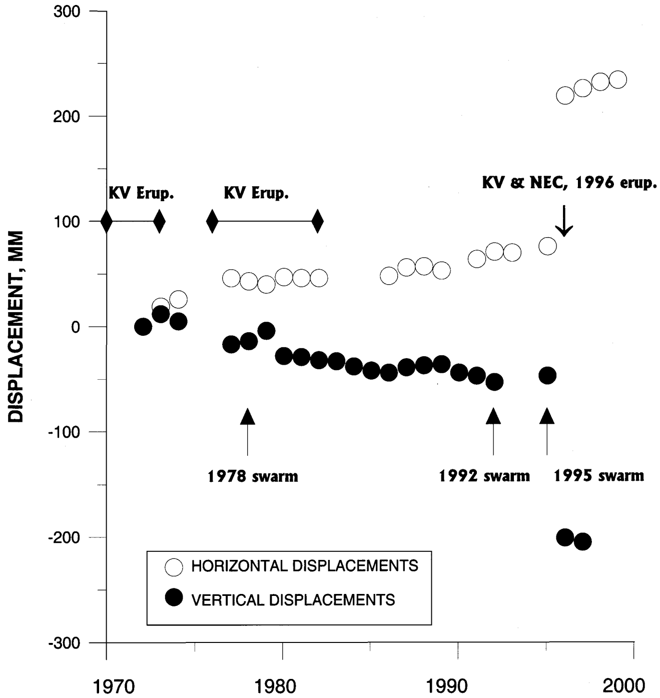

Fig. 6 Variations of the horizontal and vertical displacements of the Earth's surface at KVC for 1972–1999. Positions of main earthquake swarms and volcanic eruptions during the period of observations are indicated

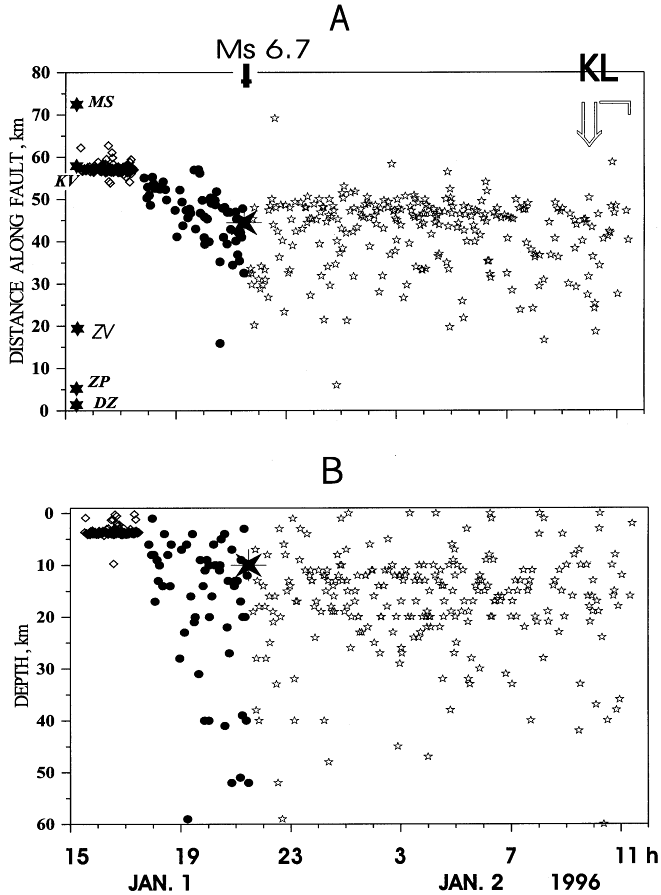

Fig. 7 Migration of earthquake foci during the three earthquake sequences of 1–2 January 1996 along the regional fault (**A**) and downwards (**B**). The probable time interval for the beginning of the NEC eruption is noted. *Symbols* are the same as in Fig. 4B. Beginning and end of cross section **A** is shown in Fig. 4B along the regional fault. Projection of volcanoes on the regional fault is shown. Volcanoes cited: *MS* Maly Semyachik; *KV* Karymsky; *ZV* Mt. Zhupanovsky Vostryaki; *DZ* Dzenzur; *ZP* Zhupanovsky

from 0–60 km and culminated in the large Ms 6.7 earthquake. The depths of these earthquakes were controlled by the nearest seismic station KRY. Unfortunately, the mainshock destroyed it, and the aftershock depths are less well defined. The aftershock sequence of seismic events occupied the area of the foreshock epicenters and spread also to the southwest along the regional fault, with increasing average depth of events (Fig. 7). This sequence consisted of 261 events of magnitude greater than 2. The epicenters of the third group filled the area between Karymsky and Dzenzur and Zhupanovsky volcanoes. The total area occupied by seismic events of the three sequences was about 50×20 km^2.

The Ms 6.7 mainshock occurred in the southern part of the epicentral zone of the second (foreshock) sequence. Its focal mechanism (see Fig. 4B) was characterized as a left-lateral strike-slip motion along a fault plane coinciding with the strike of the regional fault (Gordeev et al. 1998; Zobin and Levina 1998). The application of finite-fault, broadband, teleseismic *P* waveform inversion to the Ms 6.7 earthquake (Zobin and Levina 1998) demonstrated that the main feature of the rupture process was the breaking of two large asperities at depths from 0–12 km and from 20–35 km beneath Karymskoye lake (Fig. 5B).

Figure 5B shows the relative distribution of hypocenters of the three sequences and the asperities destroyed by the mainshock. It is seen that the deeper asperity was situated in the zone free of the events of the second sequence that occurred mainly within two depth levels, 0–20 km and 40–60 km, while the events of the third sequence (aftershocks) filled the space of this asperity.

Results and discussion

The double eruption of andesitic-dacitic material at Karymsky volcano and of juvenile basalts at Akademia Nauk volcano occurred on 2 January 1996. The phreatomagmatic eruption at Akademia Nauk caldera in Karymskoye lake was its first eruption in historical time, and it was an unusual basaltic eruption within an acidic volcanic center. Seismic and deformation monitoring of volcano-tectonic process in KVC shows that the crustal deformations of the KVC for about 20 years before the 1996 double eruptions were characterized by a gradual extension with a constant velocity. The seismic activity in 1972–1995 developed along the regional fault between Karymskoye lake and Dzenzur and Zhupanovsky volcanoes at the depth interval from 0–20 km. The seismic gap

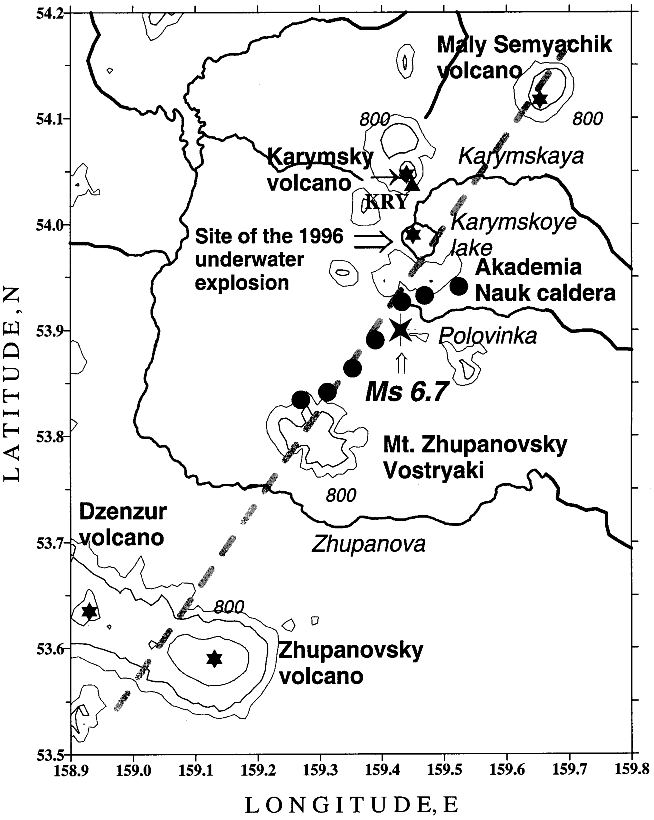

Fig. 8 Epicenters of strongest (Ms=5.0–5.3) earthquakes (*circles*) of the third sequence. They outline the fault connecting Mt. Zhupanovsky Vostryaki with the Akademia Nauk caldera

interrupted the band of epicentres at the latitudes between 53.75 and 53.85°N beneath Mt. Zhupanovsky Vostryaki.

The seismic activity in January 1996 before and during the volcanic events at KVC was recorded at first beneath the Karymsky volcano (a swarm of shallow microearthquakes) and then developed along the regional fault over a depth interval of 0–60 km, culminating in the Ms 6.7 (Mw 7.1) earthquake, one of the three largest earthquakes of the twentieth century associated with volcanic activity in the world (Zobin 2001). The band of earthquake epicenters filled the previous gap below Mt. Zhupanovsky Vostryaki.

The different composition of magmatic material for the two eruptions allows speculation about two different sources of magma feeding the eruptions. The airline pilots and satellite photos suggest that early on the morning of 2 January (at 08:00) only one volcanic center (Karymsky volcano) erupted. So the eruption at Karymsky volcano was the first; and it was typical for this volcano being an andesitic-dacitic event. Gordeev et al. (1998) and Fedotov (1998) considered that the first swarm of microearthquakes beneath Karymsky volcano was caused by magma intrusion that fed the eruption of Karymsky.

The basaltic eruption in Karymskoye lake occurred between 10:00 and 15:00 on 2 January (see Fig. 3), when the double eruption at KVC was observed by helicopter (Fedotov 1998). Figure 2 shows that we have a sharp peak in number of earthquakes from 14:00–15:00. It may mark the start of Karymskoye lake rupturing. This eruption may be related to the seismic activity along the regional fault. Belousov et al. (1997) suggest that the basaltic material feeding the ancient eruptions at Akademia Nauk volcano was supplied along this fault.

The steady character of crustal deformations without any anomaly before 1996 shows that the 1996 seismovolcanic crisis was not a regular process of tectonic stress release. Normal process of preparation of the Ms 6.5–7.0 earthquake is observable as the anomalies in crustal movement 2–3 years before the event (Scholz 1990). Our geodetic measurements were carried out at a distance of about 15–20 km from the earthquake epicenter and should not miss any long-term anomalies even with our rather infrequent observations. Therefore, it is possible that the Ms 6.7 earthquake was triggered by an additional (magmatic?) factor.

Seismic activity at KVC was common during 1972–1995. It followed the regional fault at a depth of 0–20 km. What new element in seismic activity was observed before the Ms 6.7 earthquake and the NEC eruption? The deeper (depth from 30–60 km) events occurred directly below the deeper asperity, which was destroyed later during the Ms 6.7 earthquake (Fig. 5). One of the strong earthquakes of this sequence (mb=3.8) occurred at a depth of 52 km, 33 s before the mainshock. We speculate that the sequence of earthquakes that occurred at depths of 30–60 km triggered the stress release accumulated within the deep asperity and initiated the Ms 6.7 earthquake rupturing.

The deep asperity destruction is a key event in the Karymskoye lake eruption. Figure 5A shows that the low limit of depth distribution of the 1972–1995 earthquakes was the upper part of the deep asperity. The destruction of this asperity by the Ms 6.7 earthquake rupture allowed a change in the volcano-tectonic situation.

Figures 4B and 5B show that after the Ms 6.7 earthquake the epicenters filled the 1972–1995 gap in seismicity below Mt. Zhupanovsky Vostryaki; the hypocenters also filled the space that was occupied by the deep asperity. We propose that the gap in seismicity was due to a magma chamber situated beneath Mt. Zhupanovsky Vostryaki at depths greater than 20 km. The destruction of the deep asperity opened a passageway for magma along the regional fault. Figure 8 shows that the strongest shallow earthquake epicenters of the third sequence, with Ms ≥ 5.0, outline clearly the fault section reactivated before the NEC eruption, between Mt. Zhupanovsky Vostryaki and Akademia Nauk caldera along the regional fault.

What type of magma resides below Mt. Zhupanovsky Vostryaki? Masurenkov (1980) describes the eruption products of this ancient volcano as basalts and andesite-basalts with a mean SiO_2 content of 55.34%. The NEC basalts had a mean SiO_2 content of 53.0% (Belousov et al. 1997). If the Ms 6.7 earthquake was the event that broke the asperities and opened the door for magma migration from the southern area to the new volcanic center of Karymskoye lake, then the basalt-rich magmas could migrate laterally to the north. The distribution of the Ms ≥5.0 earthquakes along the fault zone from Mt. Zhupanovsky Vostryaki to Karymskoye lake (Fig. 8) could indicate magma migration in this direction. The total passageway would be about 10–15 km.

So we speculate that the NEC eruption was associated with the foreshock–aftershock sequence of the Ms 6.7 earthquake and was fed by laterally migrating basaltic magma from the magma chamber beneath Mt. Zhupanovsky Vostryaki. An alternative hypothesis was proposed by Fedotov (1998), who suggested that the feeding eruption fissure for the NEC was located between the Akademia Nauk and Karymsky calderas, or that the NEC eruption was supported by the magma from the through-crust basaltic dyke cutting the dacitic magma chamber of KVC. However, it is very problematic that the upper-mantle basaltic magma could be released simultaneously with the portion of upper-crustal andesitic-dacitic magma that fed the Karymsky eruption. The only factor that supports this hypothesis is the significant surface faulting between the two volcanic structures (Maguskin et al. 1998), but this faulting might be produced by the Ms 6.7 earthquake rupture system.

Therefore we prefer our hypothesis of basaltic magma lateral migration from the magma chamber of Mt. Zhupanovsky Vostryaki. The feeding of an eruption by the lateral migration of basaltic magma from a distant magma chamber is not so rare.

The 1996 seismovolcanic activity at KVC may be compared with the famous 1912 seismovolcanic activity of Katmai, Alaska (Abe 1992). It has been proposed that the collapse of Katmai summit was caused by withdrawal of supporting magma from beneath Mount Katmai towards Novarupta, the actual vent of eruption, 10 km west of Mount Katmai. Based on geochemical and structural relationships, Hildreth (1987) suggests that the magma drained from beneath Katmai volcano to Novarupta via the plumbing system beneath Trident volcano. It is possible that the Mw 7.0 seismic event, which was located very close to Novarupta (Abe 1992), was the decisive one in the Mount Katmai caldera collapse, opening the fault as a passageway for withdrawal of supporting magma from beneath Mount Katmai, and towards Novarupta.

The migration of earthquakes accompanying intrusions is often reported for Hawaii. The length of dyke paths from Kilauea caldera towards the adjacent rift zones reaches as much as 20 km (Klein et al. 1987). The migration of basaltic magmas is also a common feature for Icelandic volcanoes. The migration length of magma from Krafla caldera towards the adjacent rift zone during the 1977 eruption was about 10 km (Brandsdottir and Einarsson 1979); the total distance of propagation of epicenters from Krafla caldera that marked the lateral magma injection into the northern fault swarm was about 30 km (Einarsson and Brandsdottir 1980). The migration of magma from the Plosky Tolbachik caldera (Kamchatka) towards the southern vent of the 1975 eruption was marked by earthquake epicenters for a distance of about 30 km (Fedotov et al. 1984). These examples show that the migration of magma over long distances of about 10–30 km is a frequent feature of volcanic eruptions, especially for basaltic eruptions.

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