ISSN 0742-0463, Journal of Volcanology and Seismology, 2008, Vol. 2, No. 5, pp. 322–339. © Pleiades Publishing, Ltd., 2008.
Original Russian Text © M.A. Magus'kin, S.A. Fedotov, V.E. Levin, V.F. Bakhtiarov, 2008, published in Vulkanologiya i Seismologiya, 2008, No. 5, pp. 22–40.

Deformations Related to a Large (*M* 6.9) Earthquake, the Magma Discharge, and Eruptions in the Karymskii Volcanic Center in 1996–2005

M. A. Magus'kin[a], S. A. Fedotov[a], V. E. Levin[b], and V. F. Bakhtiarov[b]

[a] *Institute of Volcanology and Seismology, Far East Division, Russian Academy of Sciences, Petropavlovsk-Kamchatskii, 683006 Russia*

[b] *Kamchatka Branch, Geophysical Service, Russian Academy of Sciences, Petropavlovsk-Kamchatskii, 683006 Russia*

Received December 25, 2007

Abstract—A network of interconnected stations was established in the entire area of the Karymskii Volcanic Center and near the active Karymskii Volcano, Kamchatka in 1971–1988 for the purpose of studying ground deformation. Multiple observations by this network yielded quantitative characteristics of the ground deformation related to the following phenomena: the eruption of Karymskii Volcano during the periods 1976–1982 and January 1, 1996, to 2005 (still continuing, written in February 2008); the discharge of basalt on January 2, 1996, in the bottom of Lake Karymskii situated in the caldera of Akademii Nauk Volcano (this volcano had previously been thought to be extinct) and the subsequent phreatomagmatic eruption lasting approximately 24 hours; and the large (*M* 6.9) earthquake of January 1, 1996, occurring at 21 h 57 min local time in the Karymskii Volcanic Center at a depth of ~10 km. This paper discusses the relationships of ground deformation to volcanic activity and to the abovementioned unique natural occurrences, and their mechanism as deduced from geodetic data.

DOI: 10.1134/S0742046308050047

INTRODUCTION

The Karymskii Volcanic Center, which is 40 by 60 km in size, is situated in the middle of the active Eastern Volcanic Zone of Kamchatka about 120 km northeast of the town of Petropavlovsk-Kamchatskii. It contains 19 volcanic edifices, with two of these being active volcanoes today (I and II, see Fig. 1) [4, 16].

Karymskii Volcano has been one of the most active Kamchatkan volcanoes in the 20th century [4]. Its eruptions were generally long-continued and occurred from 1911 to 1912, in the 1920s, and from 1934 to 1947, 1952 to 1966, and 1970 to 1982 [4, 19, 21]. The volumes of erupted lava during the last three active periods were 0.020 km^3, 0.056 km^3 [3], and 0.122 km^3 [14], respectively. The most recent eruption began on January 2, 1996, and still continues today (February 2008) with some intermissions. However, this time unique events occurred at the beginning of the eruption.

A few hours before the start of the eruption on Karymskii Volcano, a magnitude 6.9 earthquake occurred at a depth of ~10 km in the Karymskii Volcanic Center on January 1, 1996 [2, 20, 22]. No earthquake this size has been recorded in the Kamchatka volcanic belt during the preceding 50 years of seismological observation conducted on Kamchatka volcanoes. The start of the eruption on Karymskii Volcano was followed, at 6 km from the volcano and about 12 hours after it on January 2, 1996, by an underwater phreatomagmatic eruption in Lake Karymskii, which is situated in the caldera of Akademii Nauk Volcano that was thought to have been extinct; the underwater eruption lasted less than 24 hours [15, 20].

The Karymskii Center contains another active volcano, Malyi Semyachik, situated 17 km from Karymskii Volcano (Fig. 1). In its crater is a lake of high salinity with a brine temperature varying between 0° and 40° C, apparently because of the processes occurring in the shallow magma chamber [17]. No eruptive activity has been observed on the volcano from 1996 to 2006.

Swarms of volcano-tectonic earthquakes are episodically occurring in the central part of the Karymskii Volcanic Center, with the area being at present one of the most active segments of the Kuril–Kamchatka volcanic belt [2, 19].

Studies in the ground deformation in this center conducted to investigate recent movements, crustal structure, magmatic and volcanic processes in the crust (magma emplacement in crustal layers, the generation of magma chambers and their depths, the mechanism of volcanic eruptions), and eruption prediction were begun in 1971 by the Institute of Volcanology (IV) of the Far East Science Center (FESC) of the USSR Academy of Sciences (AS) near the active Karymskii Volcano, and in 1975 by the Far East Aerogeodetic Concern (FEAGC) of the Federal Service of Geodesy and Cartography of Russian Federation over the entire area of the Karymskii Volcanic Center [13]. From 1972 to 2005, almost annual geodetic measurements of ground

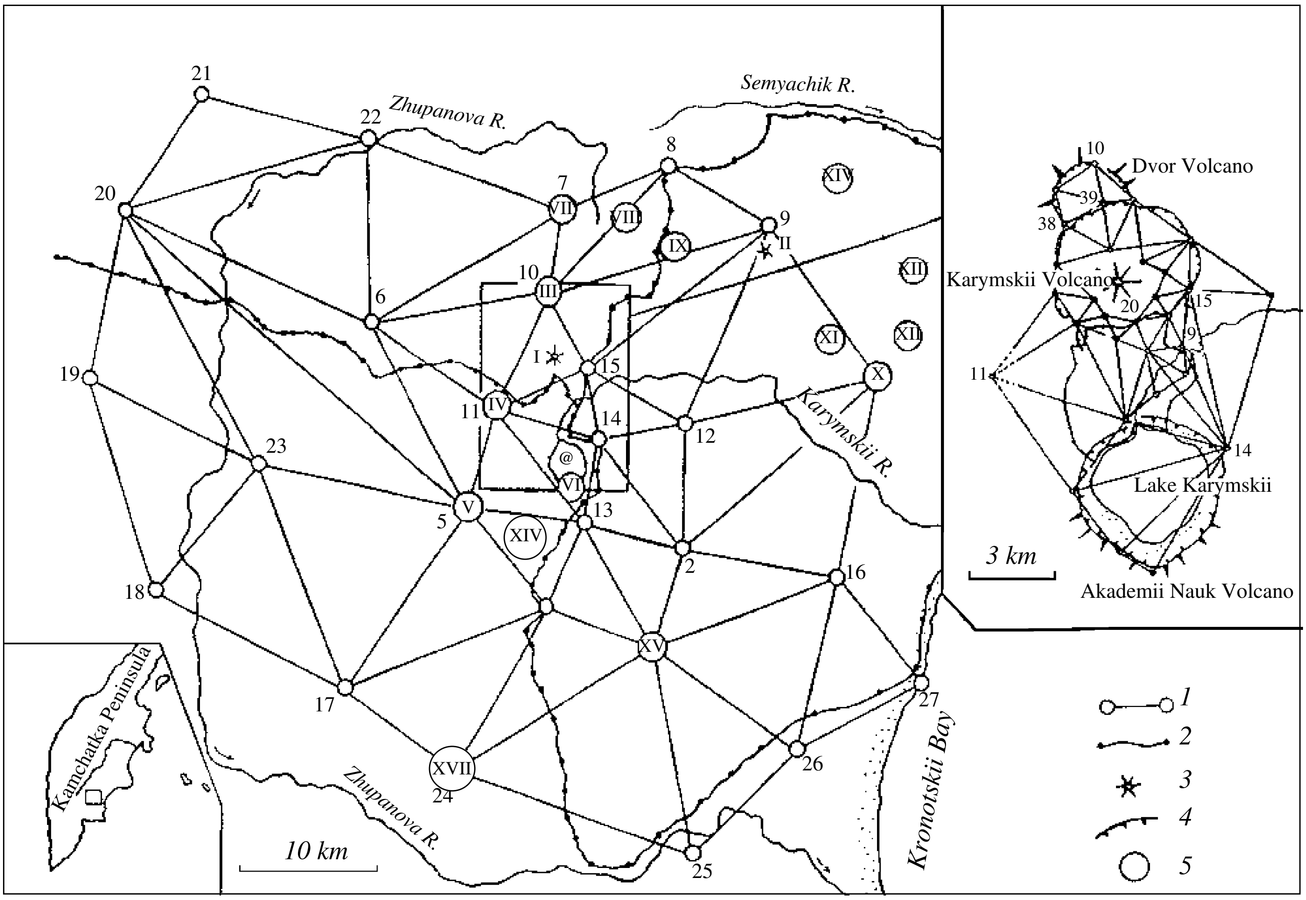

Fig. 1. A map of geodetic stations in the Karymskii Volcanic Center: (*1*) sides of triangulation network, (*2*) high precision leveling lines, (*3*) active stratovolcanoes: (I) Karymskii, (II) Malyi Semyachik; (*4*) calderas of Karymskii, Akademii Nauk, and Dvor volcanoes (inset), (*5*) extinct volcanoes of the Karymskii group (numerals in circles): (III) Dvor, (IV) Razlatyi, (V) Krainii, (VI) Akademii Nauk and Odnobokii, (VII) Sobolinyi, (VIII) Stupenchatyi Bastion, (IX) Sukhoi, (X) Pribrezhnyi Yuzhnyi, (XI) Stena, (XII) Pribrezhnyi Severnyi, (XIII) Massivnyi, (XIV) Berezovyi, (XV) Ditmara, (XVI) Belyankina, (XVII) Zhupanovskie Vostryaki.

deformation near Karymskii Volcano were carried out by the IV FESC USSR AS, later the Far East Division of the Russian Academy of Sciences (FED RAS), and at present by its successor, viz., the Institute of Volcanology and Seismology (IVS) FED RAS (the only years with no measurements were 1975, 1976, 1994, and 2002). The FEAGC carried out observations in the Karymskii Volcanic Center in 1975, 1977, 1981, 1983, and 1988 with progressively greater coverage of area.

The results of geodetic measurements of vertical and horizontal components of ground deformation near Karymskii Volcano conducted in 1972–1974 are reported in [10]. It should be remembered when dealing with these measurements that the accuracy of determination for horizontal movements at sites (their mutual displacements for intersite distances of 1–3 km) was not better than $\pm(1–3) \times 10^{-5}D$, where D is intersite distance in cm.

The 1977–1988 measurements with consideration of the 1972–1974 results are discussed in [14].

The results of work done by the FEAGC in the Karymskii Volcanic Center during the period 1975–1988 and of measurements near the volcano carried out by the Laboratory of Geodesy, IV FED RAS during the period 1972–1991, as well as their relation to the activity of Karymskii Volcano and the seismicity of the area, are set forth in [13].

The 1975–1988 data on horizontal components of ground deformation in the Karymskii Volcanic Center in a 30×50 km area [13] were used by S.A. Fedotov to find the position and mean depth of the pressure center in the magma chamber equal to 18.3 ± 0.8 km [20]. The centers of ground dilatation in an area of radius 15 km observed in 1975–1977, 1977–1981, 1981–1983, and 1983–1988 were situated along the 3-km line between Akademii Nauk and Karymskii volcanoes, in that location where later, on January 1–2, 1996, basalt was erupted through a new feeding fissure and the subsequent underwater eruption occurred in Lake Karymskii.

Observations of ground movements in 1992, 1993, and 1995 were carried out by the IV Laboratory of

Geodesy, but this work covered a much smaller area near the volcano. We note that since 1986, in connection with the appearance of high precision geodetic instruments, the accuracy of determination for horizontal deformation was greatly improved to become at most $\pm 2 \times 10^{-6} D$.

The deformation near Karymskii Volcano and the new eruptive center in Lake Karymskii measured immediately after the January 1–2, 1996, events in the caldera of Akademii Nauk Volcano was reported in [12].

Later it was possible to obtain data on horizontal movements over a much larger area, 40 by 45 km. This information was given very briefly in [11] and can be used to refine models of pressure sources [7].

Investigations of these unique natural phenomena (simultaneous eruptions on Karymskii Volcano and in the caldera of Akademii Nauk Volcano and the related postvolcanic processes) were conducted by the IV FED RAS since their very beginnings [15, 20]. For these investigations a Karymskii multidisciplinary expedition of the IV FED RAS was set up containing four field teams, viz., volcanological, geodetic, biohydrogeochemical, and structural geological ones. The science supervisor of the expedition was academician Fedotov, and M.A. Magus'kin was the Expedition Director.

In 1996–2005, the multidisciplinary investigations of the unique eruptions on Karymskii and Akademii Nauk volcanoes, the related processes, and their influence on the environment became possible thanks to significant support for several programs and projects on the part of the Ministry of Science of Russian Federation, the Russian Academy of Sciences, the Russian Foundation for Basic Research, and several other organizations.

The Ministry of Science and the Ministry of Industry and Science of Russian Federation supported the following works and projects: the work on "Investigation of Eruptions on Akademii Nauk and Karymskii Volcanoes, of the Related Geological, Geophysical, and Geochemical Processes and Their Influence on the Environment" in 1996–2002 (decrees 0261f, 477f, 1457f, 175f, 723f, 1447f, 2037f, 10.900/43-419, 06.900/43-182); the project "Contribution of Active Volcanoes into the Processes of Environment Change and Prediction of Volcanic Eruptions" in 1997–1998, Subproject 1.2.1, Governmental Science and Technology Program no. 16 "Global Environment and Climate Changes"; for the project "Monitoring of Volcanoes, Prediction and Investigation of Eruptions and Their Impact on the Environment" in 1999–2004, project 1.2.1, subprogram "Global Environment and Climate Changes" sponsored by the Ministry of Industry and Science of Russian Federation. The support of the Ministry of Science in 1996–2004 was secured by the assignment of Minister academician M.P. Kirpichnikov.

In 2003–2005, the Program of Basic Science of the RAS Presidium no. 13 "Environment and Climate Changes: Natural Disasters" included the major project "Eruptions of Kamchatka Volcanoes: Magma Supply, Mechanism, Evolution, Products, Related Processes, Hazards, and the Impact on the Environment" (project of the FED RAS no. 03-1-0-08-006).

The projects supported by the Russian Foundation for Basic Research include 95-05-79003, 96-05-66243 and others.

The above 1996–2005 projects were supervised by academician Fedotov. Much space in these projects was allotted to geodetic studies.

The Eruption of Karymskii Volcano was occurring during the preparation of the present publication (November 2007). In 2007 repeated geodetic measurements were made in order to obtain quantitative characteristics on the ground deformation near the volcano.

The present paper summarizes the conclusions reached by previous geodetic investigations (1972–1995), Section 1. We also deal in sufficient detail with results from the 1997–2005 measurements of ground deformation around Karymskii Volcano and in the area of the January 1–2, 1996, basaltic eruption in the Akademii Nauk caldera, as well as with measurements over a greater part (40 by 45 km) of the Karymskii Volcanic Center area around them, sections 1 and 2. Geodetic, seismological, and volcanological data are used to discuss the mechanism of the January 1–2, 1996, simultaneous eruptions, the volcanic activity and related phenomena in the Karymskii Volcanic Center, Section 4.

1. GROUND DEFORMATION IN THE KARYMSKII VOLCANIC CENTER IN 1972–1995 BASED ON INSTRUMENTAL MEASUREMENTS

By the beginning of geodetic investigations in 1972, Karymskii Volcano was in a current state of eruptive activity, which began in May 1970 and ended in December 1982 [4, 19, 21].

The main conclusions on the ground deformation in the Karymskii Volcanic Center in a 30×50 50 km area based on data obtained by discrete geodetic measurements carried out in 1972–1995 were as follows.

(1) The Karymskii Volcanic Center (Fig. 1) was dominated by extension, primarily along the direction perpendicular to the axis of the Kuril–Kamchatka seismic dipping zone and the volcanic belt. Especially significant extension occurred during swarms of volcano-tectonic earthquakes [13].

(2) The maximum (up to5×10^{-6} yr^{-1}) extension during the period 1975–1988 occurred in the middle of the volcanic structure 7–15 km south of Karymskii Volcano [13].

(3) The geometric center of the maximum horizontal deformation during the period 1975–1988 was almost identical with the future center of basaltic magma outpouring on the bottom of Lake Karymskii on January 2, 1996 [20].

The annual geodetic measurements in 1972–1995 carried out near the active Karymskii Volcano in an area of about 5 × 10 km provided more detailed information on the relative ground deformation coupled with the eruption of the volcano [11, 13]. The deformation had the following features.

(1) A general relative subsidence of the area (~40 km^2) that included Karymskii Volcano occurred during the period 1972 to 1995. The subsidence seems to have been symmetrical about the crater of the volcano within its caldera. On this assumption the subsided volume is about 0.057 km^3 during 23 years [11].

(2) The 1970–1982 eruptive activity of Karymskii Volcano was accompanied by long-term ground fluctuations of 5 to 20 mm near the base of the volcanic cone upon the background of a relative general subsidence of the ground within the caldera [11].

(3) The field of vertical movements near Karymskii Volcano observed within 1.7–3.5 km of its crater during the period 1972–1995 was satisfactorily explained by any isometric or axisymmetric source of pressure beneath the volcano, whose top is 1.5 km at the minimum from the ground surface [14].

(4) It is difficult to highlight any main factor responsible for the generation of horizontal extension near Karymskii Volcano within 3–4 km of its summit. The deformation seems to be primarily related to a more general process, viz., tectonic movements involving the Eastern volcanic belt of Kamchatka, and secondly to stress changes in the magma feeding system of the volcano and to swarms of local crustal earthquakes. The 1976, 1979, and 1980 eruptions involving outpouring of lava were occurring during a period when the ground surface was under extension at a rate of approximately 1.5×10^{-6}. At the same time, during the period 1989–1995, when the volcano was in repose, the ground surface was experiencing extension in almost all directions at a double rate (3×10^{-6} yr^{-1}) in the volcano's southeastern base, including the area of hot springs near the outlet of the Karymskii R. from Lake Karymskii (Fig. 1, inset), prior to the new 1996–2007 eruption. This may have been a sign that magma was coming to the volcano's peripheral chamber from greater depths [11, 13].

2. DEFORMATION AFTER THE JANUARY 1–2, 1996, EVENTS IN THE KARYMSKII VOLCANIC CENTER AND DURING THE 1996 ERUPTION OF KARYMSKII VOLCANO

The data on the ground deformation occurring after the start of the Karymskii eruption and when the January 1–2, 1996, eruption in the Akademii Nauk caldera stopped are given in [12]; these data were measured during February–September 1996 near these eruptive centers, no farther than within 2–8 km of them. The horizontal deformation occurring in a comparatively large area (approximately 12 by 28 km) can be found in [1]. Several preceding circumstances are to be noted. Firstly, this eruption of Karymskii Volcano was expected from seismic data. V.V. Ivanov and A.V. Storcheus, researchers at the IV FED RAS, gave an intermediate-term forecast for this eruption [5]. The measurements of vertical movements near the base of the volcanic cone carried out in the autumn of 1995 did not contradict this forecast, since the deformation changed sign, i.e., the subsidence of the base was replaced by uplift. Secondly, a large (M = 6.9) earthquake was not expected to occur in the Karymskii Volcanic Center, because such earthquakes had not been observed in the volcanic areas of Kamchatka for 50 years. Thirdly, there was even no suggestion that volcanic activity could resume in the near future in the caldera lake of Akademii Nauk Volcano (which was thought to be extinct) involving the ascent of basalts and a short-lived volcanic eruption.

The repeated geodetic measurements carried out during the period February–September 1996 after these events showed the following main features of the deformation occurring after the start of both eruptions.

(1) A local area of measured maximum deformation was outlined in the terrain. The area is situated between the calderas of Karymskii and Akademii Nauk volcanoes and extends north–south for ≈3.5 km (inset in Fig. 1) [12].

(2) East–west movements of different senses occurred in the area of maximum deformation, with the greatest measured extension being 2.3 m on a base of 3.6 km. The relative subsidence of benchmark 4 (situated 1.5 km north of the center of underwater eruption) measured by repeated leveling is equal to 0.80 m. The walls of the subsidence zone experienced an unequal rise, the west wall by 60–70 cm and the east by 20–30 cm [12].

(3) Apart from a comparatively small area (approximately 1.5 by 2.5 km), where the extension exceeded the strength limit of the rocks and was accompanied by visible faults [8], an extensive area was identified (of size approximately 15 by 16 km) around the new eruptive center in Lake Karymskii, where horizontal extension exceeds 1×10^{-5}. It was necessary to find the boundary of this deformation and the patterns governing its falloff as one moves away from the epicenter of the large January 1, 1996, earthquake and from the eruption centers by continuing and expanding repeated geodetic measurements to cover the entire area of the Karymskii Volcanic Center [12].

We should provide some explanation in this section of the 1997 paper [12]. This reference showed the horizontal movements determined for the sites 38, 39, and 40 (the inset in Fig. 1 and Fig. 2) situated in the caldera of the extinct Dvor volcano; these sites were believed to be fixed (measurements during many years showed that their relative positions have remained almost the same). This was done because there were no measurements at the distant sites at that time (connected to the network) near Karymskii Volcano. In recent years measurements were made at many sites, including distant ones, and it became possible to consider movements at sites close to the eruption relative to the distant ones. In particular, and soundly enough, site 7 was assumed to be the datum (Fig. 1), and the horizontal displacements of all the other sites relative to this datum, including the sites situated near Karymskii Volcano (Fig. 2), were determined relative to this datum. The results presented in Fig. 2 are more objective, and it is these results which should be considered in reinterpretations of the data on horizontal displacements for the period from 1989 and from 1990–1995 to May 1996.

The following measurements were made in 1996–2006 in order to determine the ground deformations occurring in relation to the eruption of Karymskii Volcano still occurring since January 2, 1996, and the accompanying seismic processes, as well as to determine the residual horizontal deformations over the entire area of the Karymskii Volcanic Center due to the large earthquake of January 1, 1996, mentioned above and to the almost simultaneous start of eruptions on the two volcanoes.

(1) Multiple measurements of 33 lines near the erupting Karymskii Volcano using geodimeters of accuracy within ±(2 mm 1×10^{-6} *D*), where *D* is the length of the line measured in millimeters (inset, Fig. 1).

(2) Repeated first-order levelings along a closed 20-km path with 34 benchmarks established as far back as in 1971 and still valid (inset, Fig. 1).

(3) Satellite GPS measurements at 21 sites of the special network (established previously by the FEAGC and consisting of 27 triangulation stations in the Karymskii Volcanic Center and adjacent areas of neighboring geologic features (Fig. 1).

Section 3 is devoted to a discussion of the 1997–2005 geodetic work.

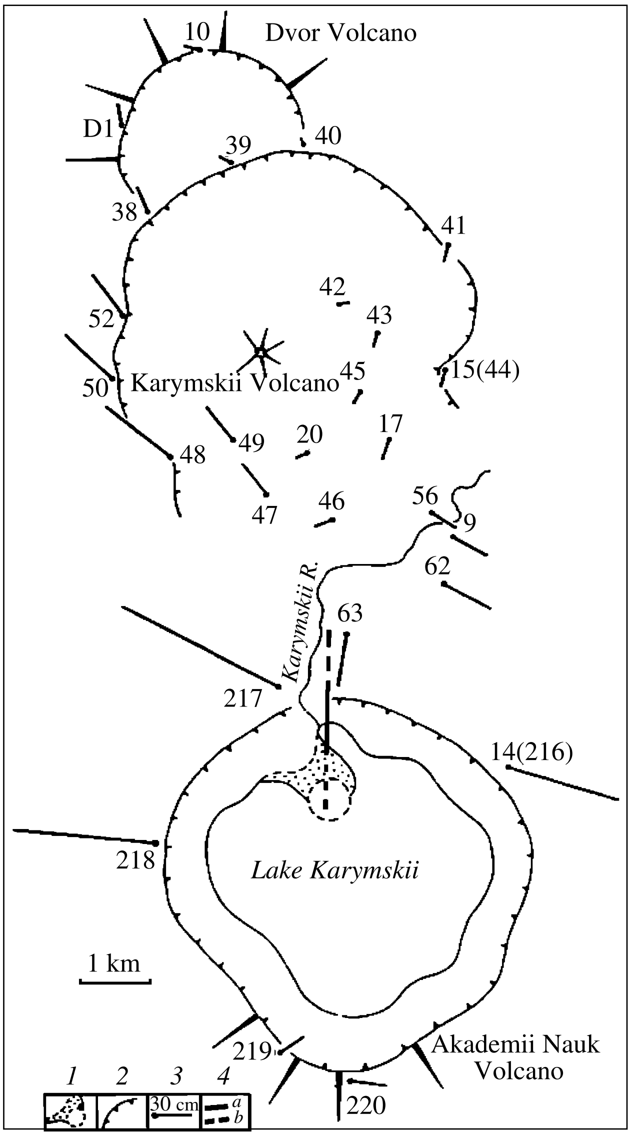

Fig. 2. Horizontal ground deformations near Karymskii Volcano and around Lake Karymskii after the January 1–2, 1996, eruptions for the period from 1989, and from 1990–1995 to May 1996 as calculated relative to station 7 and the direction 7–8 (Fig. 1): (*1*) the crater in the lake and the new peninsula generated by the eruption, (*2*) boundaries of the calderas of Dvor, Karymskii, and Akademii Nauk volcanoes, (*3*) directions and magnitudes of horizontal movements, their scale and station numbers, (*4*) open tension crack (*a*) and inferred crack extension (*b*).

3. DEFORMATIONS IN THE KARYMSKII VOLCANIC CENTER AND NEAR KARYMSKII VOLCANO DURING ITS 1997–2005 ERUPTION

The results of geodetic measurements of ground deformation using several technologies (multiple measurements of lengths of lines 0.5 to 5 km long using geodimeters and the GPS technology; lines of 5 to 20 km measured by the GPS technology, and first- and second-order levelings) are discussed separately.

3.1. Horizontal Components of Deformation

The work using Ashtech and Trimble satellite receivers of the NAVSTAR GPS system to determine distances and elevations between available geodetic stations was done in cooperation with the Laboratory of Geodynamic Research, Kamchatka Branch, Geophysical Service of the Russian Academy of Sciences (KB GS RAS) and by the Laboratory of Geodesy (IV FED RAS), now the Laboratory of Geodesy and Remote Sensing Techniques (IVS FED RAS) over four years (1996–2000) with a gradual expansion of the area covered. In the present case the observation and processing technology was able to measure distances to within ±1–2 cm and elevations (the difference between station altitudes) to within ±10 cm.

The GPS measurements determined the area of significant horizontal ground deformation (5×10^{-6} or greater) in the Karymskii Volcanic Center in an area of ≈30 × 40 km occurring in relation to the January 1, 1996, earthquake in the Karymskii Volcanic Center and the starting eruptions of Karymskii and Akademii Nauk

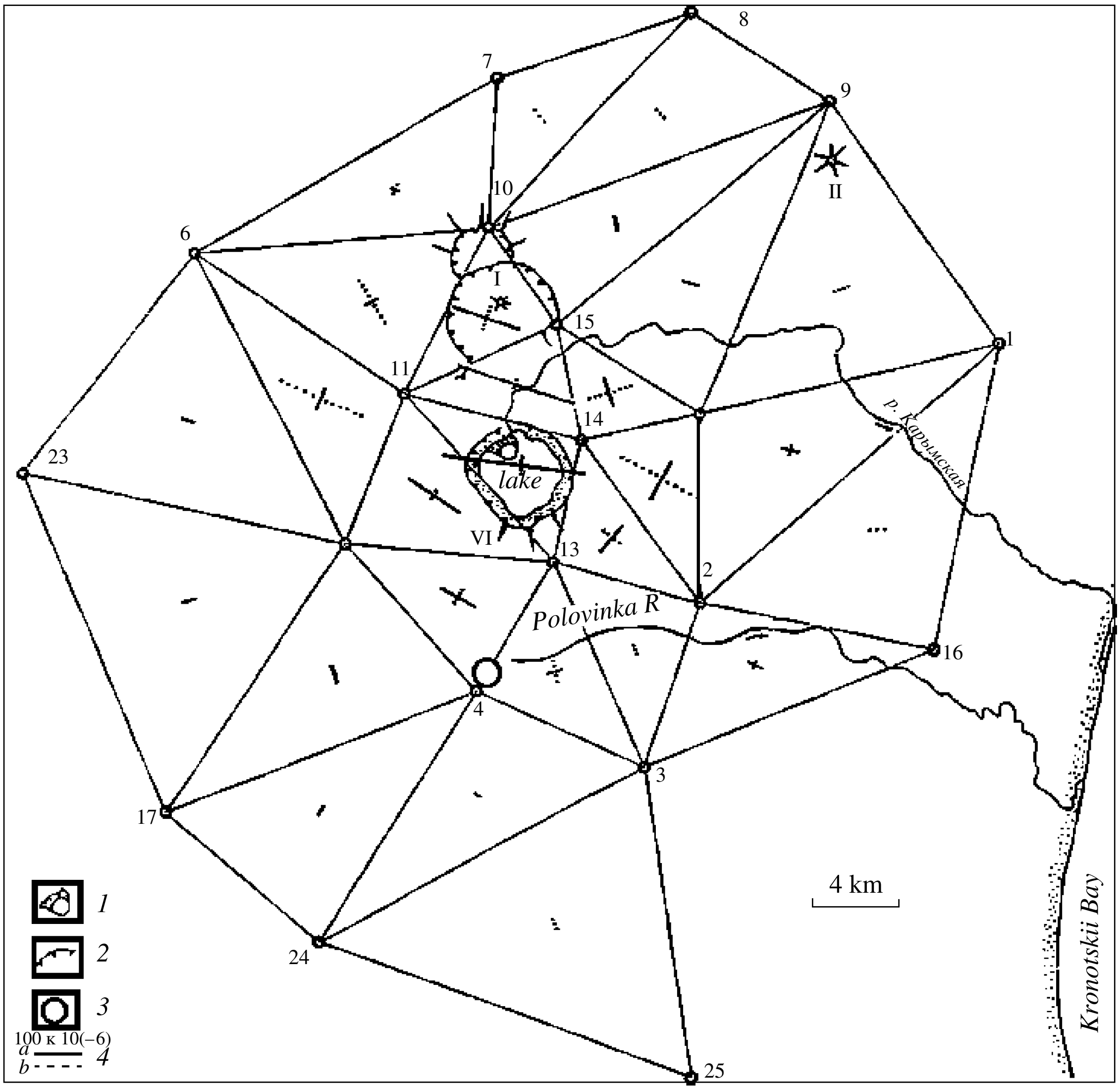

Fig. 3. Directions of the principal axes of plane extension–compression deformation and its magnitudes in the Karymskii Volcanic Center after the January 1–2, 1996, eruptions for the period from 1988 to 1996–2000 (the 1996, 1997, 1999, and 2000 data for the entire area were pooled to refer to a single epoch): (*1*) the crater of the underwater eruption in the Akademii Nauk caldera and the new peninsula generated by the eruption, (*2*) caldera boundaries, (*3*) epicenter of the mainshock magnitude 6.9, January 1–2, 1996, earthquake, (*4*) scale of plane deformation: (*a*) extension, (*b*) compression. Volcanoes: (I) Karymskii, (II) Malyi Semyachik, (VI) Akademii Nauk.

volcanoes. The maximum extensions of up to 2.34×10^{-4} were recorded in the area situated between the crater of the underwater eruption and the southern boundary of the Karymskii Volcano caldera (Fig. 3). The errors in determinations of 2D deformation along the principal axes lie within $\pm(1.2–2.4) \times 10^{-6}$.

Figure 4 illustrates changes of area (dilatation) for plane figures (triangles). These data outline the area of positive deformation. The maximum deformation is in the underwater crater area within the caldera of Akademii Nauk Volcano and equals $2.8 \times 10^{-4} \pm 2.2 \times 10^{-6}$. It is noteworthy that this same area contained the centers of ground dilatation in 1975–1977, 1977–1981, 1981–1983, and 1983–1988 as determined in [13]. The mean error of dilatation in triangles is $\pm 2 \times 10^{-6}$.

The boundary of zero deformation (in the present case the boundary between extension and compression areas) has an irregular shape; it is extended southwestward and northeastward from the center of the underwater eruption. The minimum distance of that boundary from the 1996–2000 eruptive center in the Akademii Nauk caldera is 5.3 km, the maximum is 17.6 km. The 1975–1988 line of zero horizontal deformation was more perfectly isometric, and its distance from the deformation center was 13 ± 3.5 km [20]. This shows

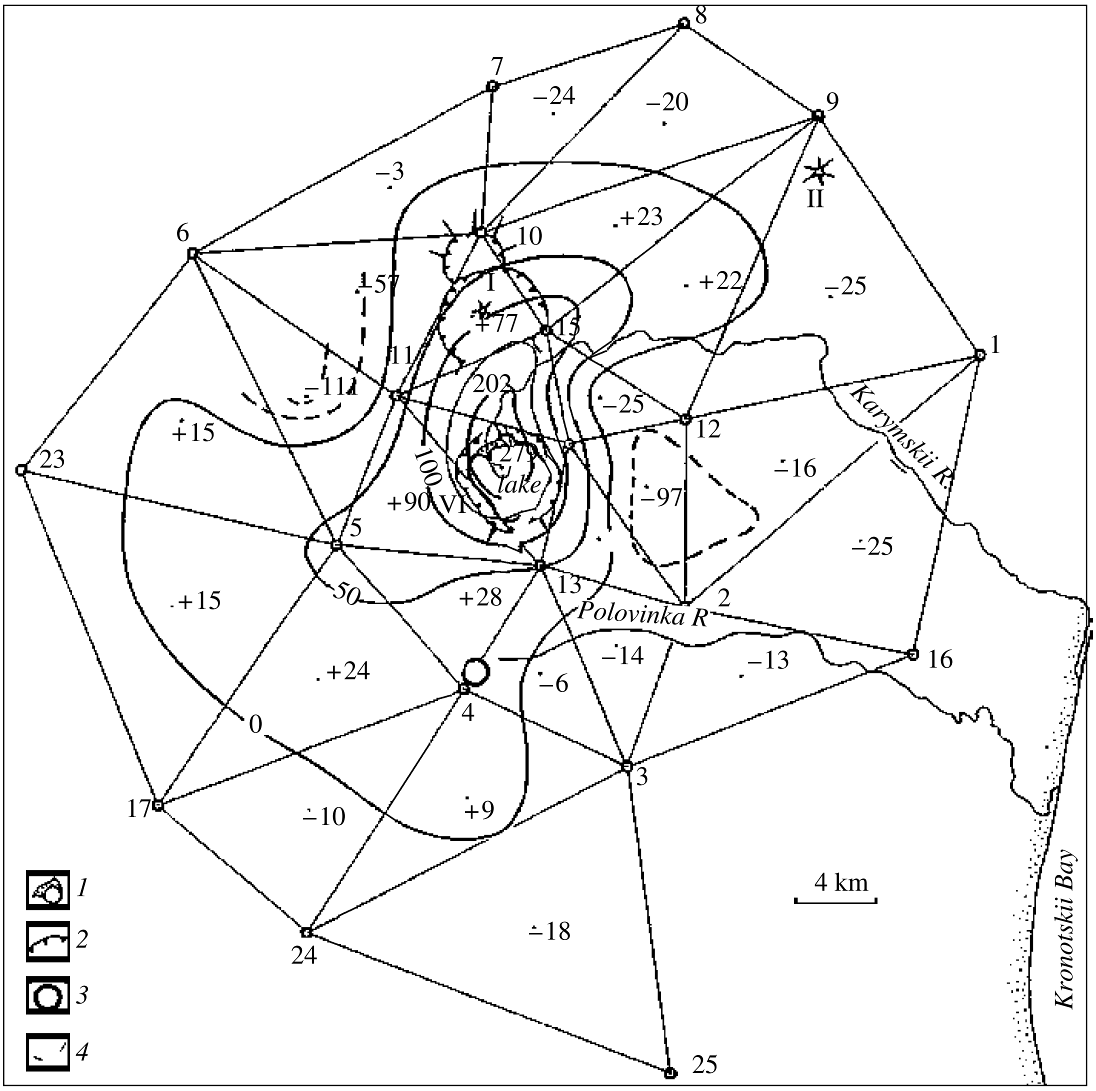

Fig. 4. Relative changes in the areas of plane figures (triangles): dilatations in the Karymskii Volcanic Center after the January 1–2. 1996, eruptions for the period from 1988 to 1996–2000 (1996, 1997, 1999, and 2000) in units of 10^{-6} (shown at the centers of triangles and as isolines over the area). The legend is as for Fig. 3; (*4*) lines of equal dilatation in 10^{-6}.

that the pressure center(s) were shallower in 1996–2000 (above 18.3 ± 0.8 km depth) than in 1975–1988.

The area of extension and positive dilatation is surrounded by a zone of compression and negative dilatation (Fig. 4). The dilatation is significant, since most of the values are well in excess of the error of determination, which varies within $\pm(1.2–2.4) \times 10^{-6}$. North and northeast the compression zone (-20×10^{-6}) goes beyond the limits of the Karymskii Geodynamic Test Site, and its boundaries can be determined (within the sensitivity of the method), when the area of repeated measurements is expanded.

Figure 5 shows the directions and magnitudes of the horizontal movements at the triangulation stations relative to station 7 and the direction angle of line 7–8; these were assumed to have been fixed during the period 1988–2000. The same figure also shows stations 18–22, 26, and 27, which had not yet been measured using the GPS technology. It is still not possible to determine their movements since 1988, i.e., since the time when the last classical geodetic measurements were made at them. The assumption of station 7 as the datum is entirely justified, since by available data the horizontal displacements in the area have always been minimal [13]. It should be noted that Fig. 5 shows, unlike Fig. 2, the horizontal movements of stations that are mostly distant from the eruptive centers. Stations 10, 14, and 15 are common to both figures. The horizontal deformation turned out to be asymmetrical about the center of the underwater eruption in the caldera of Akademii Nauk Volcano.

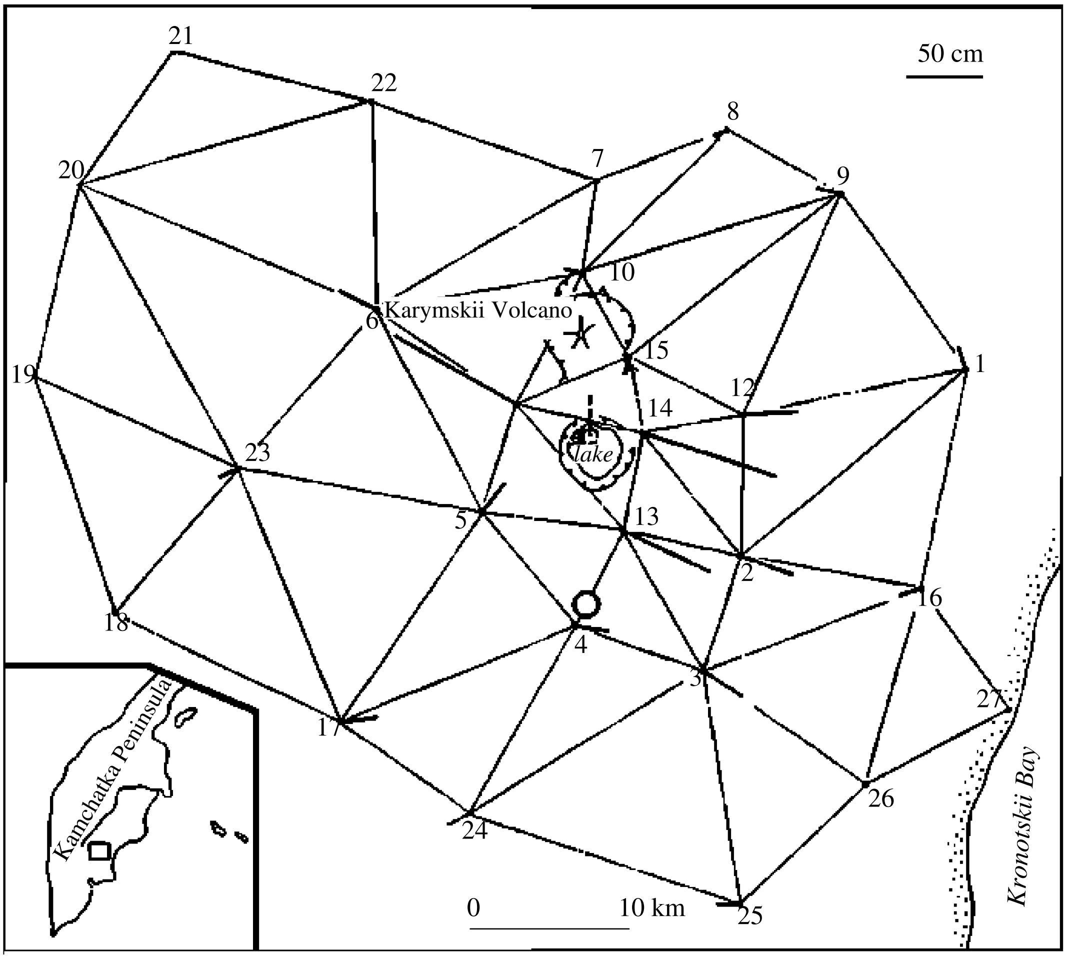

Fig. 5. Horizontal displacements of triangulation stations in the Karymskii Volcanic Center after the January 1–2, 1996, eruptions for the period from 1988 to 1996–2000 (1996, 1997, 1999, and 2000). The scale and directions of displacement are shown in the top right corner. For the legend see Figs. 2 and 3.

The observations of horizontal ground displacements close to the erupting Karymskii Volcano were conducted in 1986–2005 using a high precision SP-2 geodimeter (with accuracy ±(2 mm 2×10^{-6} D), where D is the length of the line in mm) and also in 2003–2006 using satellite two-frequency geodetic receivers. The frequency of measurement was 1–2 times per year. Figure 6 shows the positions of the stations where the instruments were installed. All stations, except 44, 216, and 218, are concrete posts. A metal plate is attached to the top of a post, and on this the instrument is placed, always in the same manner in plan view. Where there was no bedrock exposure, the post base was set at a depth of 2 to 3 m, with the bottom of the post being a massive concrete anchor. Metal supports were attached to the centers of stations 44 and 216, and these stations were set at the locations of triangulation stations 14 and 15 of the State Triangulation Network (Fig. 1). Station 218 consists of a metal tube with a cast-iron mark at the top and a concrete anchor at a depth of 1.5 m. Here, the instrument was installed on a wood support and was centered using an optic plumb bob to within ± 2 mm. The method that was used to attach the centers and to install the instruments facilitated a high precision determination of interstation distances. The choice of the area for comparatively frequent measurements was governed by the fact that the January 1–2, 1996, events in the Karymskii Volcanic Center involved large ground deformations [12].

Knowledge of the complete factual data is important for future investigations; accordingly, Table 1 lists all distances measured during the period from April 1996 to April 2005 (inclined distances, i.e., distances between the centers of geodetic stations). Horizontal ground displacements largely involve changes in the inclined distances between stations (provided there have been no appreciable vertical displacements, especially in terrains with large slope angles).

It follows from Table 1 that the April 1996 to October 1998 eruption of Karymskii Volcano was occurring

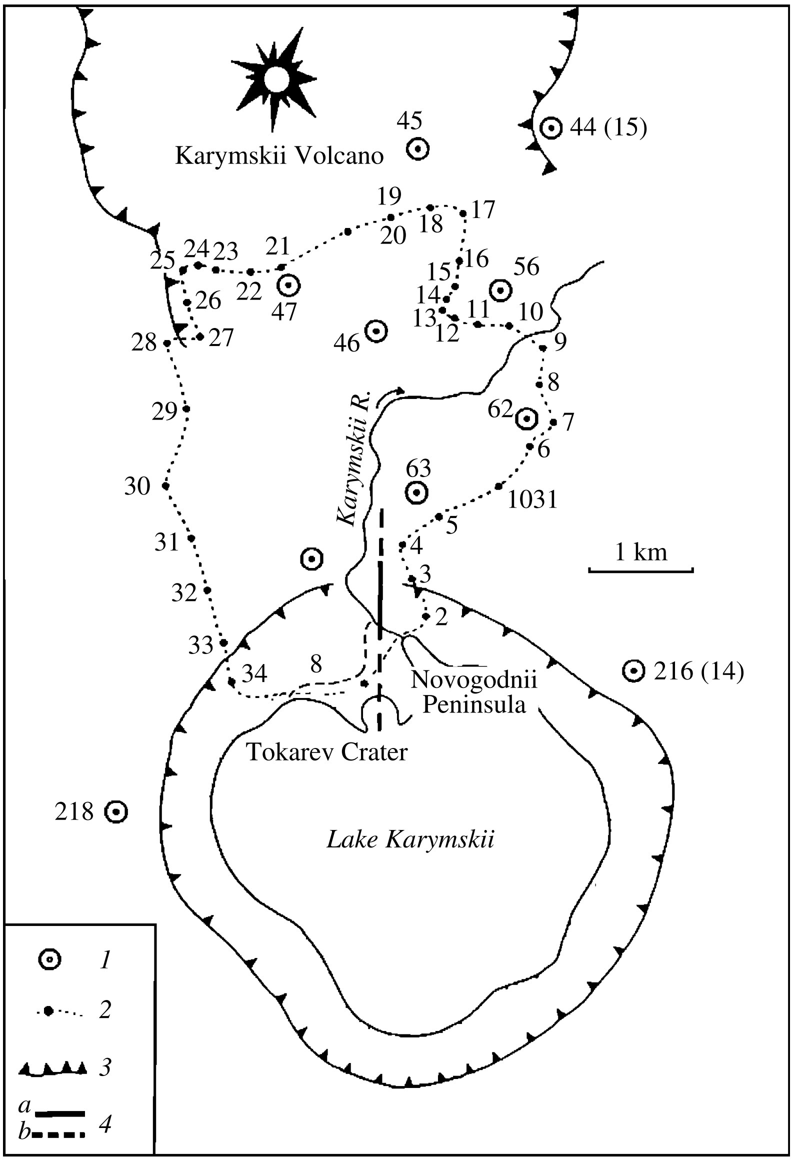

Fig. 6. Positions of geodetic sites near Karymskii Volcano and near the new eruptive center (the Tokarev crater): (*1*) sites where horizontal displacements have been measured, (*2*) leveling line and benchmark numbers. The other legend is as in Fig. 2.

in an extensional environment at an average rate of $+4.1 \times 10^{-6}$ yr^{-1} in the area outlined by the network of geodetic stations (Fig. 6). The extensional deformation had been decreasing from 1999 to 2003 at an average rate of $+1.8 \times 10^{-6}$. No significant (above the error) horizontal displacements were detected during the period of October 2003 to April 2005. It is impossible to determine the boundary of the extensional area for the period from April 1996 to April 2005 based on available data. This could be done by expanding the area of measurement. It should be noted that the changes in the lengths of lines (extensions) oriented approximately west–east are substantially greater than for the other directions (Table 1, Fig. 6).

3.2. Vertical Components of the Deformation

The vertical ground displacements in this same area were studied by repeated high precision levelings along a path having the shape of a closed polygon (Fig. 6). Complete leveling, i.e., along the entire closed path, was carried out during the summers and autumns of 1996, 1997, 2000, and 2001; as to the other years, the procedure was either carried out in some segments only or not at all. Table 2 summarizes the data, i.e., lists benchmark elevations based on determinations during the relevant years.

A previous publication of ours [12] gives vertical displacements of benchmarks along this path in relation to the January 1–2, 1996, events in the Karymskii Vol-

Table 1. Inclined distances (m) between geodetic centers measured during different years near Karymskii Volcano and between the calderas of Karymskii and Akademii Nauk volcanoes

Names of lines	Years								
	1996	1997	1998	1999	2000	2001	2003	2004	2005
9–62	634.354	4.356	4.358	4.360	4.357	4.357	4.359	4.361	4.359
9–63	1669.083	9.094	9.109	9.110	9.115	9.124	9.127	9.127	9.122
9–46	1526.896	6.906	6.916	6.923	6.925	6.927	6.928	6.930	6.930
9–47	2623.474	3.481	3.489	3.492	3.492	3.497	3.497	3.494	3.486
9–20	2233.340	3.350	3.362	3.364	3.363	3.368	3.369	3.364	3.366
9–45	2279.726	9.736	9.739	9.738	9.744	9.747	9.754	9.746	9.748
9–15	2159.299	9.300	9.303	9.305	9.308	9.310	9.322	9.318	9.315
9–56	444.264	4.265	4.263	4.268	4.263	4.269	4.266	4.264	4.265
62–63	1138.315	–	–	8.344	8.347	8.348	8.347	8.348	8.347
62–46	1500.042	–	–	0.056	0.055	0.059	0.056	0.058	0.058
62–56	869.095	–	–	9.103	9.102	9.099	9.107	9.108	9.108
63–47	2200.610			0.603	0.608	0.612	0.592	0.606	0.593
63–46	1330.215	0.222	–	0.221	0.224	0.223	0.220	0.221	0.218
46–47	1128.399	–	–	8.386	8.389	8.397	8.388	8.381	8.379
46–20	1050.891		0.894	0.892	0.894	0.897	0.892	0.893	0.896
46–45	1752.539	–	–	2.561	2.565	2.571	2.572	2.566	2.564
46–17	1301.632	–	–	1.654	1.660	1.664	1.668	1.659	1.657
46–56	1166.846	–	–	6.883	6.889	6.903	6.898	6.893	6.898
20–47	804.016	–	4.012	4.014	4.017	4.030	4.014	4.012	4.008
20–45	1011.237	–	1.242	1.248	1.251	1.263	1.246	1.247	1.252
20–15	2087.188	–	7.210	7.217	7.230	7.236	7.234	7.224	7.225
20–17	1091.601	–	–	1.613	1.617	1.617	1.624	1.614	1.622
20–56	1792.511	–	–	2.527	2.536	2.536	2.540	2.526	2.522
17–45	751.536	–	–	1.546	1.554	1.544	1.561	1.560	1.562
17–15	1148.806	–	–	8.819	8.822	–	8.838	8.834	8.827
17–56	1123.472	–	–	3.474	3.476	3.471	3.482	3.468	3.467
56–15	1907.291	–	–	7.301	7.302	7.312	7.315	7.309	7.304
45–15	1186.128	–	–	6.147	6.162	–	6.166	6.162	6.160
217–15	4803.211	3.233	–	–	3.232	–	3.257	3.256	3.255
217–9	3114.016	4.036	4.048	4.051	4.063	4.063	4.061	4.048	4.051
217–14	3573.322	3.365	3.362	–	3.376	–	3.367	3.366	3.364
14–15	5542.372	2.380	2.386	–	2.375	2.393	2.366	2.377	2.379
14–220	4986.851		6.838						
14–218	4914.097	4.085	4.114	–	4.123	4.129			
217–46	2418.960	–	–	–	8.952	8.960	8.966	8.961	8.964
217–47	2775.201	5.207	–	–	5.202	5.220	5.214	5.220	5.224
14–56	3822.381	–	2.402	–	2.404	2.407	2.381	2.387	2.386
217–218		2687.842	–	4.360	–	–	7.845	7.828	7.836

Note: The positions of geodetic stations are shown in Fig. 6.

Table 2. Benchmark elevations (m) found by leveling for different years near Karymskii Volcano and between the calderas of Karymskii and Akademii Nauk volcanoes

Benchmark no.	Heights above the Baltic Sea level			
	08.1996 ,,.	08.1997 ,,.	08.2000 ,,.	08.2001 ,,.
Benchmark 9	599.382	599.382	599.382	599.382
Benchmark 10	592.947	592.947	592.946	592.946
Benchmark 11	599.205	599.203	599.200	599.200
1 Ск. рп. 12@@	622.030	622.024	622.016	622.015
1 Ск. рп. 13@@	629.602	629.596	629.586	629.586
1 Ск. рп. 14@@	640.684	640.678	640.670	640.669
1 Ск. рп. 15@@	656.758	656.753	656.749	656.748
Benchmark 16	687.550	687.545	687.542	687.541
Benchmark 17	715.733	715.732	715.727	715.724
Benchmark 18	759.760	759.758	759.749	759.745
1 Ск. рп. 19@@	808.250	808.246	808.234	808.229
Benchmark 20	840.265	840.262	840.247	840.242
1 Ск. рп. 21@@	831.504	831.494	831.468	831.463
1 Ск. рп. 22@@	829.117	829.103	829.077	829.073
1 Ск. рп. 23@@	818.483	818.476	818.463	818.459
1 Ск. рп. 24@@	813.664	813.664	813.656	813.654
1 Ск. рп. 25@@	824.294	824.293	824.282	824.279
1 Ск. рп. 26@@	812.001	811.996	811.984	811.980
1 Ск. рп. 27@@	785.809	785.809	785.806	785.801
Benchmark 28	784.328	784.332	784.332	784.327
Benchmark 29	775.196	775.197	775.199	775.195
Benchmark 30	784.338	784.336	784.338	784.335
Benchmark 31	790.227	790.221	790.225	790.222
Benchmark 32	765.797	765.784	765.786	765.782
Benchmark 33	711.384	711.371	711.368	711.365
Benchmark 34	651.358	651.347	651.342	651.341

Note: The benchmark positions are shown in Fig. 6.

canic Center relative to station 40, which is situated in the caldera of the older Dvor volcano (inset in Fig. 1). A word of explanation is called for. At first, in May 1996, we determined the relative vertical displacement of benchmark 9 (Fig. 6) using lines of multiple trigonometric levelings (measuring angles of tilt and lengths of lines) to within ±2–3 cm. The January 1–2 events caused benchmark 9 to rise vertically, i.e., to rise relative to benchmark 40 in the Dvor caldera by 93 mm ± 20–30 mm. Subsequently, in September 1996, the vertical displacements of benchmarks on the leveling path itself were determined as before, from measurements of uniform accuracy, but in this case relative to benchmark 9 (Fig. 7), because there was no geodetic connection of this to the stations in the Dvor caldera. If an amount is added to or subtracted from the elevation of benchmark 9, the pattern of relative vertical displacements along the leveling path will not be affected. The error of elevation differences for the same benchmarks based on determinations carried out in different years (consequently, of vertical displacements) is equal to ±0.7 mm $\times \sqrt{L} \times \sqrt{2}$, where L is the distance (in kilometers) from the benchmark of interest to the benchmark that was assumed to be fixed.

Figure 8 illustrates the changes (relative to benchmark 9) in the ground level along the closed leveling path during different periods of time. One can see, in particular, that the 1996–2000 period of intensive effusive and explosive activity on Karymskii Volcano involved large (up to 12 mm per year) vertical movements (mostly subsidences) of the benchmarks. When the volcano's eruption was weaker in 2000–2001 (based on reports from the heads of the field teams), the subsidences of individual benchmarks did exceed 5 mm per year.

Special mention should be made of the movement (subsidence) of benchmark **B**. That benchmark is a temporary one. It was installed in 1997 in the peninsula which formed during the underwater eruption in Lake Karymskii. The peninsula is largely composed of coarse volcanic cinder and rock fragments ejected by explosions from the underwater crater and deposited by tsunami waves [15, 20]. The 2000 measurements showed a subsidence of this benchmark by 43 mm during the period 1997–2000; it practically retained its position during 2000–2001 (Fig. 8). The total subsidence of benchmark **B** for the period 1996–2001 might be about 70 mm, judging from the subsidence of benchmarks 21 and 22 in 1996–1997.

An analysis of the 1996–2005 observations (Table 2, Figs. 7, 8) shows that the deformation had the following properties.

(1) The benchmarks nearest to the crater of Karymskii Volcano, 18 to 26 (Figs. 6, 8) were subsiding at an average rate of 5–9 mm/yr during 1996–2001, but there is no direct relationship between the magnitudes of benchmark subsidence and the distance to the crater.

(2) The greatest vertical movements of different senses (Figs. 7, 8) were invariably observed in the segment between benchmarks 23 and 28 where the leveling path intersects the western boundary of the Karymskii Volcano caldera (Fig. 6). Less pronounced contrasting movements are also present in the segment of the leveling path in the area of benchmarks 3, 4, 5, 1031, and 6, near the northern boundary of the Akademii Nauk caldera (Figs. 6–8).

(3) The vertical movements along the leveling line during 1996–1997 and 1997–2000 were similar: a subsidence in the Karymskii caldera, benchmarks 17–24; the level maintained constant at the junction between the calderas, benchmarks 28–31 and 7–10; a subsid-

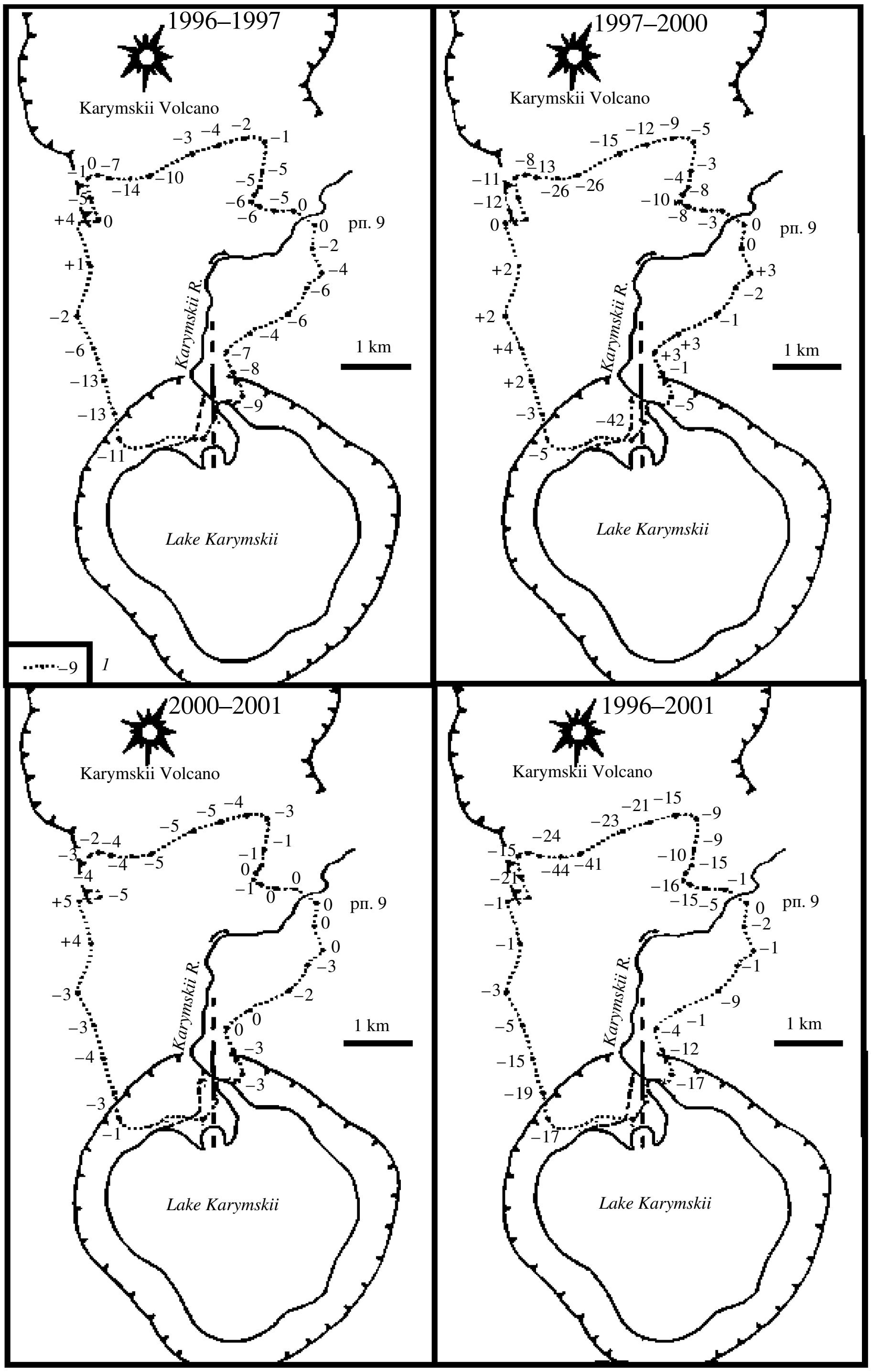

Fig. 7. Vertical benchmark movements in mm during different periods of time: (*1*) leveling line and vertical benchmark movement. For the other legend see Fig. 2.

ence near the northern edge of the Akademii Nauk caldera, benchmarks 33–3 (Figs. 6, 8).

(4) The results of the 1996–2001 levelings (Fig. 7) show that the vertical movements near the underwater crater in Lake Karymskii decrease away from the crater and are almost zero at a distance of about 2.2 km from it. The same occurs near the cone of Karymskii Volcano, but here the boundary of "zero" movements is farther off, at a distance of 3.2 km from the crater (Figs. 6–8).

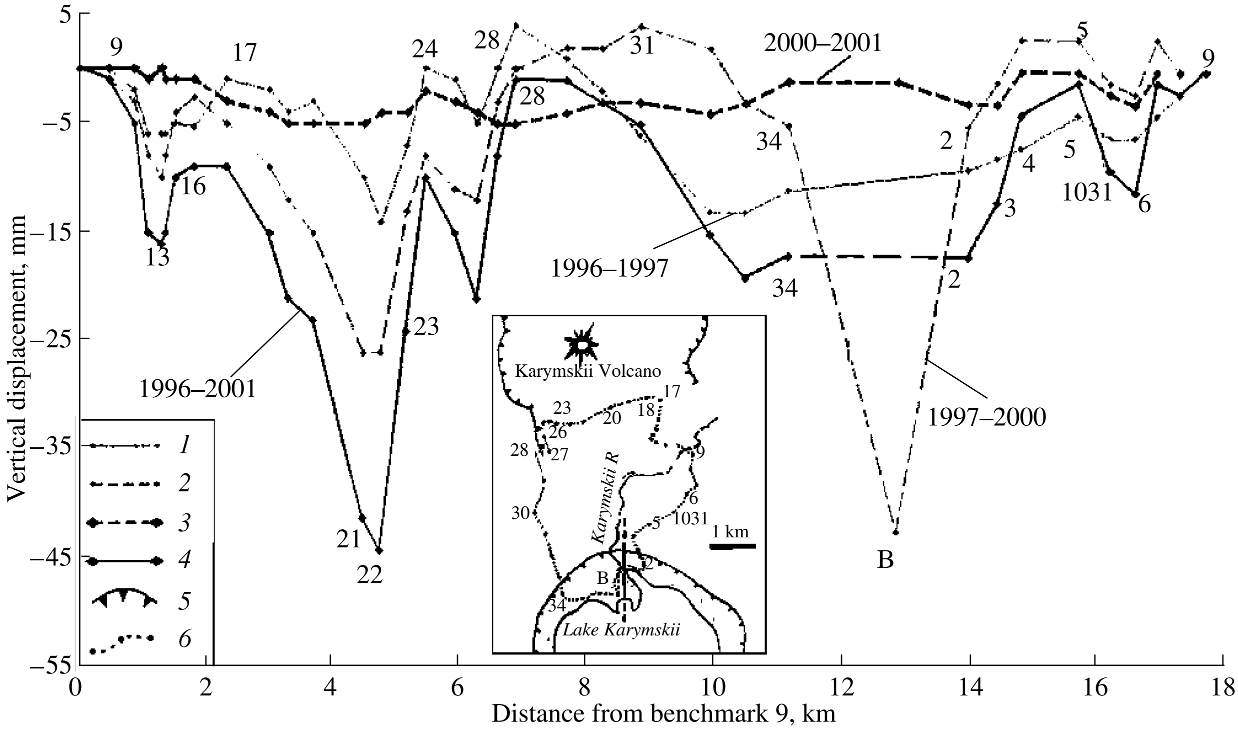

Fig. 8. Vertical movements along the leveling line during the following periods: (*1*) 1996–1997, (*2*) 1997–2000, (3) 2000–2001, (*4*) 1996–2001. The letter **B** marks the benchmark established in the new peninsula. The legend is as for Figs. 2 and 6.

(5) The subsidence of benchmark **B** probably was partially due to the compaction of deposits in the new peninsula.

Figure 9 shows an attempt at establishing a relationship of the ground deformation within the caldera of Karymskii Volcano to the volcano's activity and explosion earthquakes. Some of these data (for the year 1991) were given and discussed in [13]. Here we plot new data for 2005, which are of special interest in connection with the January 1–2, 1996, events in the Karymskii Volcanic Center. The upper broken line $\mathbf{a}_1$ reflects the 1973–1982 behavior of mean relative (in units of 10^{-6}) changes in the lengths of lines in the triangulation network around the volcano's cone at a distance of 2–4 km from its summit (inset in Fig. 1). The error of each 1982 data point is equal to $\pm 3 \times 10^{-5}$. Since 1986 similar data are shown (the broken line $\mathbf{a}_2$) for the area south-southeast of the crater (the area delimited by stations 20, 45, 44, 9, 62, 63, 217, and 47), (Figs. 6, 9, inset). The error of each data point is $\pm 3 \times 10^{-6}$ here, that is, an order less, which is explained by the advent of high precision instruments which could then be used at the time to measure the lines.

The data for the broken line of vertical displacement **b** have the same accuracy everywhere. The error of each determination (data point) is ± 2.4 mm. The curve shows the vertical displacements of benchmark 20 (that which is the closest to the active crater) relative to benchmark 9 (Fig. 9, inset). Since large vertical movements occurred in 1996 throughout the area, south of the older Dvor volcano [12], including those at benchmark 9, we considered the movements of benchmark 20 relative to station 40 situated in the caldera of the older Dvor volcano. It is this value (13 cm) that is indicated as the relative subsidence of benchmark 20 for the period 1995–1996. The error is ±2 cm. Subsequent determinations (points in the plot) are again the vertical movements of benchmark 20 relative to benchmark 9, as determined by first- and second-order leveling to within less than ±2.4 mm. The above actions are justified, because prior to 1996 the plot of vertical movements of benchmark 20 relative to station 40 had remained (within the error of determination) similar to that plotted relative to benchmark 9.

Figure 9 shows that the summarized slopes of broken curves representing horizontal and vertical ground deformation around the cone of Karymskii Volcano and its caldera for 33 years (1972–2005) did not change after the jumplike movements during the January 1–2, 1996 events in the Karymskii Volcanic Center.

We remind the reader that the Karymskii Geodynamic Test Site contains over 160 geodetic stations and benchmarks established for long-term operation, about 100 of these had relative altitudes to within a few millimeters and over 60 stations had their relative plan positions to within a few centimeters prior to the events referred to above. Some of these stations had been visited with high precision gravity surveys. It is rare good luck in "instrumental" volcanology, when an area of future volcanic and seismic events has been covered

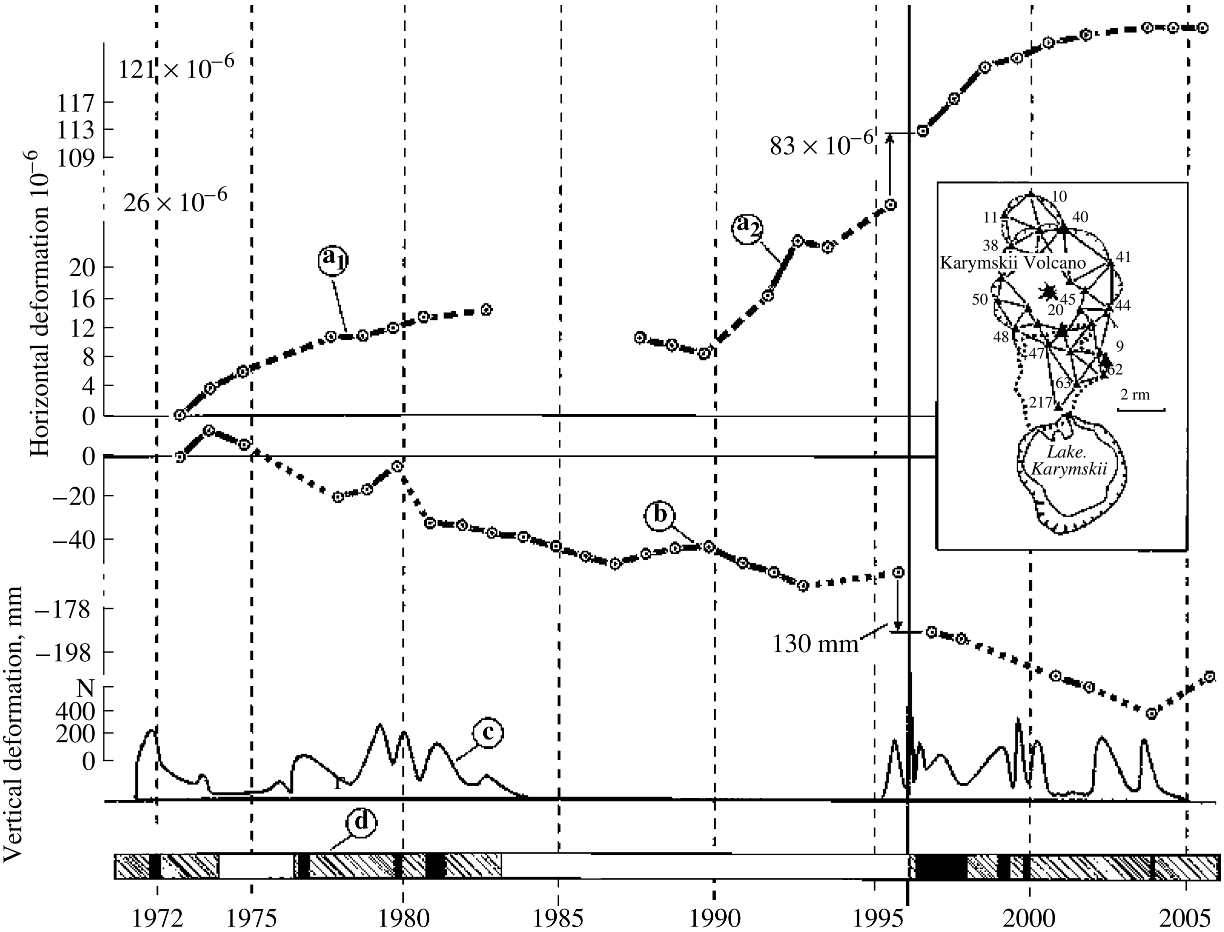

Fig. 9. Ground movements and the volcano's activity compared for 1972–2005: (**a**$_1$) mean value of changes in the lengths of lines (in 10^{-6}) of the triangulation network around the volcano's cone delimited by the stations 48–50–38–11–10–40–41–44–9–47, (**a**$_2$) same for the area delimited by the stations 20–45–44–9–62–63–217–47, **b**) vertical displacements of benchmark 20 relative to station 40 for the period 1972 to 1996, and relative to benchmark 9 for the period 1996 to 2005, (**c**) daily number of explosion earthquakes (of type N_4 after [18]); (**d**) volcano's activity: (I) repose phase, (II) phase of explosive eruption, (III) phase of effusive–explosive eruption [18]. The inset shows the triangulation network and the leveling line.

beforehand by a network of high precision geodetic measurements. The repetition of unique measurements at all these stations following the large (M = 6.9) earthquake of January 1, 1996, and simultaneous eruptions of two volcanoes in the Karymskii Volcanic Center is a very important scientific task. Such measurements are necessary for determining the changes that have occurred in the magma chambers beneath the Karymskii Volcanic Center.

If we want to get more reliable vertical deformation data over the entire area of the Karymskii Volcanic Center, it is necessary to carry out repeated high precision leveling and gravity determinations along the existing east–west and north–south paths that traversed the active volcanic center.

4. DISCUSSION OF RESULTS

First of all, we wish to note that the geodetic measurements near Karymskii Volcano in a 5 × 10 km area and in the Karymskii Volcanic Center in a 30 × 50 km area were carried out during the 1970–1982 eruption on Karymskii Volcano, during the 1983–1995 repose period [13, 14], and during its next eruption lasting from January 1, 1996, until now (April 2008) [11, 12]. This time the start of the eruption was accompanied by unusual and unique phenomena. A large (M = 6.9) earthquake occurred a few hours before it with the epicenter about 10 km south of Lake Karymskii. No earthquakes this size have been recorded in the Karymskii Volcanic Center in over 50 years (since the start of earthquake recording on Kamchatka volcanoes, 1946). Approximately 12 hours after the awakening of Karymskii Volcano, a simultaneous phreatomagmatic eruption began in Lake Karymskii situated in the caldera of Akademii Nauk Volcano. This volcano had been thought to be extinct. The eruption was caused by an emplacement of basalts along a fissure and lasted about 24 hours [15, 20].

These phenomena afforded the most favorable opportunity to observe and study a combination of unique natural phenomena occurring in the well-studied Karymskii Volcanic Center [20]. The occurrences studied included the eruptions and their evolution, the ejecta, the associated earthquakes, ground deformation, hydrogeochemical phenomena, the impact on the environment, and many other things. Comprehensive reviews of these issues can be found in many publications that appeared in 1996–2007. One of the main problems was to study the magma chambers and passageways, the magmatic feeding system, and the mechanism of volcanic activity in the Karymskii Volcanic Center. Seismological and geodetic data were an important contribution into the study of these problems. Below we briefly review some of these publications.

Fedotov [20] considered the start of the eruptions, estimated the position, depths, and dimensions for the shallow magma chambers beneath the calderas of Karymskii and Akademii Nauk volcanoes, and for the major intermediate crustal magma chamber of the Karymskii Volcanic Center, discussed the emplacement of a new basalt dike and a possible mechanism of the 1996 eruptions, and distinguishing features of the phreatomagmatic eruptions.

The intensive seismic activity that accompanied the 1996 eruption, the focal mechanism of the mainshock *M* 6.9 January 1, 1996, earthquake, and the evolution of swarms of its foreshocks and aftershocks are discussed in [2, 22].

Possible combinations of the magmatic pressure sources that could have caused the geodetic deformation in 1996–2000 are given in [6, 7].

The surface breakage that appeared along the extension of the feeding fissure supplying magma to the underwater eruption in the caldera of Akademii Nauk Volcano, and the relation of this breakage to the fault zone traversing the Karymskii Volcanic Center were considered in [8, 9].

The complicated and strongly varying deformation field observed in 1972–1995, 1996, and 1997–2005 in the Karymskii Volcanic Center around Karymskii Volcano and the location of the January 2, 1996 underwater eruption in the caldera of Akademii Nauk Volcano was due to several pressure sources. The present section of this paper deals with the relationship between the deformations and the volcanic activity and their mechanism inferred from geodetic data, primarily those recorded in 1996–2005.

Figures 2–5 show that the January 1, 1996, summit eruption of Karymskii Volcano and the starting eruption discharging basaltic magma at the bottom of the caldera lake of Akademii Nauk Volcano on January 2, 1996, were accompanied by a major west–east extension of the ground on both sides of the erupting fissure.

Horizontal and vertical ground deformations were measured, as was described above, in the Karymskii Volcanic Center in a 30×50 km area, around Karymskii Volcano in a 40 km^2 area, near the location of basaltic outpouring, and at the junction between the calderas of Karymskii and Akademii Nauk volcanoes. The deformations turned out to have all possible senses of movement, i.e., there were areas of extension and compression, subsidence and uplift. The direct geodetic measurements made in early February 1996, about one month after the January 1–2, 1996, events, revealed large horizontal (1 to 2.5 m) and vertical (–0.7 to +0.6 m) movements at the sites between the calderas of Karymskii and Akademii Nauk volcanoes. Visual observation after snow removal revealed abundant surface breakage around the source of the Karymskii River flowing from the lake and farther on the eastern slopes of the river valley. The largest fissure had a continuous visible length of 700 m, its width varied between 50 cm and 2–2.5 m, the east side was downthrown by about 1 m [8]. Relatively smaller fissures interpreted in airborne photographs and by visual observation were seen in an area measuring 1.6 km east–west and 2.2 km north–south (personal communication by V.N. Dvigalo). A detailed investigation of this area revealed the fact that all faults (fissures) strike nearly north–south and were found on both sides, eastward and westward, of the Karymskii River for 1.7 and 2.2 km from it, respectively [9]. It is somewhat difficult to elucidate the origin of this breakage, because there were no observers at the time of their generation and we do not know whether they appeared at the time of the large earthquake (10 km from its instrumental epicenter) or after it.

A number of studies have considered the probable mechanisms for and the relations among the eruptions on Karymskii Volcano, in the caldera of Akademii Nauk Volcano, and the ≤ 6.9 earthquake of January 1–2, 1996 in the Karymskii Volcanic Center [2, 20, 22, etc.]. Below we discuss some features that are related to ground deformation.

The geodetic measurements in the Karymskii Volcanic Center during the period 1983–1988 revealed ground extension, which was the greatest between Karymskii and Akademii Nauk volcanoes [13]. This may have been due to the increasing pressure in the crustal magma chamber beneath the Karymskii Volcanic Center and, as a consequence, to a ground extension above the pressure center (probably accompanied by ground uplift above the pressure center). The extension in the main fault zone striking northeast could create favorable conditions for the emplacement of basaltic magma from the crustal chamber.

Simultaneously with this process, precursory phenomena before the January 1, 1996, summit eruption of Karymskii Volcano were taking place. Microearthquakes began to occur under the volcano's southeastern slope. Judging from the occurrence times of earthquake hypocenters [2], this was related to the generation of fissures in the junction zone between the calderas of Karymskii and Akademii Nauk volcanoes, and farther southward. This could have accelerated the time of occurrence of a large volcano-tectonic earthquake that occurred in the southern Karymskii Volcanic Center and was due to independent tectonic processes. A magnitude 6.9 earthquake occurred there at 21 h 57 min Kamchatka time, 4 hours after the start of an earthquake swarm (Figs. 3–5). Approximate estimates give the depth of that earthquake as 10 km. The eruption of Karymskii Volcano began in a few hours. We note that moderate earthquakes ($M = 4.6$ in 1977 and $M = 5.5$ in 1978) occurred in that part of the Karymskii Volcanic Center without any apparent relation to the eruptions of Karymskii Volcano [2].

This large earthquake of January 1, 1996, $M = 6.9$, may have facilitated the emplacement of basaltic magma from the crustal chamber into the fault zone through a fissure that afterwards was the main feeding dike of the eruption.

The basalts came onto the surface at the lowest point of the fissure on the bottom of Lake Karymskii. The dike emplacement caused an extension of the surface by 2.5 m and a local subsidence in a narrow fault zone (Figs. 2, 7). At the same time, the walls of that zone remained uplifted. This could happen, if the cracked narrow zone adjacent to the main tension fissure settled down into it by its own weight. From geodetic data the approximate subsided volume in a 1×4 km area with an average subsidence of 0.5 m was 0.002 km^3. The empty upper cavity of the feeding fissure could have approximately the same volume and equal $1 \times 2000 \times 1000$ m $= 2 \times 10^6$ m^3.

The relative vertical benchmark movements measured near the base of the Karymskii Volcano cone (Figs. 6, 7) could be caused by a spherical and cylindrical pressure source, the peripheral magma chamber beneath the cone and caldera of Karymskii Volcano.

The large benchmark subsidences near the eruptive center in Lake Karymskii (Figs. 7, 8) were observed in the location where basalts were emplaced along the eruptive fissure to cause the greatest ground extension, about 3 m (Fig. 2).

Overall, direct measurements of horizontal and vertical ground deformations and their changes as monitored, as well as the volcanological and seismological data [20, etc.] suggest the following sequence of events and the most likely causes of the deformations.

(1) The long-term excess pressure in the crustal magma chamber at a depth of about 18 km beneath the Karymskii Volcanic Center, which has connection with a deep mantle magma source, caused the 1983–1995 ground extension between Karymskii and Akademii Nauk volcanoes.

(2) The pressure in the peripheral magma chamber beneath Karymskii Volcano began to increase. This gave rise to microearthquakes under the volcano, which propagated southward along the weakened fault zone toward Akademii Nauk Volcano.

(3) The increased seismic activity of the area between Karymskii and Akademii Nauk volcanoes was followed in a space of 4 hours by the January 1, 1996, magnitude 6.9 volcano-tectonic earthquake occurring 10 km south of Lake Karymskii at a depth of about 10 km.

(4) The large earthquake accelerated the start of the explosive eruption on Karymskii Volcano, whose first signs were noticed a few hours after the earthquake.

(4) The large earthquake and its faulting facilitated the emplacement of magma from the crustal magma chamber along fissures into the weakened fault zone, which extends along the Eastern Kamchatka volcanic belt across Karymskii and Akademii Nauk volcanoes. Basalts penetrated to the surface in that part of the zone between Karymskii and Akademii Nauk volcanoes, their calderas and peripheral chambers. The fault zone is about 1 km wide in that part.

About 14 h after the large earthquake, the basaltic magma that was being emplaced along a fissure reached the surface at the lowest point of the fissure on the bottom of Lake Karymskii; the phreatomagmatic eruption which began there lasted about 24 h.

CONCLUSIONS

(1) The ground deformations in the Karymskii Volcanic Center were due to increasing pressure in the associated magma chamber during the period from 1972 to 1995 (the center of the chamber is at a depth of about 18 km) and to three almost simultaneous events: the shallow magnitude 6.9 earthquake, the start of the next (after a 13-year repose period) eruption on the andesite–dacite Karymskii Volcano, the outbreak of basalts, and the short-lived eruption in the caldera of Akademii Nauk Volcano generating surface breakage (cracks).

(2) The 1988 geodetic measurements revealed deformations (as large as 8×10^{-6} yr^{-1}) that were extending the ground surface mostly east–west in the area between the calderas of Karymskii and Akademii Nauk volcanoes and farther south. The deformations continued in 1992–1995 and were precursors to the 1996 eruption in the area.

(3) The successive period of activity on Karymskii Volcano lasting from 1996 until now (February 2008) was preceded by a mostly northeast ground extension around the volcano's cone at a rate of 3.5×10^{-6} yr^{-1}. The extension may have begun in 1991. The base of the volcano's cone was subsiding at a rate of 5 mm per year in 1991–1993, but rose by 5 mm in 1995 compared with 1992. The rise was a precursor to the eruption of Karymskii Volcano.

(4) The 1996–2003 eruption of Karymskii Volcano was occurring in an extensional and subsiding environment existing around the volcano's cone and caldera. An extension was occurring at a rate of 4.1×10^{-6} yr^{-1} during the period April 1996 to October 1998 in a 3×5 km area situated southeast of the volcano's cone and containing hot springs in a cuplike valley 1–2 km from the source of the Karymskii River. The extension was decreasing from 1999 to 2003, the average rate was

$+1.8 \times 10^{-6}$. No significant (above the uncertainty) horizontal movements were found to occur between October 2003 and October 2005. At the same time, leveling revealed a beginning of uplift affecting the southeastern base of the volcano's cone. The benchmark rose +15 mm during these two years (Fig. 9).

(5) The epicenter of the magnitude 6.9 January 1, 1996, earthquake in the Karymskii Volcanic Center was situated near the region of compression for the upper crustal layers found from geodetic data.

(6) The greatest ground deformations observed by geodetic methods in the Karymskii Volcanic Center during the period 1972–2005 were horizontal extensions as large as 3 m occurring at the location where basalts were forced to the surface and discharged on January 2, 1996, between Karymskii and Akademii Nauk volcanoes. The distance between the vent of Karymskii Volcano and that of the phreatomagmatic eruption in Lake Karymskii, which erupted simultaneously on January 2, 1996, is equal to 6.5 km. The main fissure extending from the vent of the underwater eruption toward Karymskii Volcano is about 2.5 km long. This fissure of basalt penetration formed above the pressure center situated in the crustal magma chamber at a depth of 18 km.

(7) We conclude by noting that the deformation processes occurring in the Karymskii Volcanic Center can be comprehensively studied by continuous geodetic measurements conducted over the entire area. To a first approximation these processes can be found by discrete geodetic measurements. Continuous measurements are practically impossible without automatic equipment. Measurements in the entire area require considerable financial expenditures. Knowledge of the deformation and its further evolution over the entire area of the Karymskii Volcanic Center is important and necessary for understanding the processes responsible for magma emplacement in the upper crust, the depth, dimensions, and mechanism of magma chambers, and the mechanism of and hazards posed by volcanic eruptions.

ACKNOWLEDGEMENTS

The authors thank V.V. Yudin, A.V. Babenko, K.M. Magus'kin, N.N. Titkov, V.M. Miroshnikov, V.V. Pilipenko, and all colleagues with the Geodetic Team of the Karymskii Expedition organized by the Institute of Volcanology and Seismology, FED RAS for their contributions into the performance of field geodetic measurements in the Karymskii Volcanic Center during the period 1996–2005 and help in data processing.

This work was supported by the Russian Foundation for Basic Research projects nos. 05-05-64730a and 06-08-08169 and by the Program for Basic Research no. 16 of the RAS Presidium, project 2.7.

REFERENCES

1. Karymskii Volcano. Seismic, Geodynamic, and Postvolcanic Processes. Problems in Short-Term Prediction of the Start of Eruption, in *Noveishii i sovremennyi vulkanizm na territorii Rossii* (Neotectonic and Recent Volcanism in the Area of Russia), Moscow: Nauka, 2005, pp. 510–542.
2. Gordeev, E.I., Droznin, D.V., Kasahara, M, et al., Seismic Phenomena Associated with the 1996 Volcanic Eruptions of Karymskii Volcano and in the Akademii Nauk Caldera, *Vulkanol. Seismol.*, 1998, no. 2, pp. 28–48.
3. Ivanov, B.V., *Izverzhenie Karymskogo vulkana v 1962–1965 gg. i vulkany Karymskoi gruppy* (The 1962–1965 Eruption of Karymskii Volcano and the Volcanoes of the Karymskii Group), Moscow: Nauka, 1970.
4. Ivanov, B.V., Braitseva, O.A., and Zubin, M.I., Karymskii Volcano, in *Deistvuyushchie vulkany Kamchatki* (The Active Volcanoes of Kamchatka), vol. 2, Moscow: Nauka, 1991, pp. 182–203.
5. Ivanov, V.V., Predictions of Major Volcanic Eruptions in Kamchatka and Their Success Rate, *Vestnik DVO RAN*, 2003, no. 5, pp. 97–107.
6. Levin, V.E., Magus'kin, M.A., Bakhtiarov, V.F., et al., Recent Crustal Movements in Kamchatka and Their Relation to Seismic and Volcanic Activity, in *Kompleksnye seismologicheskie i geofizicheskie issledovaniya Kamchatki. K 25-letiyu Kamchatskoi opytno-metodicheskoi seismologicheskoi partii* (Multidisciplinary Seismological and Geophysical Studies of Kamchatka. The 25 Years of the Kamchatka Technique Testing Seismological Team), Petropavlovsk-Kamchatskii: Kamchatskii Pechatnyi Dvor, 2004, pp. 113–135.
7. Levin, V.E., Magus'kin, M.A., Bakhtiarov, V.F., et al., The Multisystems Geodetic Monitoring of Recent Crustal Movements in Kamchatka and the Commander Is., *Vulkanol. Seismol.*, 2006, no. 3, pp. 54–67.
8. Leonov, V.L., Surface Breakage Associated with the Earthquake and Eruptions which Occurred in the Karymskii Volcanic Center on January 1–2, 1996, *Vulkanol. Seismol.*, 1997, no. 5, pp. 113–129.
9. Leonov, V.L., Theoretical Models and the Reality: Conditions for Faulting in the East Kamchatka Volcanic Belt, in *Geofizicheskii monitoring Kamchatki* (Geophysical Monitoring of Kamchatka), Petropavlovsk-Kamchatskii: Ottisk, 2006, pp. 194–201.
10. Magus'kin, M.A., Ground Displacements in the Karymskii Volcano Area Based on the 1972–1974 Measurements, in *Sovremennye dvizheniya zemnoi kory. Issledovaniya na geodinamicheskikh poligonakh* (Recent Crustal Movements: Investigations at Geodynamic Test Sites), Novosibirsk: Nauka, 1978, pp. 45–50.
11. Magus'kin, M.A. and Levin, V.E., Geodetic Monitoring of Crustal Deformation in the Karymskii Volcanic Center, in *Problemy eksplozivnogo vulkanizma (k 50-letiyu katastroficheskogo izverzheniya vulkana Bezymyannyi): Mater. mezhdunarodnogo simpoziuma 25-30 marta 2006 g.* (Problems of Explosive Volcanism: The Fifty Years of the Catastrophic Eruption of Bezymyannyi Volcano. Materials of the First International Symposium March 25–30, 2006), Petropavlovsk-Kamchatskii: IViS DVO RAN, 2006, pp. 157–165.

12. Magus'kin, M.A., Fedotov, S.A., Levin, V.E., and Bakhtiarov, V.F., Ground Deformation Related to the Seismic and Volcanic Activity in the Karymskii Volcanic Center, January 1996, *Vulkanol. Seismol.*, 1997, no. 5, pp. 97–112.

13. Magus'kin, M.A. and Sharoglazova, G.A., Ground Deformation in the Karymskii Volcanic Center, *Vulkanol. Seismol.*, 1992, no. 4, pp. 90–110.

14. Magus'kin, M.A., Enman, V.B., Seleznev, B.V., and Shkred, V.I., Ground Deformation on Karymskii Volcano Based on Geodetic and Photogrammetry Data for the Period 1970–1981, *Vulkanol. Seismol.*, 1982, no. 4, pp. 49–64.

15. Murav'ev, Ya.D., Fedotov, S.A., Budnikov, V.A., et al., The 1996 Volcanic Activity in the Karymskii Center: The Summit Eruption of Karymskii Volcano and the Phreatomagmatic Eruption in the Akademii Nauk Caldera, *Vulkanol. Seismol.*, 1997, no. 5, pp. 38–71.

16. Selyangin, O.B., *Petrogenezis bazal't-datsitovoi serii v svyazi s evolyutsiei vulkanostruktur* (The Petrogenesis of the Basalt–Dacite Series in Connection with the Evolution of Volcanic Structures), Moscow: Nauka, 1987.

17. Selyangin, O.B. and Braitseva, O.A., Malyi Semyachik Volcano, in *Deistvuyushchie vulkany Kamchatki* (Active Volcanoes of Kamchatka), vol. 2, Moscow: Nauka, 1991, pp. 162–176.

18. Tokarev, P.I., *Vulkanicheskie zemletryaseniya Kamchatki* (Volcanic Earthquakes of Kamchatka), Moscow: Nauka, 1981.

19. Tokarev, P.I., Karymskii Volcano in 1965–1986, *Vulkanol. Seismol.*, 1989, no. 2, pp. 3–13.

20. Fedotov, S.A., On the 1996 Eruptions in the Akademii Nauk Caldera and on Karymskii Volcano, Kamchatka, the Study and Mechanism of These, *Vulkanol. Seismol.*, 1997, no. 5, pp. 3–36.

21. Khrenov, A.P., Dubik, Yu.M., Ivanov, B.V., et al., The Eruptive Activity of Karymskii Volcano for Ten Years (1970–1980), *Vulkanol. Seismol.*, 1982, no. 4, pp. 29–40.

22. Zobin, V.M. and Levina, V.I., Rupture History of the January 1, 1996, M_S 6.6 Volcanic Earthquake Preceding the Simultaneous Eruption of Karymsky and Akademia Nauk Volcanoes in Kamchatka, Russia, *J. Geophys. Res.,* 1998, vol. 103, no. B8, pp. 18 315–18†324.

SPELL: 1. Ск