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Contemporary Crustal Movements (CCMs) in Kamchatka

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Abstract—The works on geodetic monitoring of the contemporary crustal motions (CCMs) in the region of the Kamchatka Peninsula and Komandor Islands for the 40-year history of instrumental observations are reviewed. The examples of CCM recording by the classical geodetic methods and, since 1996, by the Global Positioning System (GPS) are presented. The deployment of the regional network for GNSS observations by the Kamchatka Branch of the Geophysical Survey of the Russian Academy of Sciences (KAMNET) made it possible to study the geodynamical processes at the junction of three major plates (Eurasian, North American, and Pacific) and smaller plates (Okhotsk and Bering). The interpretation of the examples of recorded CCMs is presented. The prospects of further development in the field of studying the geodynamics of the Koryak-Kamchatka region are outlined.

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INTRODUCTION

The works on studying the contemporary crustal motions (CCMs) on the Kamchatka Peninsula were started by the scientific institutions of the Academy of Sciences of the former USSR (Institute of Physics of the Earth and Institute of Volcanology and Seismology, hereinafter, referred to as IVS FEB RAS) and Organization 2 of the Main Geodesy and Cartography Board (GUGK) at the Council of Ministers of the former Soviet Union as early as the 1970s. For implementing these works, local research test areas were organized in the regions of active volcanoes (Avacha, Karym, Tolbachik, Klyuchevskoi, Gorelyi, Ksudach) and epicentral zones of the probable strong earthquakes (Avacha, Kronotskii, and Kamchatka bays) (Fig. 1a). Long profiles of high-precision leveling were set up along the eastern coast of Kamchatka and the central Kamchatka depression, and perpendicular to the Kuril-Kamchatka seismofocal zone (Fig. 1b). In 1979, laser rangefinder monitoring of CCMs in the region of Avacha Bay from the Mishennaya Observatory was organized. The similar optical distance monitoring was later launched in the United States (California), Japan, and in other regions of the former Soviet Union at the prognostic test areas in Tajikistan (Garm), Kyrgyzstan (operated by the Joint Institute for High Temperatures of the Russian Academy of Sciences, JIHT), and Turkmenistan (Ashkhabad).

The CCM studies in Kamchatka were intended for the solution of the following tasks:

—to carry out the detailed analysis of CCMs in active volcanoes;

—to explore the CCMs related to strong earthquakes;

—to measure the CCMs as the manifestation of plate motion (Fedotov and Enman, 1973).

The works in the first two directions have been conducted since the early 1970s by the classical geodetic methods (trilateration, leveling), with the instruments of highest precision achievable at that time. Trilateration allowed the researchers to determine the mutual positions of the geodetic sites in the plan with an error of 1×10^{-6} with sides of 10–30 km in length; the leveling measurements provided the mutual positions in altitude with an error of 0.5×10^{-6}.

By the end of the 20th century, the precision possibilities of the single-beam optical distance instruments, which were limited to 1×10^{-6}, for CCM monitoring were exhausted, whereas the laser rangefinder refractometers in Russia (Armand et al., 1990) providing the precision of 1×10^{-7}, had been at the prototype designing stage. A crisis was observed in the development of CCM studies. However, at the same time,

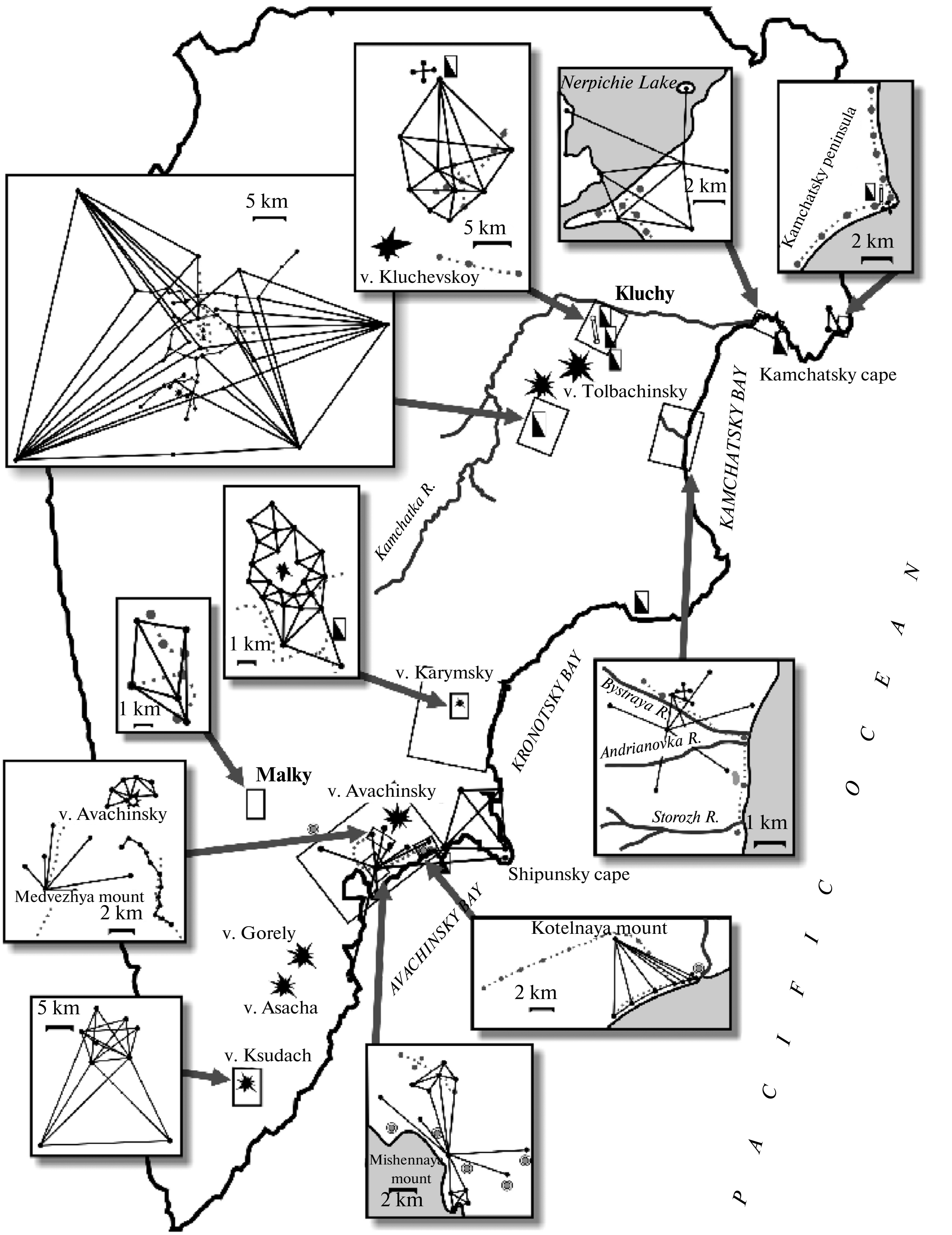

Fig. 1. The layout of the local test areas and high-precision leveling profiles organized (a) by the Institute of Volcanology and Seismology, Far East Branch of the Academy of Sciences of the former Soviet Union and (b) by GUGK Organization no. 2 at the Council of Ministers of the former Soviet Union, in Kamchatka in 1971–1984.

rapid advance was made in the Global Navigation Satellite Systems (GNSS), initially with GPS-based systems and later with the GLONASS satellites, and for the further CCM studies in Kamchatka and the Komandor Islands, the existing measurements were reoriented to using these systems.

Even the initial experience in applying GPS for geodetic purposes in the first half of the 1990s has shown that the new technologies enable the mutual positions of points located hundred kilometers from each other to be determined as precisely as within ±2–3 cm and, moreover, these measurements are highly efficient from the financial standpoint. Towards the mid-1990s, many foreign companies began to produce special-purpose geodetic receivers. Simultaneously, progress was achieved in the methodical questions associated with the allowance for the atmospheric effects by designing the advanced models of dry and wet air components. The ability of GPS receivers to work with dual frequency transmissions made it possible to accurately take into account the ionospheric delays by the same dispersion method that was applied in the precision rangefinder refractometers. The critical step towards increasing the precision of the civil GPS applications was the organization in 1994 of a special service working in close cooperation with the international community and intended for providing all customers with high-precision orbital parameters of the satellites. This service was named the International GNSS Service (IGS). During IGS's operation it turned out that the highest (possible) precision of the measurements is primarily necessary for the specialists dealing with geodynamical problems. These are the problems of studying the contemporary crustal motions, deformational precursors of the earthquakes, postseismic deformations, global lithospheric plate motions, and deformations at the plate boundaries.

The transition to the GNSS-based measurements for exploring the CCMs in Kamchatka was made in the mid-1990s. After this, it became possible to conduct the studies on regional and global scales. The present stage of the GNSS-based CCM research is characterized by the development of global and regional networks on the basis of permanent (constantly operating) stations.

Besides the use of geodetic technologies, the CCM studies in Kamchatka since the mid-1970s have also been conducted with the liquid-level tiltmeters designed by Yu.S. Dobrokhotov (1972); in the 1980s, these measurements were changed for the TM-1B borehole tiltmeters manufactured in the United States (*Operating...*, 1975). In the 1990s, the borehole strainmeter and tiltmeter designed by Isia were used. The strainmeters is a nonrecoverable three-component sensor installed in the borehole at a depth of 30 m. The sensitivities of the strainmeter and tiltmeter are 5×10^{-8} and 0.1 μrad, respectively, which was sufficient for recording both the tidal waves with amplitudes of ~0.05 ppm and 1 μrad, respectively, as well as the deformation signals associated with the earthquakes of different magnitudes that occurred at different distances from the sensor.

After a long pause, the observations with tiltmeters were resumed in 2010 after installation of eight tiltmeters in Kamchatsky Krai. Due to their enhanced construction, the APPLIED GEOMECHANICS 701-2A lag-free tiltmeters, which were initially designed for the very special purpose of monitoring the vibrations of tall buildings, are now used for geodynamical observations. Two groups of tiltmeter stations were installed. One group includes four stations in the area of the town of Petropavlovsk-Kamchatsky: PETT (Petropavlovsk seismic station), MIHT (Mishennaya), IVIS (IVS FEB RAS), and KRMT (Karymshina seismic station). Another group was installed in the scientific cooperation between the University of Hokkaido (Japan), IVS FEB RAS, and the Kamchatka Branch of the Geophysical Survey of the Russian Academy of Sciences (hereinafter, KB GS RAS) in the area of the Klyuchevskaya Sopka volcano: KLYT (Klyuchi seismic station), LGNT (Loginova), APHT (Apakhonchich seismic station), and CYRT (Tsirk seismic station) (Fig. 2). The data from the PETT, MIHT, KLYT, and IVIS stations are received in the real-time mode with a 1-h delay. The information from the other stations is transferred via external memory devices with the periodicity of one week to three months.

In future, it is planned to equip the stations in the region of the Klyuchevskaya group of volcanoes with autonomous power supply systems, which will speed up data retrieval and processing. The data can be used for gaining insight into the nature of deformation processes associated with tectonic, volcanic, and man-made impacts. Another promising application is the joint analysis of the waveforms from the earthquakes recorded by seimsometers and tiltmeters.

ORGANIZATION OF THE GNSS OBSERVATION NETWORK IN KAMCHATKA AND THE KOMANDOR ISLANDS

Until 1997, the northern part of Eurasia was highly nonuniformly covered by GPS stations, which caused significant errors in the CCM modeling for Siberia and the Russian Far East. In 1997, KB GS RAS deployed a reference network of GPS stations, which is incorporated into the IGS for the entire territory of Northern Eurasia (NEDA network). It encompasses the continent from the East European platform through the Ural Mountains and all of Siberia, to

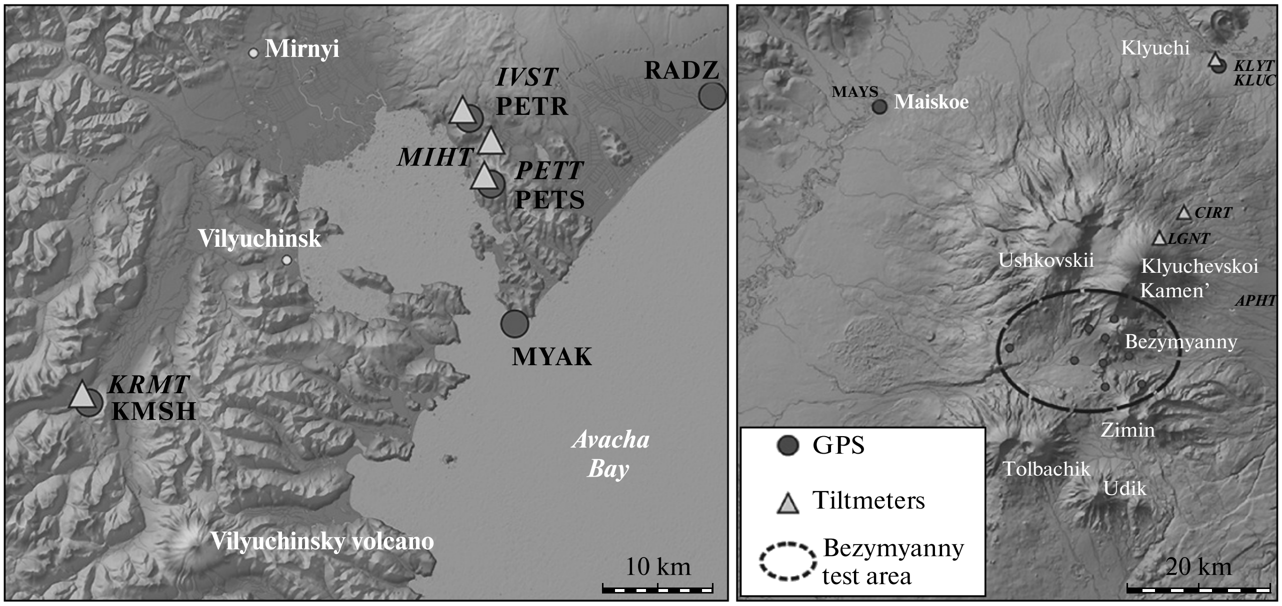

Fig. 2. The locations of permanent GPS stations and points of tiltmeter observations in the regions of (a) Petropavlovsk-Kamchatsky and (b) Klyuchevskaya group of volcanoes.

Chukotka, Kamchatka, and Sakhalin (Bykov et al., 2009).

In order to solve the regional problems, it was required to create a denser regional network of GPS stations in Kamchatka and the Komandor Islands with a step of 200–300 km between the stations. The works on organizing the KAMNET network were started in 1996 by the combined efforts of KB GS RAS (Kamchatka Experimental and Methodical Seismological Party at that time) and IVS FEB RAS as part of the international agreement with the University of Hokkaido, Japan (Study of Seismotectonics of the Okhotsk Plate) and the RUSEG project (Russia–US Experiment on Geodynamics), in collaboration with Columbia University, United States. By October 1997, a network consisting of eight permanent stations started its operation.

The main tasks that had to be solved during organizing the KAMNET regional network included designing a fully automated system for obtaining and preprocessing data at the stations, creating the Data Collection Center (DCC), as well as mastering and incorporating into routine operation the tools for precise processing and analysis of GPS observations. For installing the GPS antennas, the experience on the construction of stable towers for the near-ground scatterers for the light rangefinder instruments was applied. In view of the small and sparse population of Kamchatka and practically absent infrastructure in the region, the GPS stations were installed at the sites of the meteorological and seismic stations, which, inter alia, provided the complex of observations.

As of 2012, the network consisted of 17 stations operated by KB GS RAS, which are installed with steps of about 200 km, and the stations of the NEDA GS RAS–PETS network, which is a part of the global IGS network. The permanent KAMNET stations serve as a reference geodetic network for the episodic observations in the supposed epicentral zones of strong ($M > 7.0$) earthquakes and in the areas of active volcanoes (the insets in Fig. 3), in particular, at the Karymskyi and Bezymyannyi volcanoes. Since 1996, repeated measurements with different periodicity have been made at more than hundred stations.

The precise GNSS measurements are carried out with the TOPCON GP-R1DY, ASHTECH Z-XII3, Sokkia Radian, JAVAD Lexon-GGD, Trimble 4000, and Trimble NETRS dual-frequency geodetic-class receivers. A necessary condition for the operation of a GPS station which is included in the CCM monitoring network is a rigid and unambiguous fixation of the receiving antenna. The geodetic station for GPS observations is a concrete building buried below the depth of soil freezing. The height of the tower above the surface should exclude snow coverage of the antenna. The site is equipped with a geodetic center and a system for the forced alignment, which unambiguously fixes the antenna in the working position. Sometimes, the geodetic centers in the form of screwed marks placed in the roofs of the cast-in-place

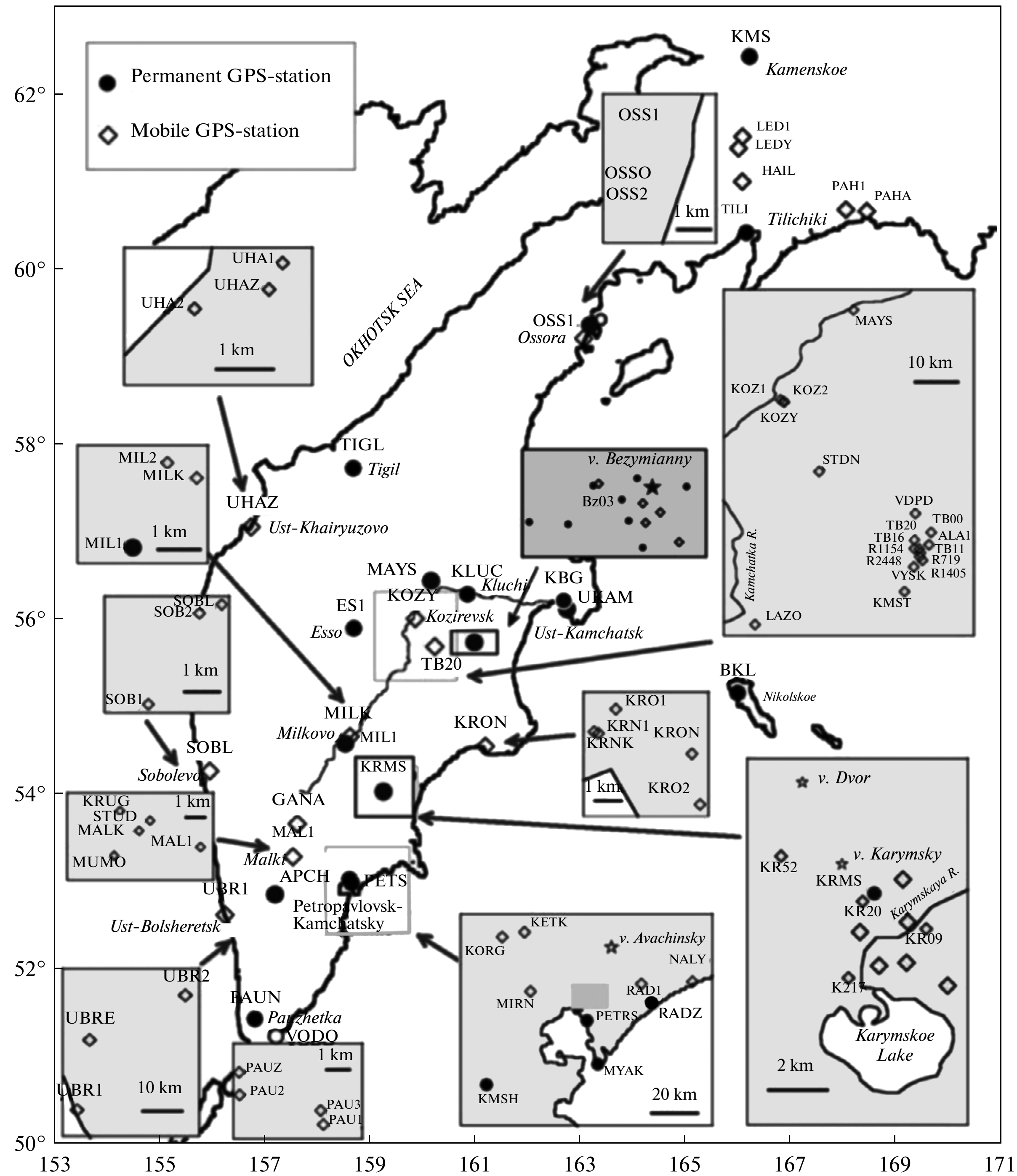

Fig. 3. The locations of permanent and temporary stations of the KAMNET network.

constructions are used. This variant reduces the time of site installation. However, the motions of the construction elements of the building enhance the noise and, thus, increase the probability to lose the geodetic station due to a strong earthquake, which has actually occurred at some GPS stations of our network during the 2006 Olyutorskoe earthquake (Levin et al., 2010).

The network of permanent stations has a fully automated system for collecting, transferring, and archiving the data. The system was developed in 2007, initially for data transferring via TCP/IP protocols. It

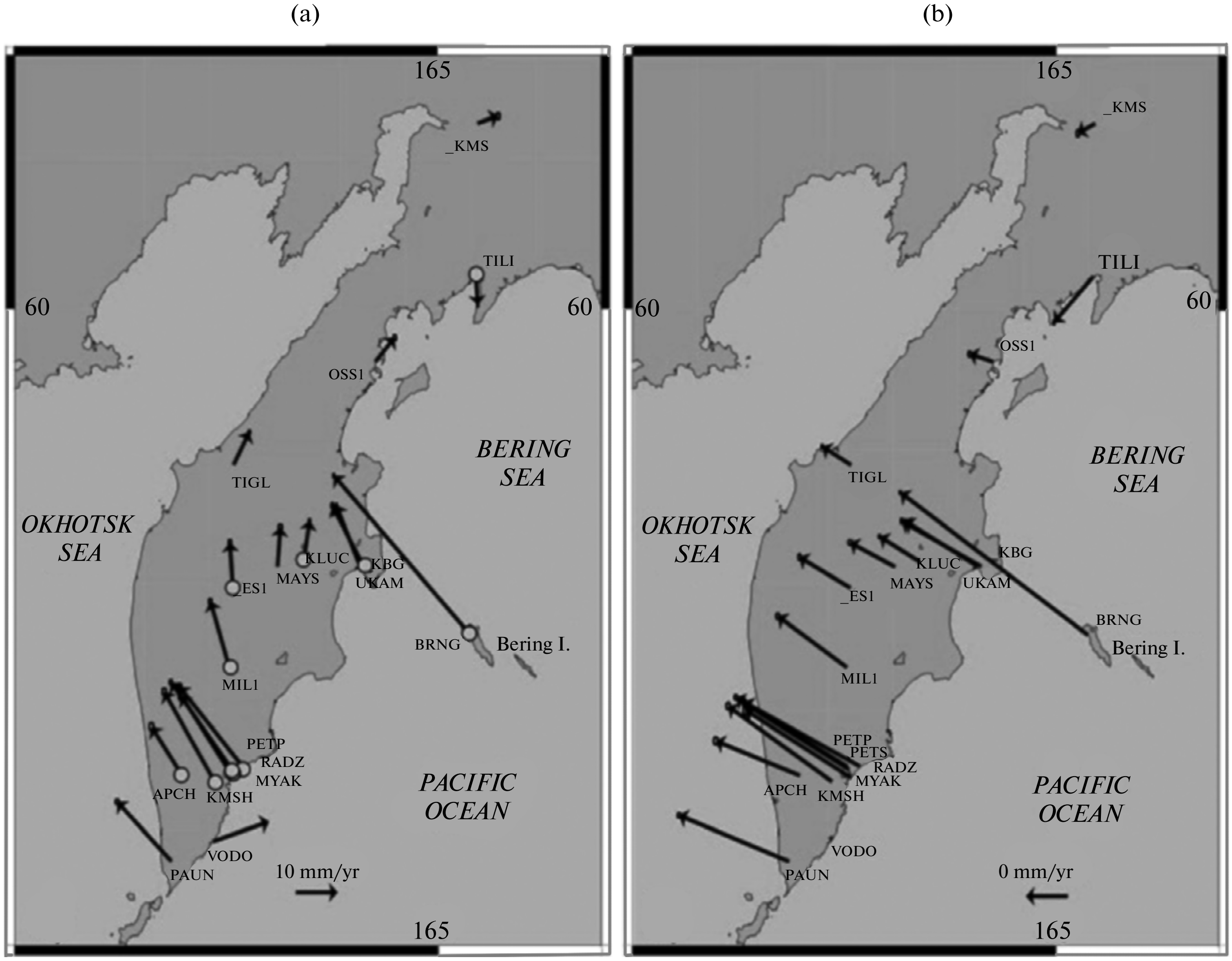

Fig. 4. The displacement velocities according to GPS measurements relative to the (a) North American and (b) Eurasian plates. The circles denote the stations with a permanent one-second recording.

supports all types of GPS receivers used. At the stations with outmoded equipment (TOPCON GP-R1DY/ASHTECH Z-XII3 and Trimble 4000), the Linux micro PCs are installed to read off the data from the receivers and to convert them into the RINEX format, to provide remote access to the archive, and to help in remote management of the station. The Linux TsSD computer requests the data from the stations according to the schedule, arranges the archive, and provides the stats of stations' operation. Debugging of the data collection system enabled recording with 1-s interval at the stations of the KAMNET network to start in 2009. At present, all the stations connected to the system either operate in this mode (Fig. 4a) or can be switched to that mode by necessity. The systems have no technical restrictions for organizing real-time data transfer; the only restricting factor is the connection quality.

THE MAIN RESULTS OF CCM MONITORING IN KAMCHATKA

During 14 years of constant GNSS-based observations, the KAMNET network recorded the site displacements associated with the strong seismic events and manifestations of active volcanism. The long duration of the observations makes the resulting time series suitable for obtaining the precise values of site velocities (Fig. 4) and, based on them, determining the kinematical and deformation parameters of motion and interaction of the surface blocks.

CCMs Related to the Plate Motion

The territory covered by the network falls in the zone of convergent junction of three major plates: two "slow," largely continental plates (Eurasian and North American) and one "fast" oceanic plate (Pacific). In the vicinity of their triple junction, two intermediate-

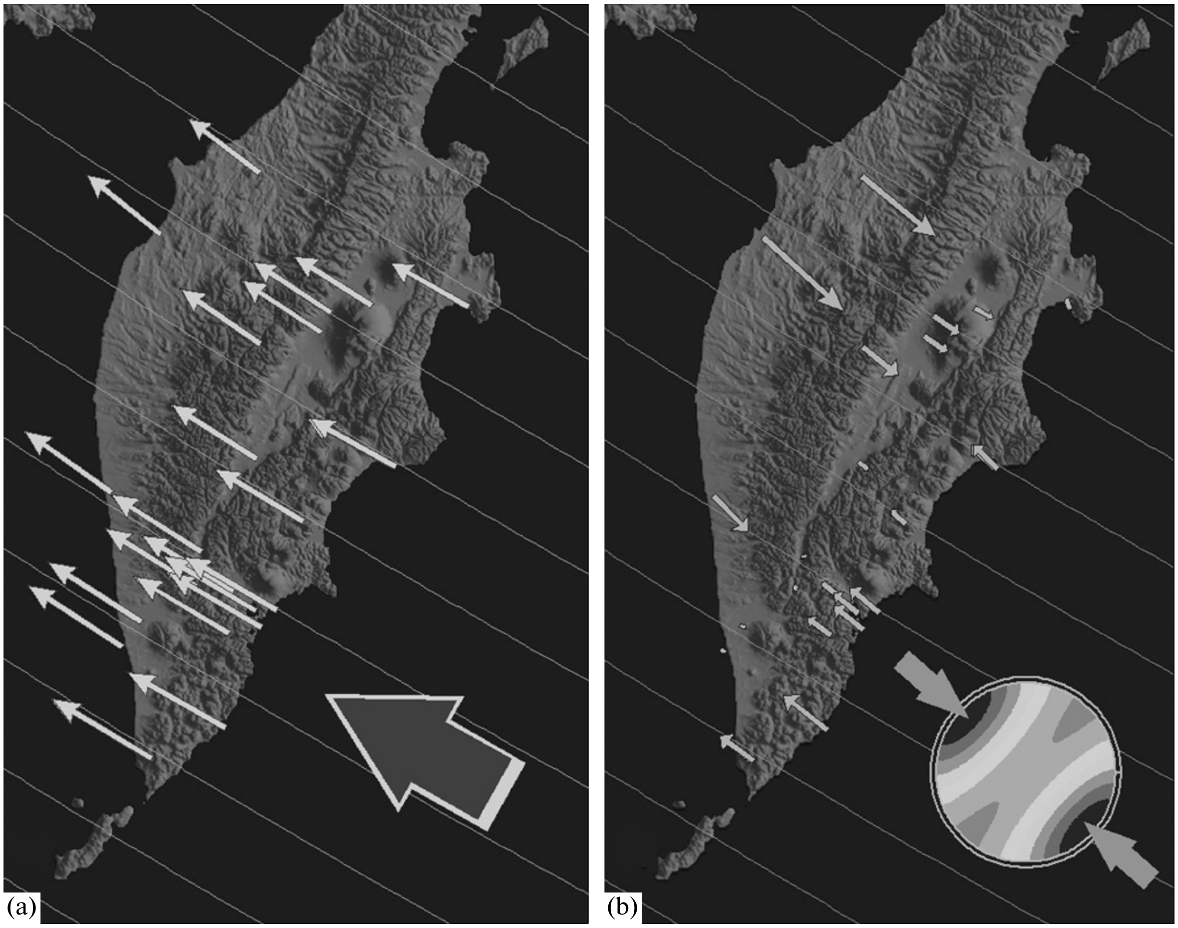

Fig. 5. The components of the rigid rotation with homogeneous deformation model:(a) rigid rotation component. The vectors are shown relative to the Eurasia–North America coordinate system. The pole of rotation is common for both plates; the angular velocities are equal in magnitude but opposite in sign. The thin arrows show vectors of rotation; the large arrow shows the velocity vector of the Pacific Plate; the parallel lines indicate the direction of motion of the Pacific Plate; (b) the homogeneous deformation component. The arrows denote the strain vectors. In the bottom right the homogeneous strain tensor with the directions of principal axis of compression is shown.

size plates—the Okhotsk and Bering—and a number of minor blocks have kept aloof. Most of them move with small relative rates, preserving the general kinematical features of the motion of the major plates (Steblov, 2004).

In the southern part of Kamchatka Peninsula, especially in its eastern segment, slow and steady deformations are observed; they are accounted for by the coupling between the Okhotsk and the Pacific plates, the latter rapidly subducting beneath the former. This territory is dominated by the deformations of horizontal compression whose principal axes almost coincide with the direction of relative motion of the Pacific Plate. The deformations result in the emergence of the corresponding tectonic stresses, which are partially released by the strong earthquakes accompanied by the rapid backward (oceanward) motion of the adjacent coastal areas (rollback). During the Kronotskii earthquake with $M_W = 7.8$, which occurred on December 5, 1997, rapid displacements of the stations were observed within a distance of 200 km from the earthquake epicenter located east of the Kronotskii Peninsula (Gordeev et al., 2001; Titkov et al., 2010).

For the interpretation of GPS site displacements in the southern part of the Kamchatka Peninsula, we developed the mathematical model of rigid rotation with homogeneous deformation (Titkov, 2009). The model describes the horizontal motions as a sum of the rigid rotation of a body on the surface of the sphere and homogeneous deformation in the tangential deformation with a pole at the center of the group of the points. The model parameters are estimated by the least square method. Using the developed mathematical model, we carried out kinematical and deformational analyses for the part of the Kamchatka Peninsula that is located within the Okhotsk Plate (Fig. 5). The motion of the Okhotsk-Sea portion of Kam-

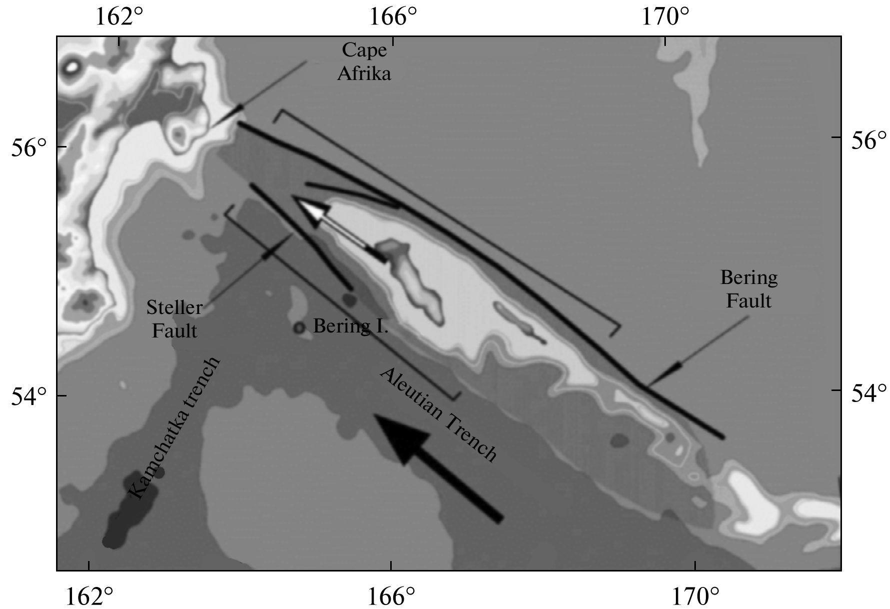

Fig. 6. The relative motion of the Komandor microplate. The black arrow is the velocity vector of the Pacific Plate relative to the Eurasian Plate (79 mm/yr), GRSM 2.1 model. The black-and-white arrow is the velocity vector of the BRNG GPS station relative to Eurasia (55 mm/yr).

chatka is mainly determined by the interaction with the Pacific Plate. The rotational component describing the motion of the rigid body is exactly aligned with the direction of motion of the Pacific Plate (Fig. 5a). The eastern coast of the peninsula experiences compression under the action of the Pacific Plate's subduction beneath the Okhotsk Plate. The compression strain rate is 5×10^{-8} per annum (Fig. 5b). The compression axis is inclined clockwise to the direction of motion of the Pacific Plate. The presence of this tilt is probably associated with the not quite precise determination of the mutual motion for the Okhotsk and Pacific plates in the subduction zone. The motion of the Pacific Plate is estimated from the stations that are remote from Kamchatka; therefore, unavoidable changes in the kinematical characteristics of motion during its deformation in the subduction zone cannot be determined by the geodetic methods.

The northern part of Kamchatka, including South Koryakiya, is located in a wide active zone of the junction between the North American, Okhotsk and Beringian plates. The region of Northeast Asia and the Bering Sea is currently among the largest for which the configurations of the tectonic plates are uncertain. The instrumental observations in this region are very sparse due to its large dimensions, sparse population, and the absence of the required infrastructure. The M_W 7.6 Olyutor earthquake that occurred on April 20, 2006 in the Koryak Plateau gave impetus to implementing geodetic measurements in the northern part of the Kamchatsky Krai aimed at the instrumental delineation of the boundary of the Beringian Plate, whose hypothesized existence is currently only supported by the manifestations of local seismicity (Levin et al., 2007; 2010).

After the Olyutor earthquake, observations were made at three additional sites located on either side of the supposed block boundary. The absence of funding did not allowed us to repeat the measurements; therefore, as of now, only a rough qualitative estimate of the parameters of mutual displacements of the plates can be made for this region. The directions of the velocity vectors of GPS sites suggest that the Ossora (OSSO) and Kamenskoe (KMS) stations belong to the North American Plate, while the Tilichiki (TIL) station is located within the Beringian Plate. The displacements of the KMS, OSSO, and TIL GPS sites indicate right-lateral shearing motion between the Beringian and North American plates at a rate of about 15 mm per annum.

Among the minor blocks there is the Komandor Microplate. With the using of the observations from the Kamchatka GPS network and the models describing the motion of the large plates (Eurasian, North American, and Pacific), which are constructed based on the GPS measurements at IGS stations, it was established that the Pacific Plate in the region of the Komandor block moves relative to Eurasia approximately northwestwards with the velocity of 79mm per

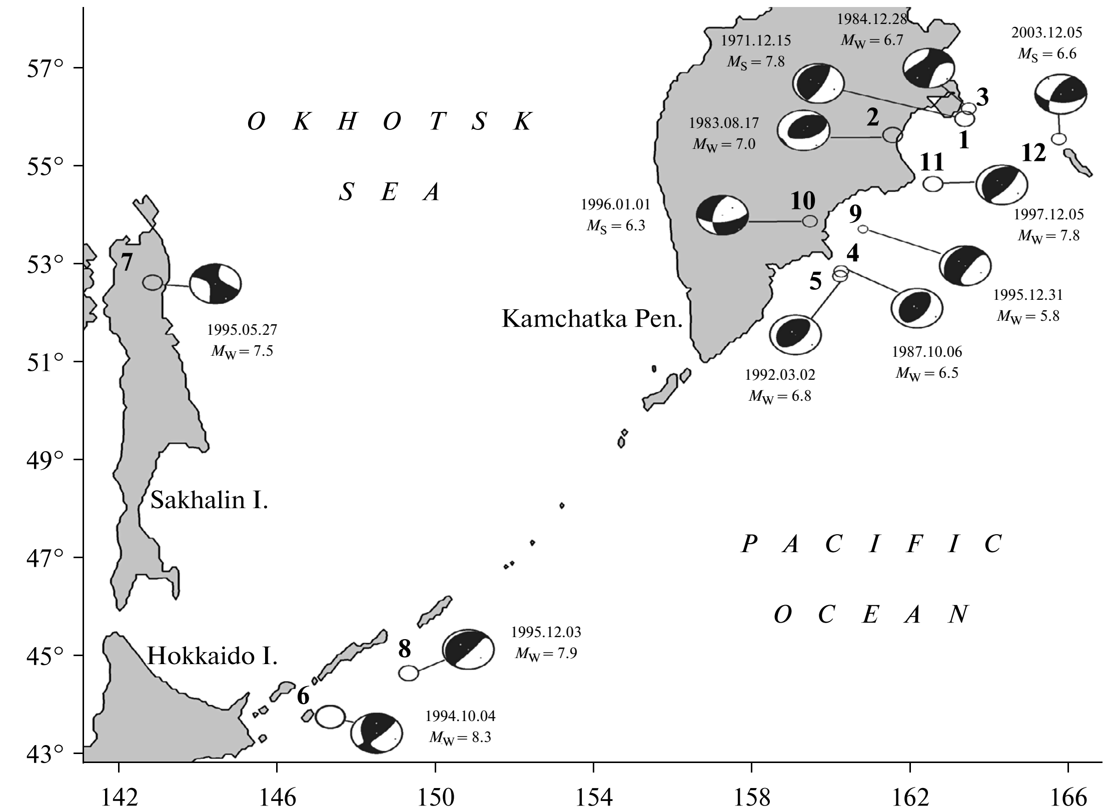

Fig. 7. The earthquakes, from which both vertical and horizontal CCM components were recorded. Dates are given in the MM.DD.YYYY format.

annum (Fig. 6). The velocity of the Komandor Microplate relative to Eurasia is 55 mm per annum. The directions of the Pacific and Komandor vectors nearly coincide, but the Komandor block lags the Pacific with a velocity of 24 mm per annum. Comparison of the two last values shows that the motion of the Komandor Microplate is stronger controlled by the Pacific Plate than by the Beringian Plate, which is located farther to the north.

Thus, both the seismological data (Lader et al., 2009) and GPS measurements (Levin et al., 2002) support the "chip" model for the Komandor Microplate: the chip moves northwestwards along the transform boundary under the predominant control of the Pacific Plate and abuts against Cape Kamchatka in the frontal face junction.

Kamchatka's CCMs Related to Seismic Events

The extensive program of instrumental studies of CCMs in Kamchatka was run in 1971 and, to date, it has recorded a few cases of horizontal or vertical deformations related to the seismicity of the studied region. The works started from organizing a network of the testing areas, which currently spreads over the entire territory of Kamchatka (Figs. 1 and 3).

Figure 7 shows the earthquakes from which both vertical and horizontal crustal deformations were recorded. The releveling measurements revealed the changes in the elevations along the leveling profile in the region of Cape Africa, which are associated with (*1*) the earthquake of December 15, 1971 and (*3*) the earthquake of December 28, 1984 (Fig. 8).

The relative changes of the reference marks up to 80 mm coincide, in terms of the sign, with the mechanisms of the earthquakes, i.e., reverse fault for the earthquake of December 15, 1971 (Gusev et al., 1975) and strike-slip with a small reverse fault component for the event on December 28, 1984.

Based on the results of optical distance monitoring of the area of the Avacha Bay from the Mishennaya Observatory, the trend of compressive deformation was revealed, and the bay-like elastic variations in strains in the Avacha Bay area were recorded (Fig. 9). We associate these features with earthquakes (2) of October 17, 1983 (M_W = 7.0, the distance from the

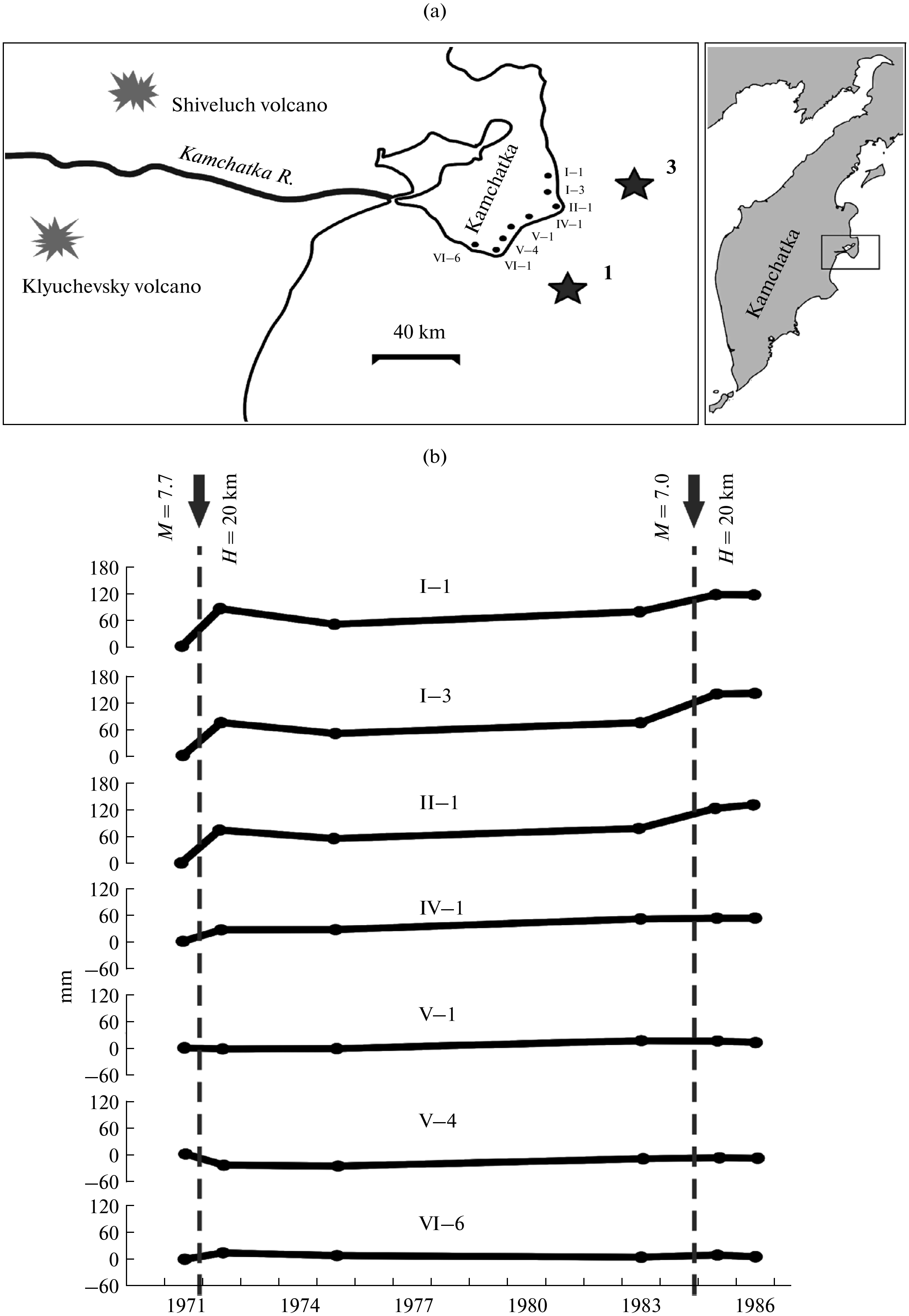

Fig. 8. The vertical deformations associated with the strong earthquakes: (a) the layout of the reference points and earthquake epicenters; (b) the displacements of reference points relative to their positions in summer 1971.

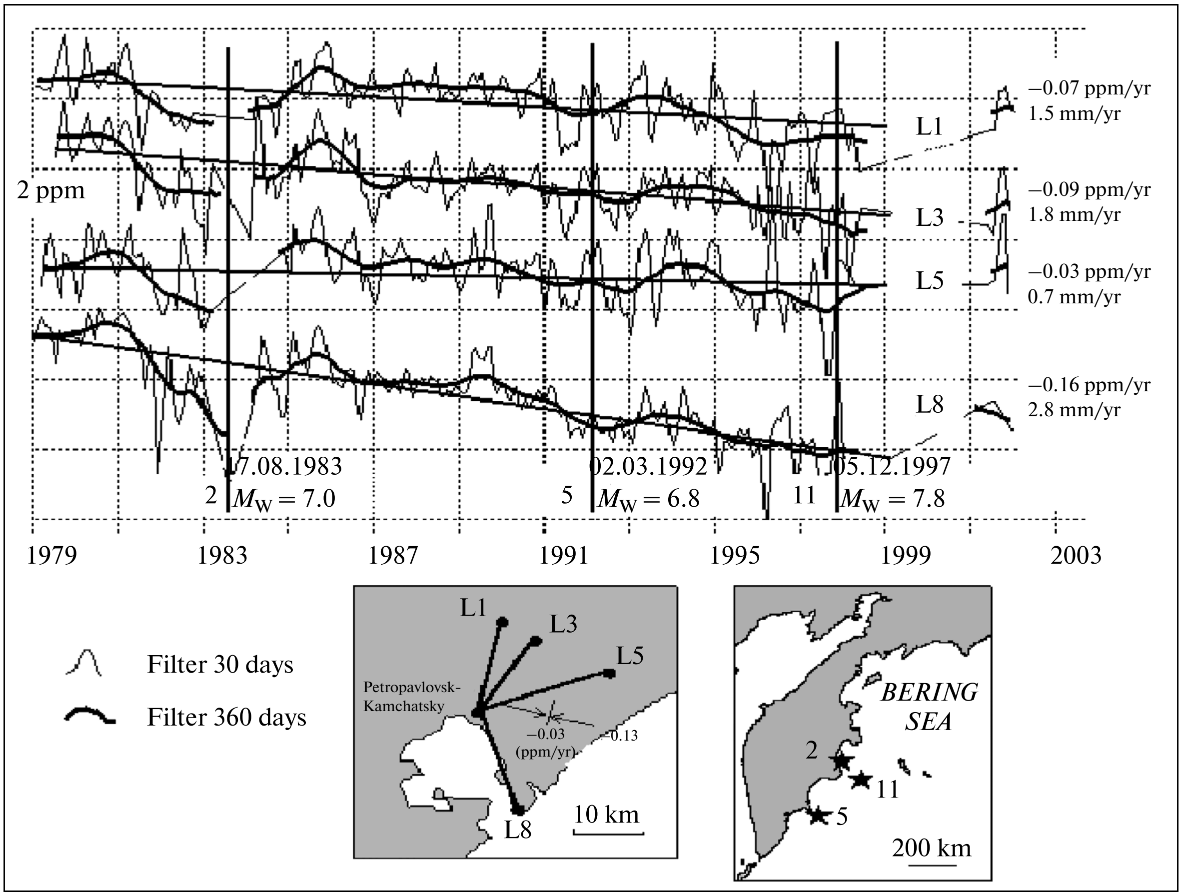

Fig. 9. The results of linear measurements at the Mishennaya Observatory.

recording station to the epicenter $\Delta = 350$ km); (5) of March 2, 1992 ($M_W = 6.8$, $\Delta = 100$ km); and (11) of December 5, 1997 ($M_W = 7.8$, $\Delta = 350$ km). The decrease in the amplitudes of the deformation bays with time is probably related to the increase in the stresses in the region of the Avacha Bay as a result of the greater compression of the region under the action of the geodynamical processes that occur in the subduction zone. Naturally, as is seen from the graph, the strong earthquakes did not release the accumulated stresses in the Avacha Bay area; however, the most intense stress releases by up to 2×10^{-6} occur after the earthquakes with $M > 7.0$. Besides, the change in the rate of the trend can serve as a precursor of the incipient strong ($M > 7.0$) earthquake in the region of Avacha Bay.

The M_W 7.0 earthquake (2) of August 17, 1983 has been successfully predicted (Gusev, 1997), due to which we were able to record for the first time both the vertical and horizontal displacements in the epicentral zone (Fig. 10) before, during, and after the seismic event. The laser rangefinder measurements in the epicentral zone of the M_W 7.0 earthquake of August 17, 1983 were arranged both along and across the supposed fault. The amplitude of the coseismic jump in deformations from 2 to 4 ppm on the mutually perpendicular lines (1–3 and 1–2), as well as the close (16.9 and 16.4 mm per annum) velocities of the subsequent aftershock-related deformations of the compression and extension along the corresponding lines, can be interpreted as a slip on the fault along the Bystraya River and as a case when the fault manifested itself during the strong ($M > 7.0$) earthquake nearby ($\Delta =$ 7 km).

The instrumentally measured CCM components from this seismic event were 2 mm per day for the vertical component and 6 mm per day for the horizontal component (both prior to the main shock), while after the main shock the horizontal component became 16 mm per annum.

A remarkable feature here is the similar pattern of horizontal deformations recorded from the earthquakes with different magnitudes (5.3, 6.5, and 7.9) occurred in the different parts of Kamchatka (Fig. 11). We see the elastic character of the deformation processes, and the higher the energy of the earthquake the

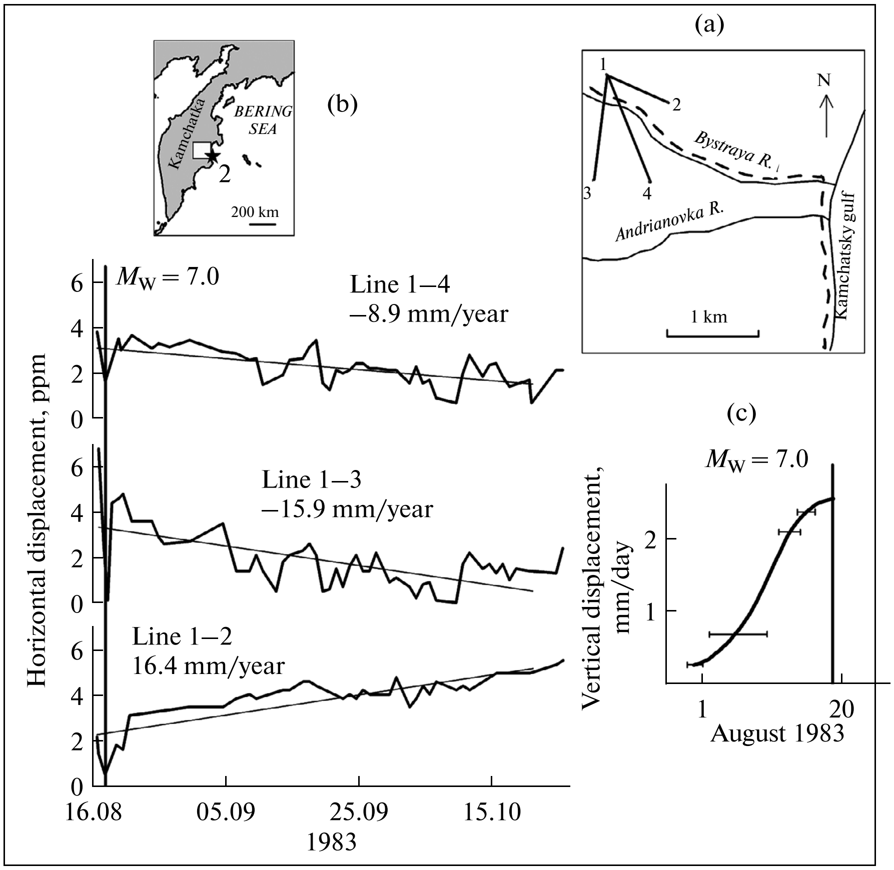

Fig. 10. The horizontal and vertical displacements in the epicentral zone of the M_W 7.0 earthquake of August 17, 1983: (a) Bystraya test area and its position in Kamchatka; (b) the graph of horizontal displacements; (c) the graph of vertical displacements.

higher the amplitude of the horizontal deformations. This was the first anomaly of horizontal deformations which we managed to reliably record and interpret as a short-term geodetic precursor of the earthquake.

In order to increase the precision of measurement of the horizontal component of the surface deformation, we applied (for the first time in Russia) the laser rangefinder refractometer for the studies in Kamchatka. The long measurements of the distances by this instrument have showed that its precision is not worse than $1–2 \times 10^{-7}$. When conducting the next series of the observations at the Mishennaya Observatory, we recorded the deformational wave. The M 7.0 Olyutor earthquake of March 8, 1991 was temporally the closest seismic event to the this phenomenon (Δ= 1050 km).

Due to the high precision of the laser rangefinder–refractometer, we managed to pick up the arrivals of the deformational wave to the observation area, which enabled us to estimate its velocity (40 km/h).

The monitoring with a borehole strainmeter and the Isia tiltmeter recorded both the tidal waves (Fig. 12) and deformational signals related to the earthquakes with different magnitudes that occurred at different distances from the place of our instrument. These are (6) the Shikotan earthquake (October 4, 1994, $M_W = 8.3$, $\Delta = 1325$) (Fig. 13); (7) Neftegorsk earthquake (May 27, 1995, $M_W = 7.5$, $\Delta = 1063$ km) (Fig. 14); (8) the Kuril earthquake (December 3, 1995, $M_W = 7.9$, $\Delta = 1154$ km) (Fig. 15); (9) the earthquake of December 31, 1995 ($M_W = 5.8$, $\Delta = 161$ km); and (10) the Karym earthquake (January 1, 1996, $M_W = 6.3$, $\Delta = 108$ km) (Fig. 16).

The borehole strainmeter data show that the orientation of the strain tensor typically coincides with the nodal plane of the fault plane solution. Almost all the recorded deformations are elastic, except the one related to earthquake (9) (Fig. 16), which is in this case most likely to be determined by the local processes in the borehole itself. This indicates that a network of three or four borehole strainmeters in the region of the Avacha Bay need to be organized.

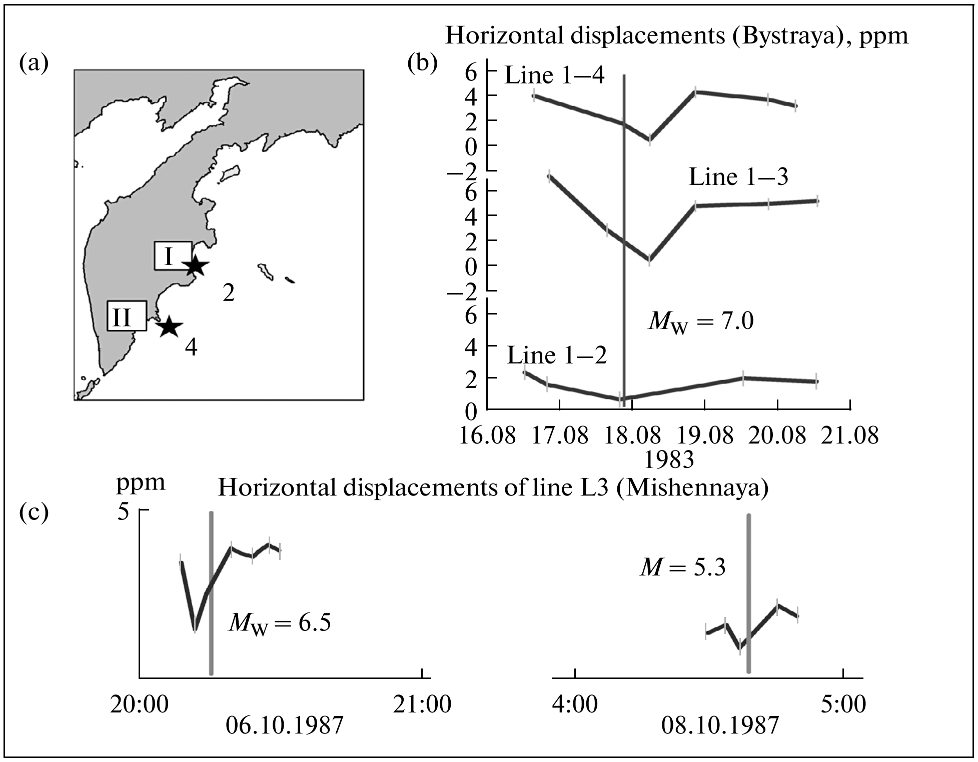

Fig. 11. Horizontal displacements at the Bystraya (I) and Mishennaya (II) test areas, associated with the strong earthquakes: (a) the layout of the test areas in Kamchatka; (b) the displacements in the Bystraya test area (see the scheme of lines in Fig. 6); (c) the displacements in the Mishennaya test area (see the scheme of lines in Fig. 9).

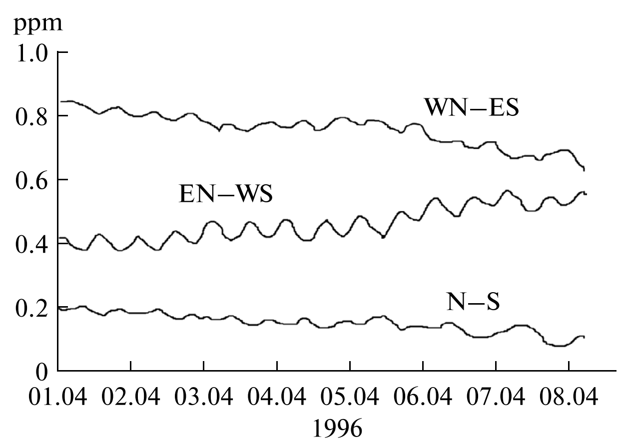

Fig. 12. Tidal deformations recorded by the borehole strainmeter.

A new stage of our studies of CCMs associated with seismic events started after the organization of the KAMNET network of the permanent GNSS observations. KAMNET recorded the coseismic displacements of GPS sites after three strong earthquakes. These are the M_W 7.8 Kronotskoe earthquake of December 5, 1997 (Levina et al., 1997; Burgmann et al., 1997) (Fig. 17); the M_W 6.6 earthquake of December 5, 2003 near Bering Island (Levin et al., 2006) (Fig. 18); and the M_W 7.6 Olyutor earthquake of April 20, 2006 (Levin et al., 2007, 2010; Pinegina, 2007) (Fig. 19). The measured coseismic deformations related to the mentioned earthquakes closely agree with the values provided by the calculations of deformations from the dislocation model that uses the Harvard solution for seis-

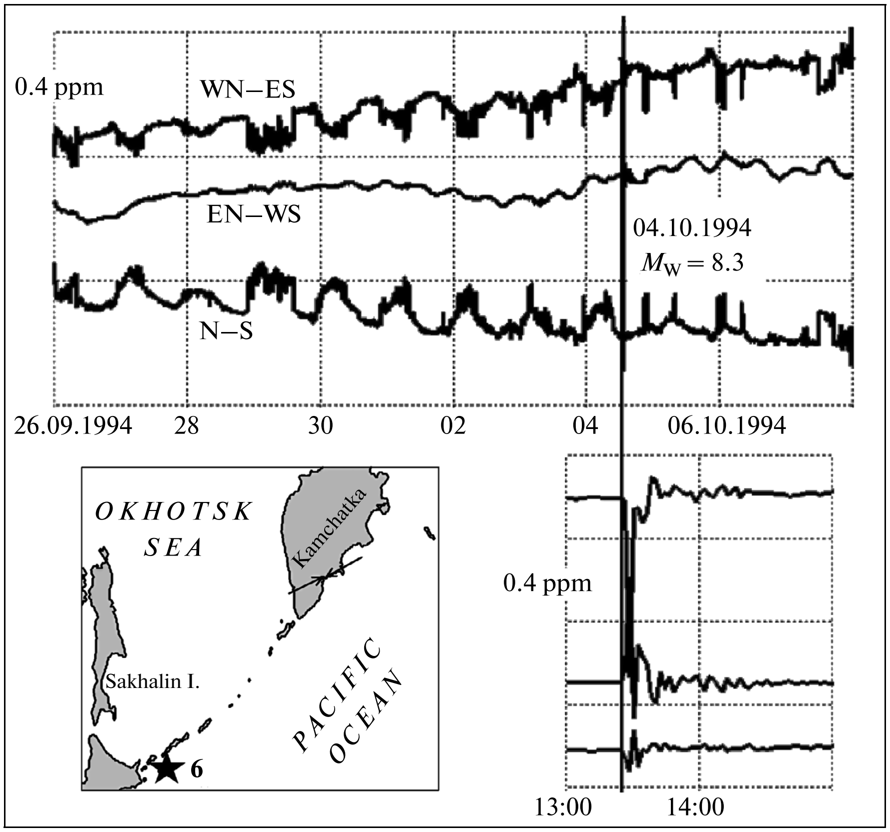

Fig. 13. Horizontal preseicmic and coseismic deformations from the Shikotan earthquake recorded by the borehole strainmeter.

mic moment tensor (Burgmann et al., 2001; Gordeev et al., 2001).

The high-frequency 1-s recording provides the time series of the motions and deformations of the Earth's crust with high time resolution. Processing these data in the kinematical mode (without averaging) makes it possible to record the surface waves from seismic events.

The Detailed Studies of CCMs in Active Volcanoes

The classical example of CCM studies in a volcano was provided by the works at the Great Tolbachik Fissure Eruption of 1975–1976 (*Bol'shoe...*, 1984). The results of CCM observations at all phases of the volcanic eruption process yielded in the first estimate for the value of the excessive pressure (*P*), which, despite the tremendous scale of the eruption process itself, turned out to be very small (100 kg/cm^2) (Fedotov et al., 1978). The model constructed from the data on horizontal displacements quite adequately determined the positions of the sources of deformations (magmatic chambers) of this eruption. The subsequent instrumental observations of CCMs in this area provided the velocities and residual strains of the postvolcanic evolution of the region of the Great Tolbachik Fissure Eruptio.

The laser rangefinder monitoring of CCMs near the time of eruption of the Avacha volcano on January 13, 1991 indicated that horizontal deformations along the baselines, which would exceed the measurement error, were absent before the eruption. The subsequent rangefinder observations on a fan of radially diverging baselines directly during the eruption recorded the deformations of up to 3×10^{-6}. The absence of seismic preparation of this eruption suggests that there was no magma motion from the interior to the peripheral source, and, hence, no deformation precursors of this eruption.

The works in the Karymsky volcanic center are the most consistent CCM study in a volcano. Here, all types of geodetic measurements have been conducted since 1972 (Magus'kin et al., 1980). After the extraordinary events in the Karym volcanic center, namely, terminal eruption of the Karym volcano, a strong (M_W = 6.3) crustal earthquake, and the eruption in Lake Karym, geodetic measurements were conducted every year on a dense network of GPS stations, in addition to the optical distance measurements and leveling (Magus'kin and Levin, 2006; Magus'kin et al., 2009). The works were carried out by the researchers of the IVS FEB RAS and KB GS RAS within

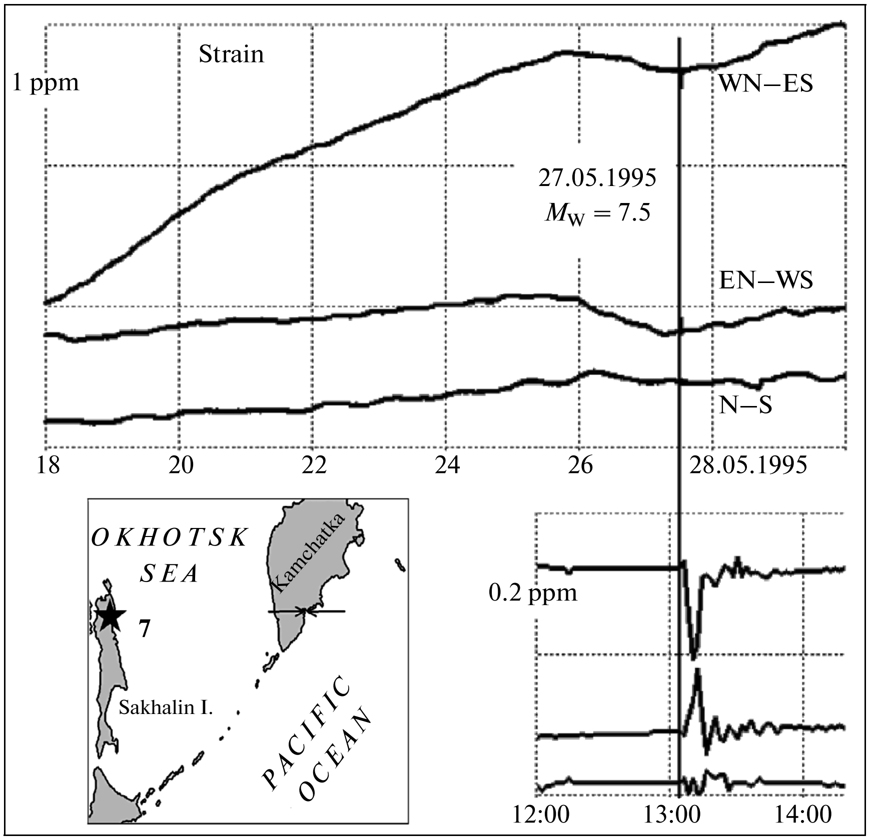

Fig. 14. Horizontal preseicmic and coseismic deformations from the Neftegorsk earthquake recorded by the borehole strainmeter.

the agreement on research collaboration. Based on the results of geodetic measurements, the deformation model was suggested for the events of January 1, 1996 in the Karymsky volcanic center. The results of this model closely agree with the horizontal displacements of the geodetic sites (Levin et al., 2006, 2010).

In 2006–2007, by the joint efforts of the IVS FEB RAS and KB GS RAS and within the PIRE project (US–Russian Partnership in Volcanological Research and Education), the local geodynamical test area with ten stations of GNSS observations was organized in the vicinity of the Bezymyanny volcano. The measurements at this test area are used for studying the relationship between the deep processes and dynamical changes of surface deformations and for constructing the model of the volcanic process. The sites are designed as concrete towers equipped with the forced alignment system at a constant displacement height above the mark. Eight stations operated in automated mode. In 2011, permanent observations were stopped at four stations, and the remaining stations were set to an autonomous power supply from solar panels. The layout of the sites of the local network in the Bezymyanny volcano is shown in Fig. 20.

Figure 21 shows the data of the observations at the closest station to the crater (BZ09) for the period from June 2006 to May 2007.A strong explosive eruption with the deposition of pyroclastic flows occurred on December 24, 2006. This moment is reflected in the graph of site displacements for the BZ09 station, where this effect is most distinct along the north–south direction. The variations in the site displacement before and after the eruption of December 24, 2006 are particularly instructive. Fifteen days before the eruption, the direction of site motion sharply changed. The eruption is marked with a sharp jump, after which the anomalous site velocity acquired before the eruption persisted for 25 days and the velocity vector turned back to its initial direction. Thus, the site motion reflects the preparatory, explosive, and posteruptive processes associated with the eruption of the Bezymyanny volcano on December 24, 2006.

A more detailed description of the results of the surface motion monitoring in the area of the Bezymyanny volcano, based on GPS technologies, is presented in (Serovetnikov et al., 2010).

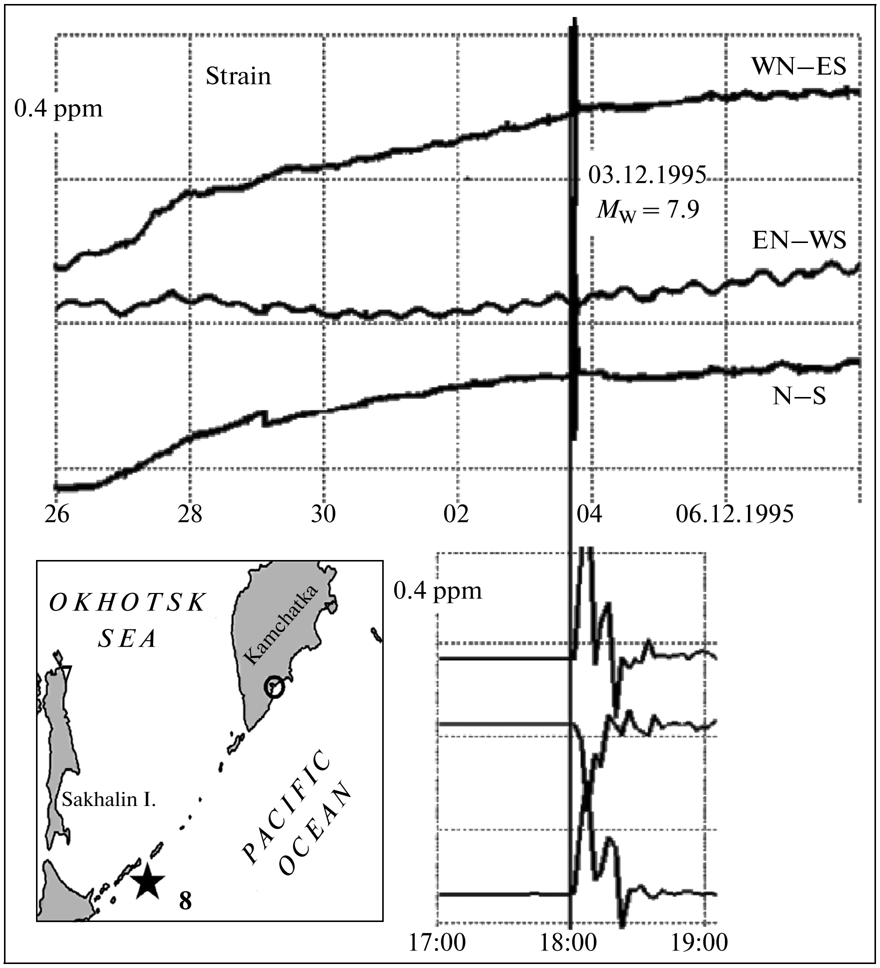

Fig. 15. Horizontal preseicmic and coseismic deformations from the Kuril Islands earthquake recorded by the borehole strainmeter.

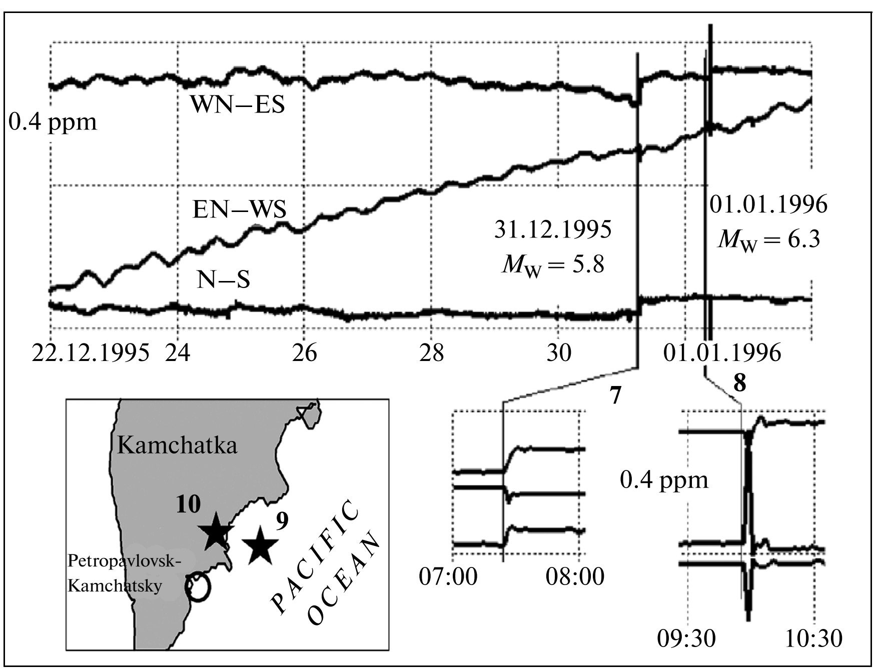

Fig. 16. Horizontal preseicmic and coseismic deformations recorded by the borehole strainmeter from the earthquakes (9) of December 31, 1995, $M_W = 5.8$, and (10) of January 1, 1996, $M_W = 6.3$.

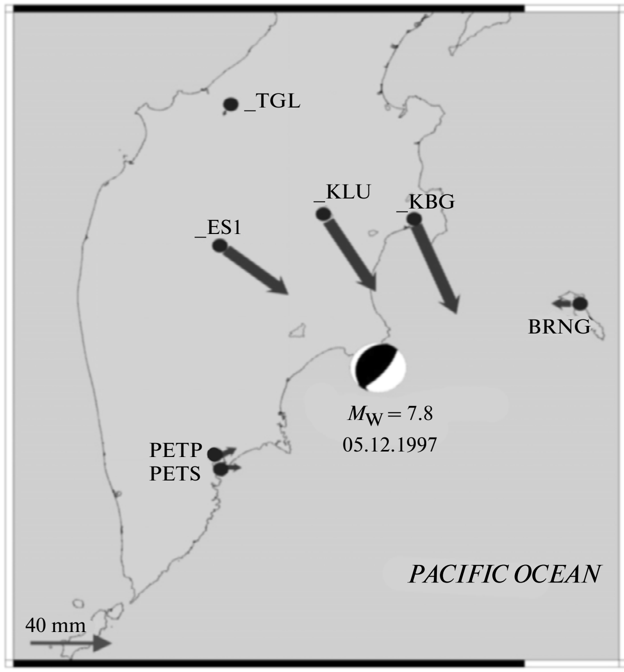

Fig. 17. Coseismic displacements of the stations of the KAMNET network during the M_W 7.8 Kronotskii earthquake of December 5, 1997.

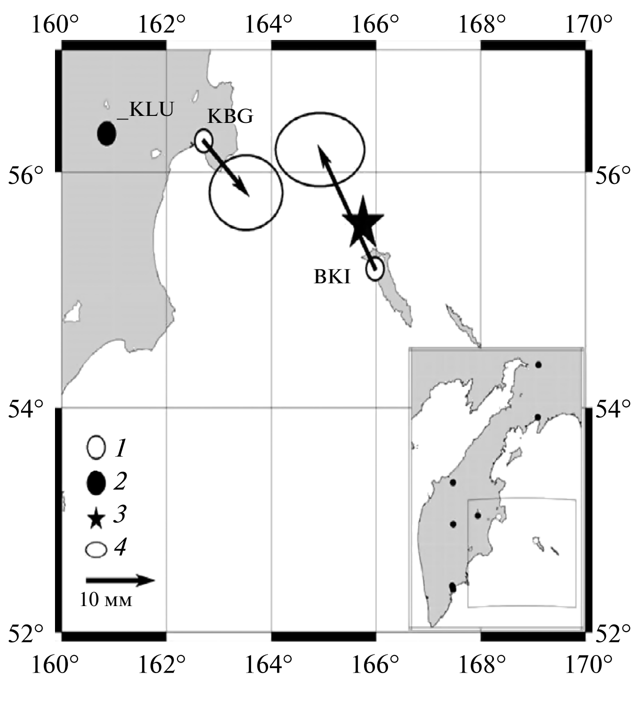

Fig. 18. Coseismic displacements for the stations of the KAMNET network during the M_W 6.6 earthquake of December 5, 2003 near Bering Island: (*1*,*2*) observation points; (*3*) earthquake epicenter; (*4*) displacement vectors with error ellipses.

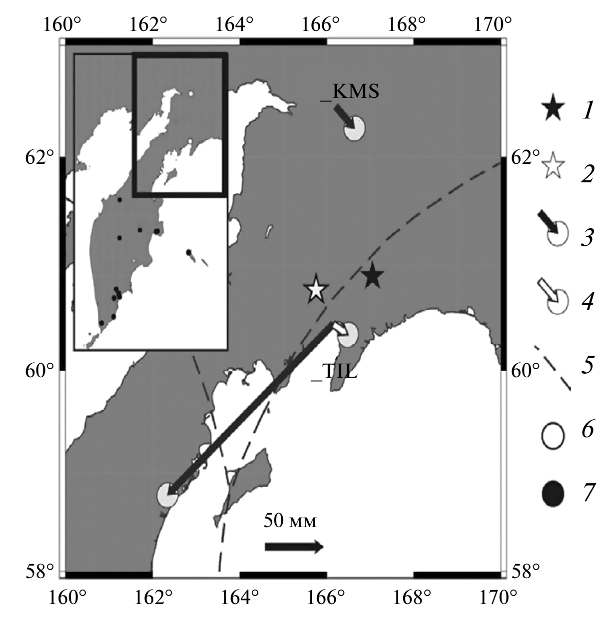

Fig. 19. Coseismic displacements of the stations of the KAMNET network during the M_W 7.6 Olyutor earthquake of April 20, 2006: (*1*) earthquake epicenter; (*2*) epicenter of the largest aftershock; (*3*) main shock displacement vectors with error ellipses; (*4*) aftershock displacement vectors with error ellipses; (*5*) implied plate boundaries (*6*,*7*) observation points.

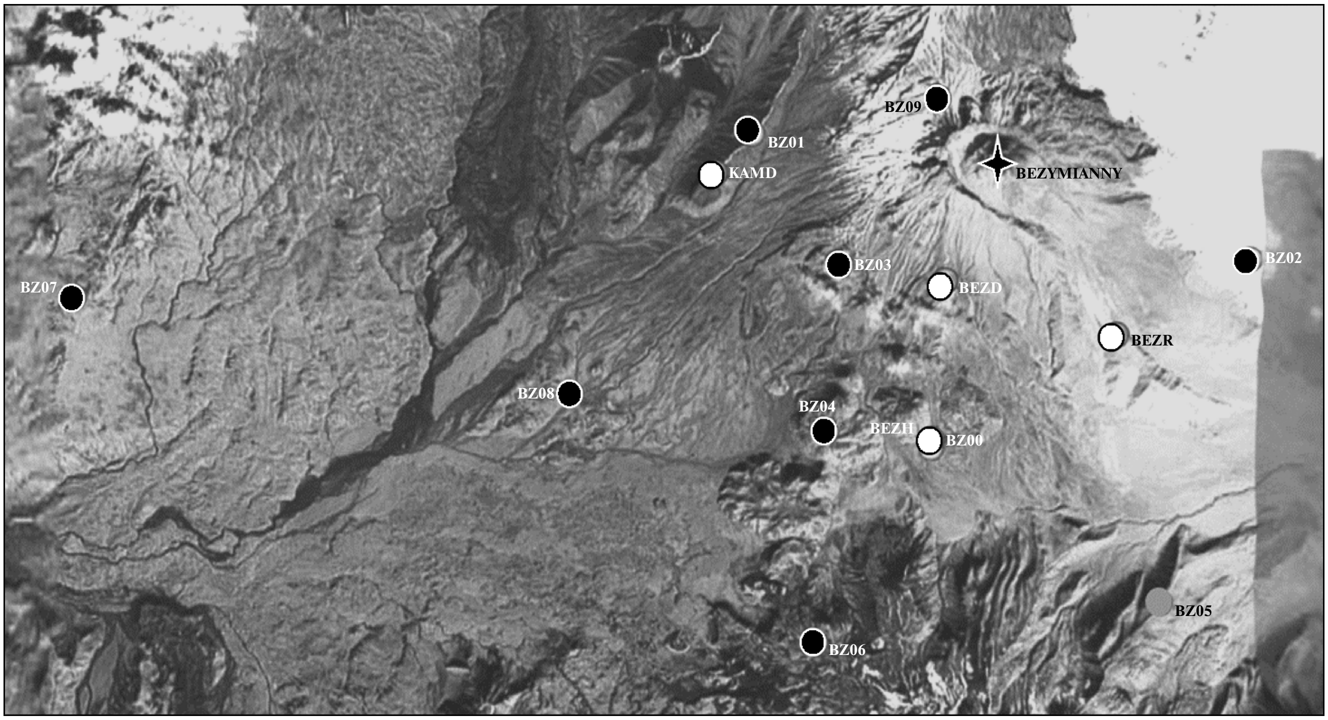

Fig. 20. The local GPS network at the Bezymyanyi volcano.

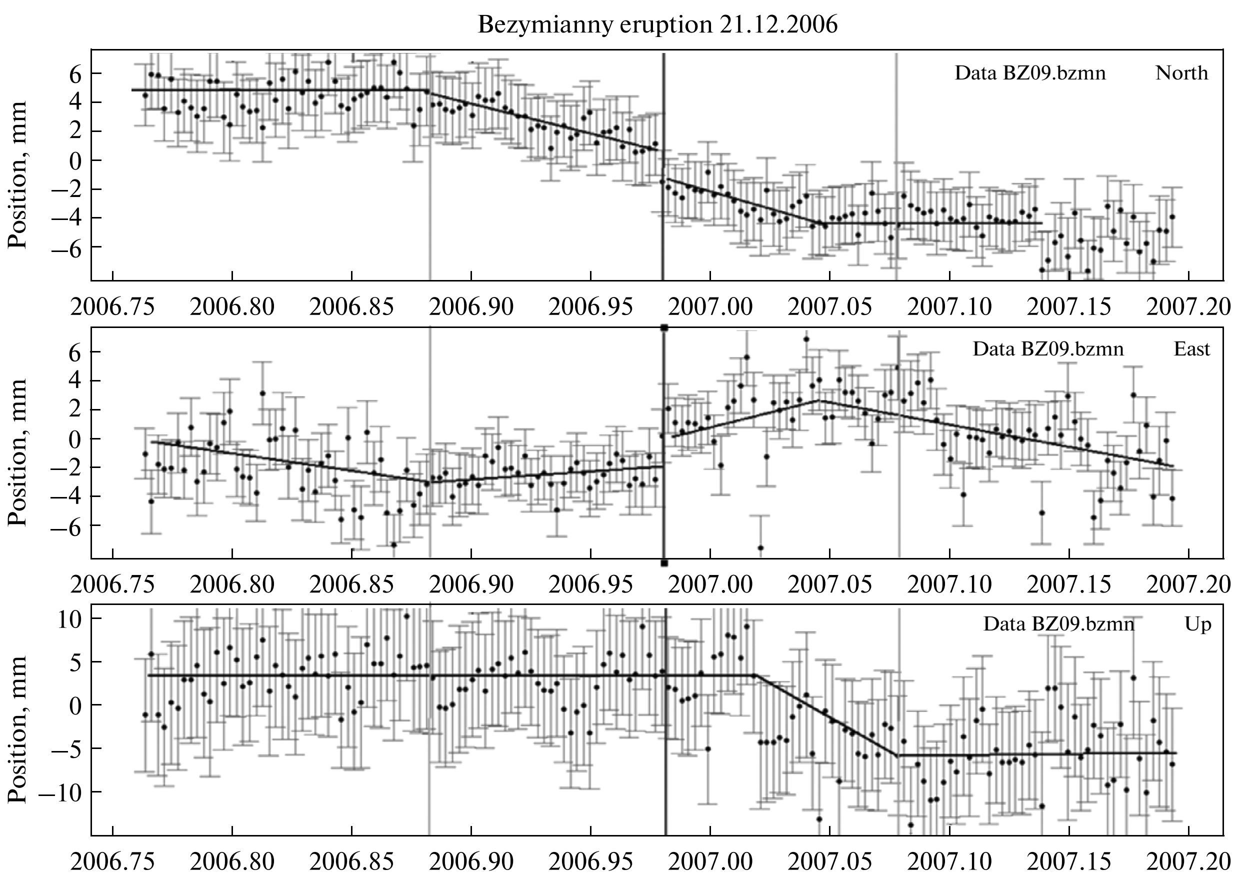

Fig. 21. The time series of the data from the BZ09 GPS station during the Bezymyanny volcano eruption of December 21, 2006. The upper plot corresponds to the north–south direction; the middle plot, to the east–west direction; the bottom plot shows the change of elevation. The black vertical line marks the time of the eruption; the gray lines indicate the interval when the velocities have changed.

CONCLUSIONS

For the 40-year history of instrumental CCM studies in Kamchatka, considerable work has been done to increase the precision of the observations and to expand the monitored area up to the entire territory of Kamchatsky Krai. The system deployed for CCM observation, which incorporates a network of GNSS receivers since 1996, enables a series of geodynamical problems to be solved, namely:

—to determine the kinematical characteristics of the global tectonic plate motion;

—to verify the hypothesis of the existence and character of motion of minor surface blocks, such as the Okhotsk and Beringian plates, and the Komandor microplate by direct measurements;

—to measure the strain accumulation rates in seismoactive regions;

—to record the deformations associated with a strong earthquake and manifestations of active volcanism.

As of 2011, the implementation of our long-term program of CCM study in Kamchatka yielded the following results:

—the physical characteristics are obtained and the models of deformation processes accompanying natural phenomena such as the Great Tolbachik Fissure Eruption of 1975–1976 and activity in the Karymsky volcanic center in 1996–2000 are constructed;

—coseismic deformations accompanying the M_W 6.6 Kronotskoe earthquake of December 5, 1997, the M_W 6.6 earthquake of December 5, 2003 near Bering Island, and the M_W 7.6 Olyutor earthquake of April 20, 2006 were recorded. These deformations closely agree with the values obtained derived from the dislocation model that uses the published Harvard moment tensor solution;

- modeling the deformation processes in the southern part of Kamchatka based on the data of permanent and episodic GNSS observations by the KAMNET network has shown that the vital role in the formation of the pattern of strains in this region is played by the subduction of the Pacific Plate beneath the Okhotsk Plate.

At present, the KAMNET network of the permanent and episodic GNSS observations has become the main instrument for studying CCMs in Kamchatka. This network monitors the deformation processes in close to a real-time mode (with a two-day delay). The works are ongoing on the transition of the GNSS network to the mode of high-frequency one-second recording and organization of the routine kinematical processing. After a long-term pause, the tiltmeter measurements have been resumed.

Despite the attractive seemingly simple measurement procedure of GNSS technology, it has certain disadvantages; for example, the extreme complexity of high-precision processing for the solution of a geodynamical task and lower, compared to the classical geodetic methods, precision on short bases of up to 10 km. Thus, in the zones of active volcanism and high seismicity, it is necessary to develop and support the measurements with laser rangefinder–geodimeters and to conduct releveling observations.

The territory covered by the network is characterized by very complex deformational conditions. It accommodates the interaction between four lithospheric plates(North American, Pacific, Beringian, and Okhotsk) and the Komandor microplate. The exposed boundaries separating the North American Plate from the Beringian and Okhotsk plates have still not been covered with the precise geodetic observation network. As a result, the question of whether the Beringian and Okhotsk are independent units still does not have a decisive answer supported by the instrumental observations. In turn, the complex deformational pattern is complicated by the processes of active volcanism, the heterogeneity of the geological structure, and nonuniform distribution of the accumulated stresses during the preparation of strong seismic events. The current network of 17 permanent stations is obviously insufficient for meeting the aims it is intended to solve. This insufficiency, in turn, impedes the construction of precise models of deformation, which are required for studying the preparation of strong earthquakes and large volcanic eruptions and predicting them.

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