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Determination of the Major Axes of Compression and Tension from Optical Distance Data by Strain-Gage Analysis (Petropavlovsk Geodynamic Polygon, Kamchatka Peninsula)

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Abstract—Data on the stress–strain state of the Earth's crust obtained by precision observations were studied using strain-gage analysis based on the geometric theory of deformation. Ground-based optical distance observations were made on one of the geodynamic polygons in Petropavlovsk-Kamchatsky to calculate the major axes of compression and tension. Out of ten baselines, four variants of the strain-gauge rosette were taken to calculate the invariant characteristics of deformation from measured displacements of the Earth's surface. The strain-gage analysis of the observation results made it possible to determine the main deformations and calculate the angle between the dominant loading axis and the shortening axis. Two sources of impact were proposed as factors that specify the dominant loading axis: magmatism (nearby active volcanoes) and the subduction zone (the impact of the subducting Pacific Plate). Since the region is seismically active, the analysis involved strong ($M > 5.5$) earthquakes to identify a possible relationship between earthquakes and deformation characteristics.

Keywords: Mishennaya observatory, subduction zone, volcanoes, optical distance measurement lines, strain gauge rosette, major axes of compression and tension, geodynamic polygon, horizontal deformations, earthquakes

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INTRODUCTION

The study of seismically active regions aimed at monitoring changes in the stress–strain state of the Earth's crust has attracted the attention of researchers for many years. Different geophysical manifestations that accompany or precede strong earthquakes and volcanic eruptions can change the characteristics of the Earth's interior in the vicinity of events and beyond them. To record the changes in these characteristics over time, prognostic geodynamic polygons have been created in different parts of the Earth for conducting comprehensive geophysical measurements. Polygons of this type were organized, for example, in Kamchatka and in the region of Lake Baikal (Russia), in California (United States), Garm (Tajikistan), and Ashgabat (Turkmenistan). Some of these polygons have been operating until now to collect continuous series of observations for more than 50 years (Kuz'min, 2021; Izyumov and Kuz'min, 2014).

An analysis of long-term series of precision observations with data on plate tectonics and movement directions makes it possible to calculate the direction of the major axes of compression and tension in suture zones using strain-gauge analysis (Kuzmin and Fattakhov, 2016).

A number of studies (Levin, 2009; Levin et al., 2006, 2014) calculated the major axes of compression and tension according to the optical distance and satellite measurements at the geodynamic polygon in Kamchatka (created more than 60 years ago); however, none of these studies revealed a change in the major axes in time. In this case, the direction of the major axes is highly different depending on the calculation method: the major axis of compression has a sublatitudinal character according to optical distance data and a submeridional one according to GPS data (Fig. 1). In addition, these studies provide no information about the time period of the calculations.

At the same time, the results of experiments on samples indicate (Kuz'min and Zhukov, 2004) that when the dominant axis of action is taken to be invariant over the entire time period (for example, uniaxial loading on the sample), the angle between the dominant axis and the axis of compression, measured by local strain gauge sensors, will always change, as happens in the local area. This is not observed in homogeneous samples. However, if cracks begin to form inside the sample, some inhomogeneities arise to lead to local changes in the stress–strain state of the sample.

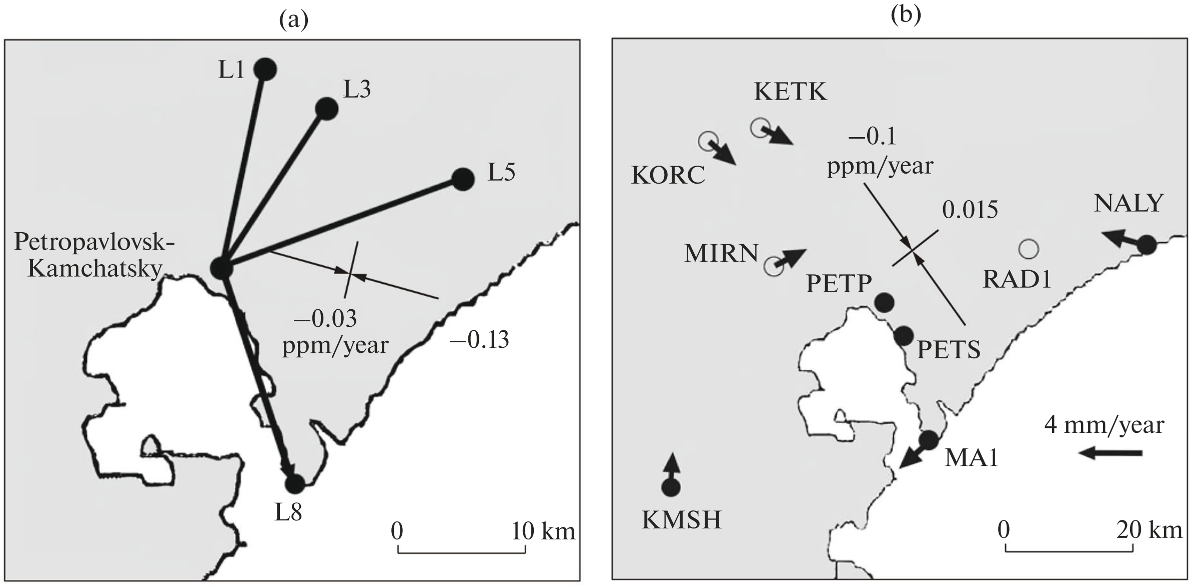

Fig. 1. The directions of the major axes of compression in Kamchatka according to (a) optical distance and (b) GPS data (according to (Levin, 2009; Levin et al., 2006, 2014)).

The same occurs on the Earth's surface, especially in seismically active regions.

This study was aimed at revealing the dynamics of change in the major axes of compression and tension over time, as well as in the angle between the major axis of compression and the dominant axis of action. It is assumed that the system of optical distance measurements is most affected by the following two sources: the subduction zone and nearby active volcanoes.

THE SYSTEM OF GEODYNAMIC OBSERVATIONS IN KAMCHATKA

The history of the geodynamic polygon in Kamchatka can be traced back to the 1970s. In the suture zone of the Eurasian, North American, and Pacific plates, geophysical and geodetic observations were arranged, including optical distance, leveling, and tilt measurements. The full system of the polygons located in the south of the Kamchatka peninsula is shown in Fig. 2.

From 1979 to 2003, quasi-continuous year-round optical distance measurements were conducted from Mishennaya Hill in the Avacha Bay, which made it possible to record horizontal displacements of the Earth's surface at sufficiently large (10–50 km) distances. These investigations are important due to the presence of a large number of volcanoes and a seismic focal zone nearby. The results of observations were described with an attempt to link the observed deformations with regional seismic events (Churikov, 1997; Levin, 2009; Bakhtiarov and Levin, 1989; Churikov and Kuz'min, 1998; Kuz'min and Churikov, 1998; Kuzmin and Fattakhov, 2018; Levin et al., 2006).

RESEARCH METHODOLOGY

Figure 3 shows the schematic of optical distance lines along which observations were conducted at the Mishennaya observatory (the Mishennaya hill). The reflectors were installed in such a way as to fix horizontal deformations at a maximum possible distance and around the entire area around the Mishennaya hill. Stations P01–P04 are located as close as possible to the Koryaksky and Avachinsky volcanoes and station P08 is located near the hydrometeorological station, whose databank was used as a source of all the required meteorological data (atmospheric pressure, precipitation, and temperature) to take the corrections during measurements into account. As a whole, these lines make it possible to record deformations in the submeridional direction. The measurements along the remaining lines (P05, P07, P09, and P10) allow sublatitudinal deformations of the region to be determined. All the stations are forcibly centered corner reflectors fixed on the Earth's surface with reinforced concrete pylons. The error of optical distance measurements is $(1–2) \times 10^{-7}$.

The set of P01–P10 lines can be represented as strain gauge sensors with readings used to calculate the invariant characteristics of the deformation process on the basis of geometric theory of deformations (it should be noted that this theory treats the axes of compression and tension as the "axis of shortening" and "axis of elongation").

The operation of modern strain gauge sensors is based on the transformation of a change in the sensor conductor parameters (for example, length or mechanical stress) into a change in its electrical resistance: the

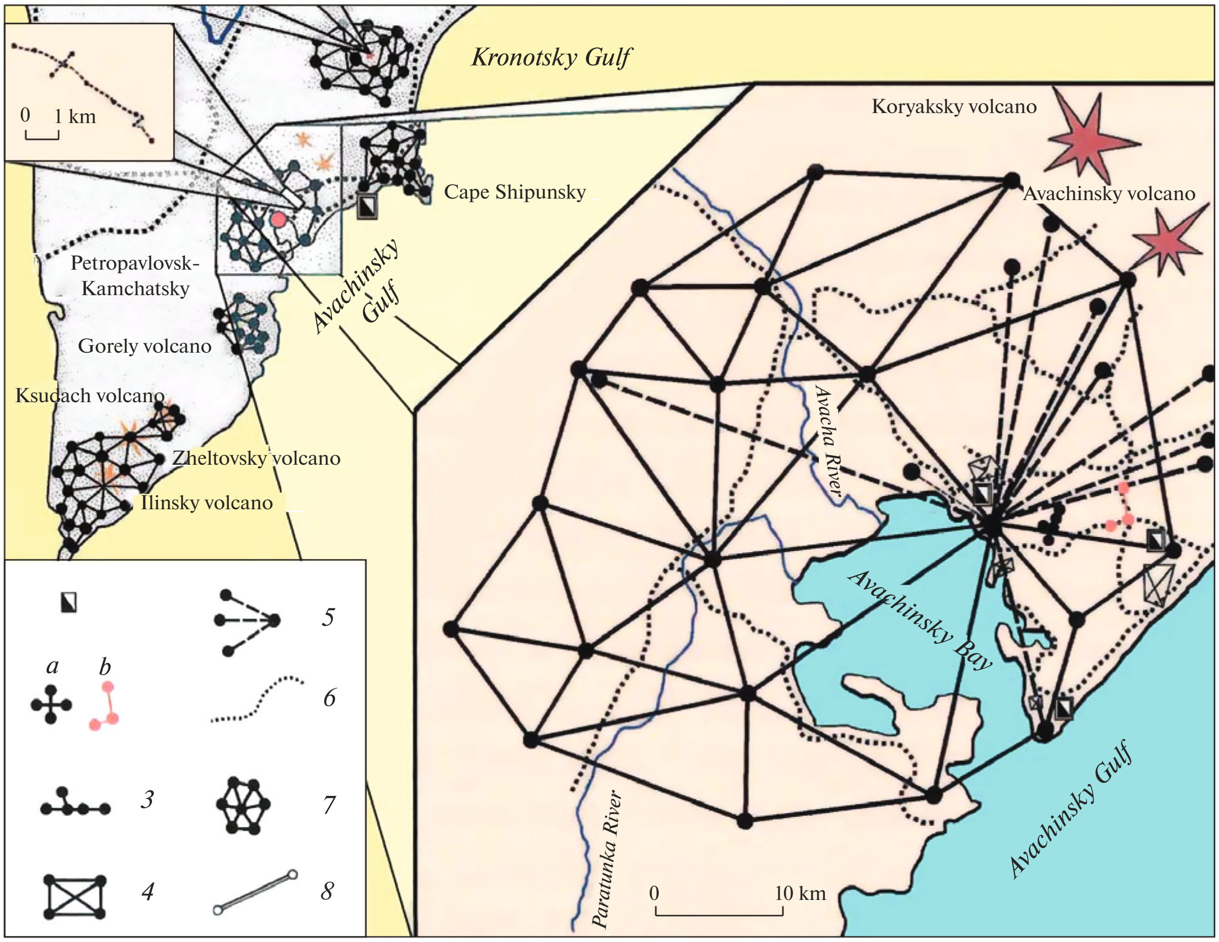

Fig. 2. The location of geodynamic polygons in the south of the Kamchatka Peninsula. The inset on the right panel shows a detailed schematic of the Petropavlovsk geodynamic test site (according to (Churikov, 1997)). (*1*) Tilt measurement stations, (*2*) leveling tilt platforms (*a*) and profile (*b*), (*3*) range measurements, (*4*) deformation platforms, (*5*) fan-shooting optical distance measurements, (*6*) extended leveling tracks of the first kind, (*7*) linear–angular triangulation, and (*8*) hydrostatic tiltmeters.

object surface deformation is transmitted to the sensor, which leads to a change in the electrical signal. In optical distance measurements, the analogs of sensor parameters are the line lengths, whose changes can be used to calculate the deformation of the Earth's surface and determine the major axes of compression (shortening) and tension (elongation), as well as the change in the angle φ_0 between the given axis of deformation and the axis of compression (shortening).

The calculations from the results of measurements with strain-gauge rosettes are based on the geometric theory of deformation derived from the Cauchy formulas (Love, 1927; Filonenko-Borodich, 1959; Novozhilov, 1958). According to this theory, if an elastic body is fixed in such a way that it cannot move as an undeformed solid, the movement of any of its points is caused only by deformation. Thus, linear deformations ε_α, ε_β, and ε_γ in three directions (x, y, z) are measured at a point of the body. In this case, the x-axis is aligned with the supposed direction of the largest deformation and the angles β and γ between lines are measured relative to the given x-axis. Linear deformations are calculated from the system of equations (Prigorovskii, 1983)

$$\begin{aligned} \varepsilon_\alpha &= \varepsilon_x \cos^2\alpha + \varepsilon_y \sin^2\alpha + \beta_{xy}\sin\alpha\cos\alpha; \\ \varepsilon_\beta &= \varepsilon_x \cos^2\beta + \varepsilon_y \sin^2\beta + \beta_{xy}\sin\beta\cos\beta; \\ \varepsilon_\gamma &= \varepsilon_x \cos^2\gamma + \varepsilon_y \sin^2\gamma + \beta_{xy}\sin\gamma\cos\gamma, \end{aligned} \quad (1)$$

where β_{xy} is the calculated shear strain in the Cartesian coordinate system.

With strains measured in three directions, one can use the system of equations (1) to obtain the angle φ_0:

$$\varphi_0 = \frac{\arctan\left(\dfrac{\beta_{xy}}{\varepsilon_x - \varepsilon_y}\right)}{2}. \quad (2)$$

Here, the geometric deformation theory does not imply knowledge of the medium, which makes it pos-

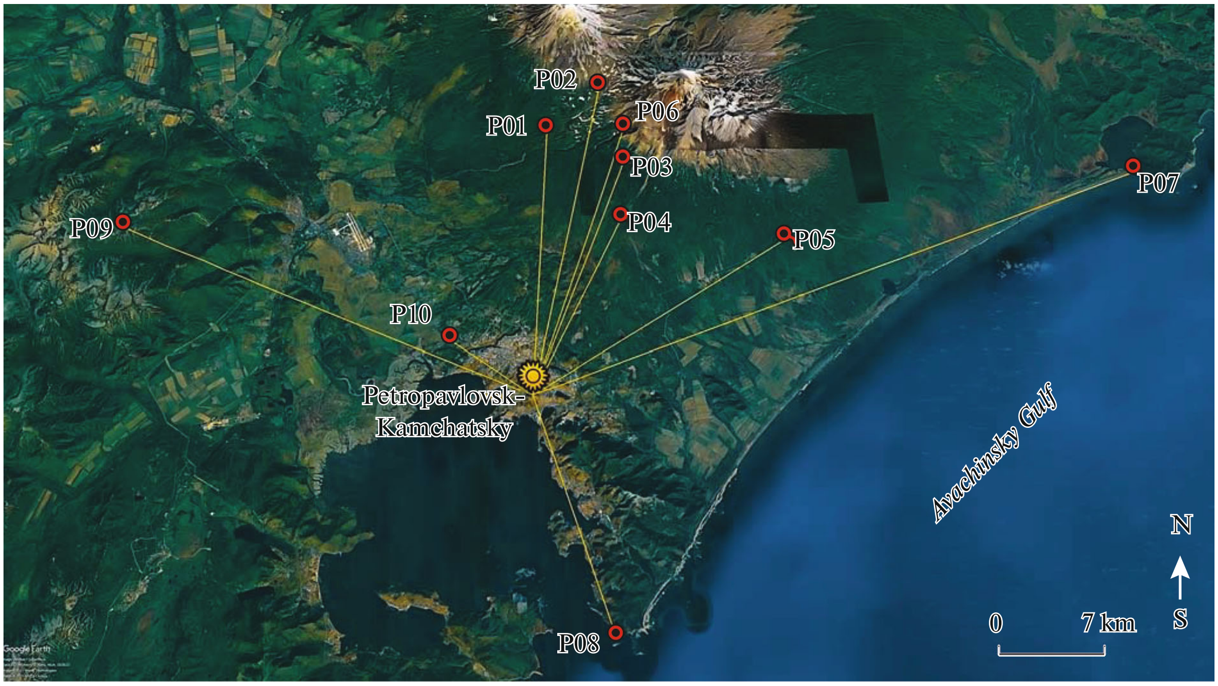

Fig. 3. A schematic of the arrangement of optical distance lines for measurements at the Mishennaya observatory (Petropavlovsk-Kamchatsky). P01–P10 are the stations with corner reflectors.

sible to use the theory for any rheological model (elastic, viscous, or plastic). The applicability of these formulas to inhomogeneous media has been substantiated in well-known monographs (Esikov, 1991; Kostrov, 1975).

The author of this paper considered it inappropriate to use programs that include any kinematic model, since all geodynamic phenomena (such as subduction, movement of magmatic matter in the near-surface layer, and processes in fault zones) that can affect the Earth's crust at the place of the polygon cannot be taken into account. Therefore, the original long-term observation series were processed using the WinABD software package, which is a comprehensive statistical system for processing and analyzing experimental geophysical time series (Deshcherevskii et al., 2016a, 2016b, 2019). In this case, the processing methods allow the presence of observational gaps and provide adequate combined processing of series that have different start dates and different frequency of observations. The WinABD package was used to perform a primary data analysis and calculate Fourier spectra and periodograms (Fattakhov, 2017).

DATA ANALYSIS AND RESULTS

Strain-gauge rosettes were chosen assuming that subduction (regional) and magmatism (local) are the two factors that have the greatest deformation effect on the territory of the geodynamic polygon. The lines were taken so as to be similar in length and in terms of the presence of gaps in the line series; therefore, the lines P06, P07, and P10 were immediately excluded from the calculations.

Lines P01–P04 are located near volcanoes (see Fig. 3) and seemed to be an optimal choice. On the basis of a detailed data analysis, we used only the lines P02 and P03, since they are the closest to the volcanoes and have the fewest number of gaps in data. In this case, these lines should not be averaged, since according to the geometric deformation theory it is the angles that play an important role, while averaging gives their average value for all lines.

According to the results obtained by Levin (2009), Avdeiko and Palueva (2008), and Levin et al. (2006, 2014) for the direction of the Pacific Plate movement as well as a model that considers the distribution of deformations in the subduction zone (Steblov and Sdel'nikova, 2019; Steblov et al., 2018), the dominant loading direction from the subduction zone is taken to be that of the P09 line. The P08 line was also added to the study, since it is the closest to the coastal zone.

The final strain-gauge rosettes consisted of lines P08–P09–P02 and P08–P09–P03, where the dominant axis of deformation was applied in the direction of subduction, as well as lines P09–P02–P08 and P09–P03–P08, where this axis was applied in the direction of volcanoes. The calculated directions of the axes are shown in Fig. 4.

Since the Kamchatka Peninsula is a seismically active region, we analyze the relationship between seismic events and the dynamics of φ_0 on the basis of

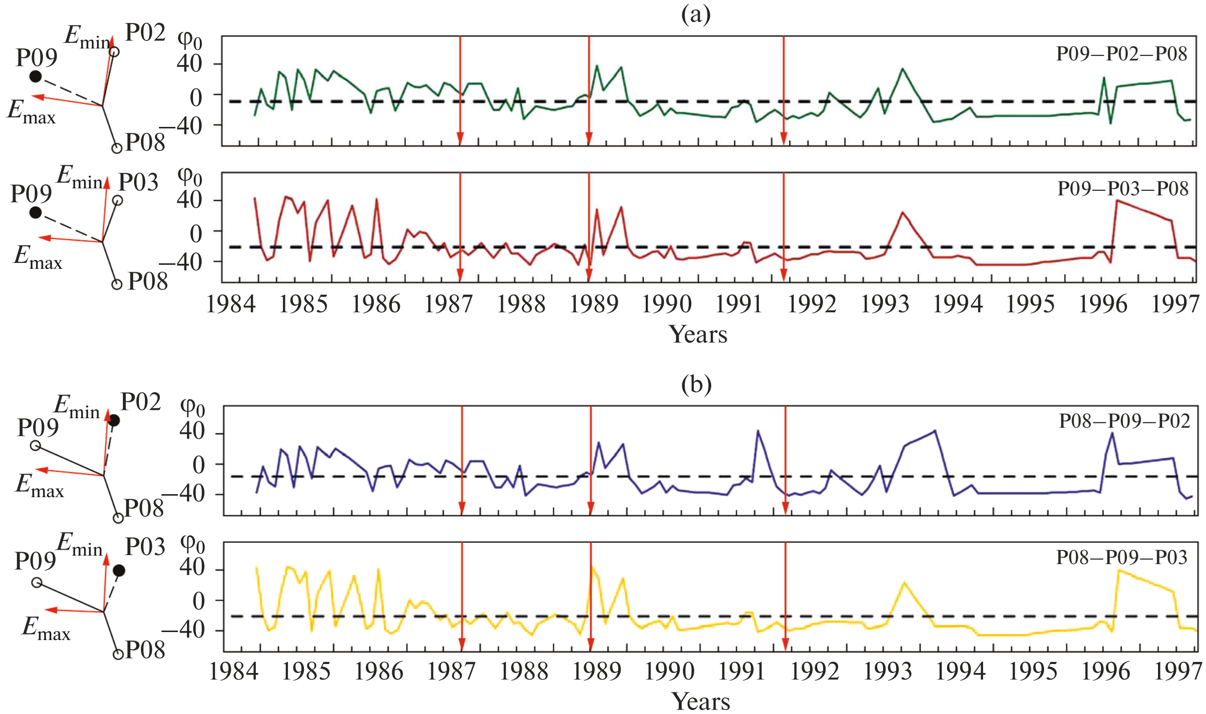

Fig. 4. The calculated directions of the major axes of compression and tension at the Petropavlovsk geodynamic polygon and temporal change in the angle φ_0 from the results of measurements with strain-gauge rosettes. (a) Dominant axis in the direction of subduction and (b) dominant axis in the direction of volcanoes. Dashed lines are average angles for strain-gauge rosettes. Arrows indicate the times of strong earthquakes in the vicinity of Mishennaya hill.

strong ($M > 5.5$) earthquakes with a source depth of no more than 50 km that occurred over the entire observation period in the vicinity (up to 100 km) of the Mishennaya hill: October 6, 1987, $M = 6.5$, $\Delta = 78$ km; July 8, 1989, $M = 5.5$, $\Delta = 80$ km; and March 2, 1992, $M = 6.9$, $\Delta = 76$ km (indicated by arrows in Fig. 4). Data on the seismic events were taken from the website of the US Geological Survey (http://earthquake.usgs.gov/).

All graphs in Fig. 4 also show the average angle φ_0 between the direction of the dominant axis of deformation (axis P09, P02, or P03) and the major axis of compression (shortening) axis. It should be noted that the nature of the temporal change in φ_0 indicates that the angle is independent of seismic events: abrupt changes in φ_0 occurred both before and after the earthquakes.

It follows from Fig. 4 that when subduction is chosen as the dominant source in the strain-gauge rosette, the major axis of compression along the rosettes P08–P09–P02 and P08–P09–P03 is directed westward. When magmatism is chosen as the dominant source, this axis changes its direction by 90° and becomes directed northward (toward the volcanoes). This change in the angle may be due to the actual geometry of the location of sources. In Kamchatka, the optical distance lines are built in such a way that the angle between the directions toward the volcano and toward the subduction zone is almost 90°.

The error in determining the major axes of deformation includes errors in the measurements of the major lines and from calculation of strain deformation. The calculated error in determining the mean angle of major axes was 5° and the difference between the resulting angles in the direction of subduction and volcanoes was 4° and 2°, respectively, which is within the calculation error.

All changes that can be traced on the graphs occur simultaneously for all strain-gauge rosettes, while the difference between the maximum and minimum values of φ_0 reaches 80°.

The time dependences of relative deformations along the major axes of compression and tension (Fig. 5) make it possible to estimate the dynamics of horizontal deformations and their relation with strong earthquakes. Since all graphs are built on the same scale, one can easily compare the deformations changes along different axes over time.

A comparison of deformations along the major axes of compression demonstrates that these deformations are subjected to sign-alternating fluctuations; in this case, there is some similarity in the temporal behavior of the deformations curves. Sharp changes in deformation signals are rather rare and these changes

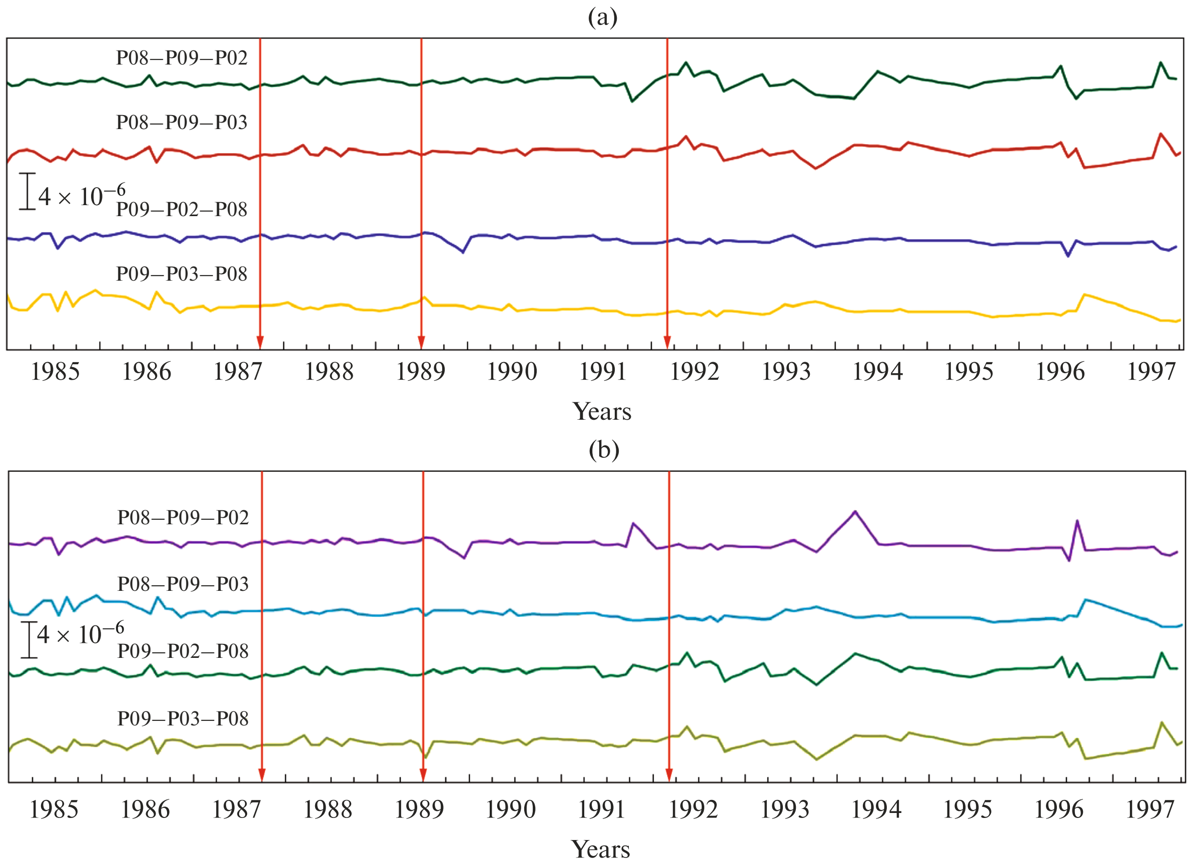

Fig. 5. Deformation changes along the major axes of compression and tension at the Petropavlovsk geodynamic polygon according to the results of measurements on strain-gauge rosettes. Arrows indicate the times of strong earthquakes.

along the axes do not always correlate with changes in φ_0 (see Fig. 4). As an example, all graphs show a sharp change in the signal in June 1996 after a rather long quiescence. At the same time, an alternating change in φ_0 occurred. A good correlation between φ_0 and deformations can be traced only when φ_0 almost does not change with time. At this time, almost no change in the magnitude of deformations can be observed.

DISCUSSION OF THE RESULTS

The results obtained in this paper show that the direction of the major axes of compression (shortening) and tension (elongation) depends on the choice of source. In this case, invariant results are obtained only in a homogeneous medium, when the action comes from a single source, as in experiment on a sample (Kuz'min and Zhukov, 2004). When one more (and perhaps more than one) local source appears, the picture changes sharply. These changes indicate that during the entire period of measurements, various factors are involved that affect the behavior of φ_0. Thus, these are nonmonotonic (inherited) motions, and both factors of the deformation effect (magmatism and subduction) equally contribute to the change in this angle.

Since the current level of spatial detail of the geodetic network does not allow one to distinguish between deformations from volcanoes and from subduction on the Mishennaya hill, we estimated the alternate and predominant impact of the two sources. Here, the average annual rates of horizontal deformation along optical distance lines, as obtained from the spectral–temporal analysis (Fattakhov, 2017), are comparable in level with 1–2 amplitudes of terrestrial tidal deformations in a region with anomalously high seismotectonic activity, which is indeed a paradoxical situation (Kuzmin, 2009, 2013, 2018, 2019b).

CONCLUSIONS

The analysis of data from precision observations of the stress–strain state of the Earth's crust in the vicinity of Mishennaya hill (the Kamchatka Peninsula) show that changes in the angle φ_0 and compressive and tensile deformations cannot indicate any single direction vector. The temporal change in the stress–strain state of the Earth's crust occurs constantly, especially in seismically active regions; in this case, various local impact sources can be involved at different time intervals. In view of this, one cannot unambiguously identify the dominant deformation mechanism of the impact on the system of optical distance observations (at a geodynamic polygon).

In conclusion, it should be noted that a network of GPS measurements has been operating in Kamchatka since 1997, which eventually replaced ground-based optical distance measurements. This is explained by the fact that the wear of optical distance equipment began to lead to systematic data gaps, which, in turn, complicated the interpretation of the results. Therefore, the emphasis was placed on satellite measurements.

On the one hand, this was a justified decision, since many researchers currently believe that the future lies in satellite observations, and on the other hand, a number of studies suggested that the accuracy and detail of observations at ground-based geodetic stations even after 20 years remains higher than those of satellite observations (Kuzmin, 2017, 2019a; Kvyatkovskaya and Fattakhov, 2019; Grunin et al., 2014; Kvyatkovskaya et al., 2017). In addition, the measurement accuracy of satellite geodesy data strongly depends on the data processing package (Tereshchenko and Lagutina, 2019). The results of this study show that optical distance observations make it possible to obtain useful information about changes in the stress–strain state of a region.

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CONFLICT OF INTEREST

The author declares that he has no conflicts of interest.

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