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Anomalous Strain Generation Mechanism before the March 2, 1992, Kamchatkan Earthquake

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Precision leveling was conducted during 3 years on a local line in a seismic fault zone in Kamchatka. The results were examined to find relations between deformation and seismicity. Superintensive vertical movements were identified in active fault zones, intersecting the leveling line, associated with the preparation of a large earthquake (M = 7.1, March 2, 1992) during the period of observation.

INTRODUCTION

This paper discusses the results of a precision leveling survey conducted along a local line established in a seismic fault zone. The aim of the measurements was to study relations between the deformation and seismicity that occurred in the Gulf of Avacha and identify possible precursors of a probable large earthquake.

A local segment about 3 km long was selected in the Kamchatka regional leveling network to be fixed in the terrain as a permanent leveling route (line). This line was surveyed during three years at a rate of 1–2 times a week. A technique had been developed for high precision leveling to be carried out on a local line; the technique was different from the standard method commonly used in State leveling networks to achieve a higher accuracy and speed of measurement. The levelling line intersected three active faults, on which vertical movements had been recorded to be as great as 8–10 cm over distances of 100 m. The results of the measurements and their analysis were summarized as practical recommendations and a substantiation of a differential measurement technique when selecting an area for a test site.

The geodetic method is one of the leading techniques used for predicting possible natural disasters in Kamchatka. Many geodynamic test sites have been set up in

Kamchatka since 1974 to study crustal deformation. At present a dense geodetic network more than 2500 km^2 in area covers the region of the Avacha-Koryaksky volcanic group, the Gulf of Avacha, and Petropavlovsk-Kamchatsky City [6], [15], [25], [26].

Measurements in such large networks are usually carried out 1–2 times per year. An experience of many years showed that this sampling rate was sufficient to monitor the background geodynamic process, not sufficient for intermediate- and short-term forecasts of probable earthquakes and volcanic eruptions. This method of measurements is only suitable in long-term prediction strategies. An attempt at increasing the sampling rate on this large geodetic network by a factor of several times inflated the cost and reduced the area to be sampled. In this connection it is very important, in order to enhance the efficiency of measurements, to significantly reduce the time required for occupying the entire network without making the results less representative. This could be achieved by short leveling lines to be established in areas of geodynamic interest and to be occupied more frequently.

GEOPHYSICAL DESCRIPTION OF THE STUDY AREA

The leveling line is situated at a distance of 15 km from the city limit, near the village of Chapaevka about 20 km from the Avacha-Koryaksky volcanic group. This area is well known geologically and geophysically. Many geological and geophysical studies were carried out there over the years, including a regional gravity survey and detailed geophysical investigations (MT and near-field TEM soundings and gravity prospecting) to search for thermal water near the cities of Petropavlovsk-Kamchatsky and Elizovo [15], [26], as well as to study deep crustal and upper mantle structure, locate feeding magma chambers of volcanoes, and determine the physical properties of rocks there [1], [2].

The location of the leveling line was chosen based on the available geophysical and geological information, as well as on the long-continued geodetic observations previously conducted in the area.

The leveling line (Fig. 1) was located around the intersection of major tectonic faults striking northeast and northwest, i.e., in the area of a deep-seated fault zone and the Avacha depression. The line traverses a local gravity high around the middle of the line and an intrusive body in the south. A tectonic fault mapped in the middle of the line by MT sounding data intersects it in the east-west direction. Another fault parallel to this one somewhat further north had been inferred from aerial photographs. The area is supposed to be divided by differently striking faults into small blocks [19].

CONFIGURATION AND STRUCTURE OF THE LEVELING LINE

The line is nearly straight and is 2.6 km long. It strikes north-south, one end being toward the volcanoes and the other toward the Avacha Bay. Its overall trend is nearly perpendicular to the dipping seismic zone in the Avacha Bay.

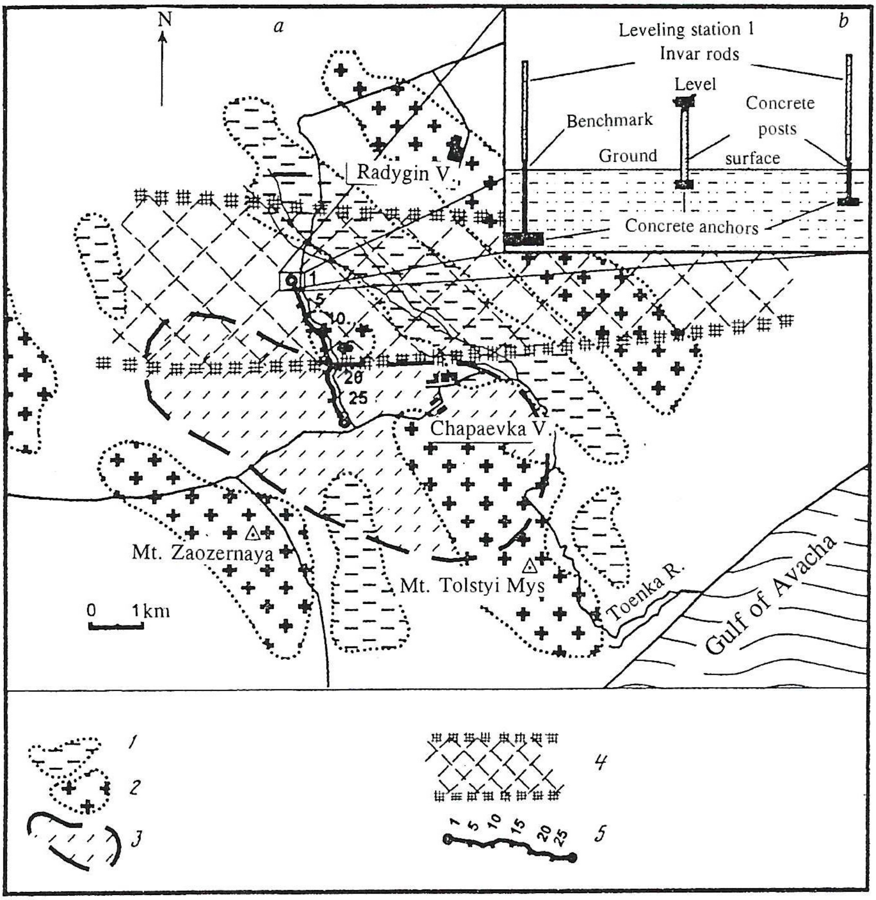

Figure 1 Detailed geological and geophysical map of the study area (after A. G. Nurmukhamedov and A. S. Zheltukhin [19]); *1* – local Δg lows; *2* – residual Δg highs; *3* – inferred intrusive body; *4* – tectonic fault inferred from MT sounding data and interpretations of aerial photographs; *5* – leveling line with station numbers.

The line is firmly fixed in the terrain by concrete posts. This was done, firstly, to completely prevent the spikes, footplates and supports from subsiding and thereby affecting the measurement accuracy; secondly, to raise the speed of measurement along the line; and thirdly, to fix benchmarks for each next occupation to be made at the same stations along the line.

The posts for placing measuring rods and the level are deepened in the ground to depths of 1–1.5 m and fastened with concrete anchors. The rod posts (jutting 1–1.2 m above the ground) have three metal pins with spherical ends to fix the rods. The pins are fastened in a post at three different heights: at ground level, in the middle, and on the top of the post. This design was proposed by V. S. Tselishchev, Institute of Volcanology, Far East Division, Russian Academy of Sciences, to facilitate measurements in any season of the year, especially during winters with large snow drifts. The posts for right and left levelings have individual (not connected) anchors and are separated by 1.2–1.5 m. The beginning and end of the line are marked with standard ground GUGK (State Geodetic and Cartographic Department) benchmarks buried together with the concrete anchor 3–3.5 m below the depth of ground freezing. The line is on loose uniform ground consisting of lahar deposits and the material produced by a directional explosion on Avacha Volcano (cinder, ash, bombs, lapilli), as well as of alluvial deposits (sand, gravel, pebble, loamy sand). The posts were fixed uniformly everywhere on the line, making 28 level stations with interstation spacings of 80–100 m on the average (Fig. 1, *b*).

The measurements on this line were conducted using a modified program for observing at a station in first-order leveling work. This was done, because the leveling line was fixed by concrete posts in the terrain. In this way the effects due to subsidence of spikes, footplates and supports that might influence the rod readings were completely removed. This increased the speed of measurement along the line by 30–40% without affecting the observation quality and reduced the influence of the environment on leveling accuracy. We used the Ni 002 Carl Zeiss level with a self-positioned sight and a set of invar rods. All needed checking operations were carried out during the measurements to test the level and the rods.

The rms errors found by the standard method prescribed for first-order leveling were as follows: 0.11 mm for a measurement at a single station and 0.4 mm per one kilometer of double-run leveling. The relative error for the entire period of observation was 0.1 ppm. Our own technique of accuracy evaluation yielded a random two-way error of 0.09 mm.

A description of the techniques used for the measurement and error evaluation is beyond the scope of this paper.

Leveling was carried out 1–2 times a week during the period of November 1989 to July 1992, except for two gaps no longer than a month due to weather or technical causes. When the measurements on the line had been completed, electronic catalogs were made to record changes in elevation at each leveling station for the entire period of observation.

ANALYSIS OF MEASUREMENTS. RELATION BETWEEN CRUSTAL MOVEMENTS AND SEISMICITY

The leveling line consisting of 28 leveling stations firmly fixed by the ground benchmarks allowed independent observation of vertical movement at each station.

Figure 2 presents vertical movements of the ground surface along the line relative to the first benchmark. Some segments are seen to experience local subsidence; five segments of this kind were recorded during the entire observation period. Bearing in mind the actual accuracy of measurement (0.1 mm at a station) and the effect of systematic error accumulation when proceeding along the line, the most significant anomalies were those around stations 4–6 (Left anomaly), 8–12 (Middle anomaly), and 13–15 (Right anomaly).

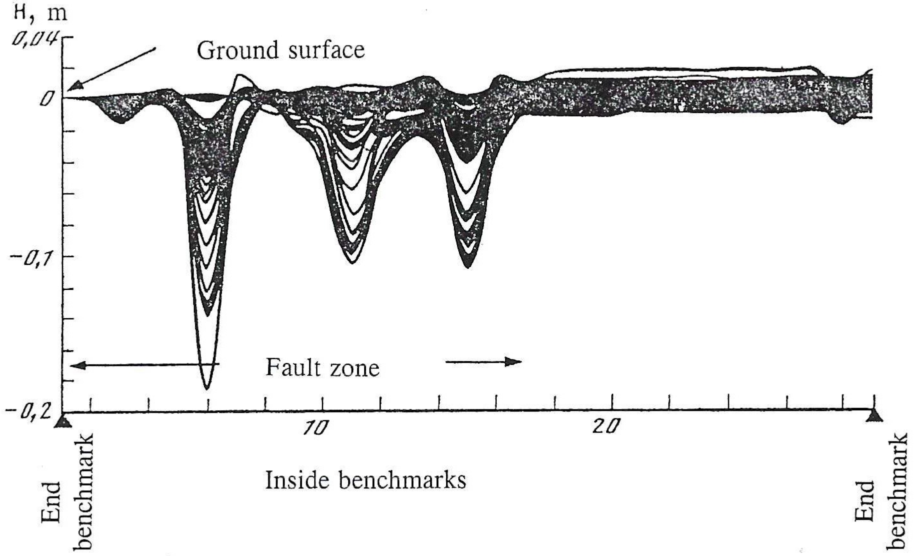

Figure 2 Displacement of ground surface along the line relative to bench mark 1.

All three curves showed peak-shaped subsidences. Besides, one notes the well-pronounced pulsational character of these subsidences. Periods of rapid subsidence alternate with periods of relative quiet. Sometimes periods of slight inversion movements were observed. The amplitudes of the local peaks decreased during these periods. However, the overall pattern is a persistent tendency of pulsational, successive subsidence in local areas.

The anomalies had amplitudes of 1–2 to 10–13 cm during different time periods and widths of 200 to 500 m, the Left and Right anomalies having nearly the same width during the entire observation period. The Middle anomaly changed its width by a factor of about two.

All these anomalous movements are in keeping with the current knowledge of the present-day anomalous geodynamic activity in the faults and fault zones [7], [8], [9], [10], [11], [12], [13], [14]. Various observations and modeling studies had proved the existence of local γ-shaped anomalies (local subsidences of the ground surface) which are confined to fault zones of varying ranks. The anomalies usually range between 0.5 and 2.8 km in width. Considering that our results were obtained for the first time using the measurements of high space-time resolution, these anomalies can now be identified with local faults. If the network had been less dense (spaced, e.g., at intervals of 0.3–0.5 km, as is usually the case in conventional near-fault strain-measurement sites deployed within various geodynamic test sites [17], [18], [22], [26]), the three anomalies could have been identified with a single broader γ-shaped anomaly.

Our results agree fairly well with relevant geologic evidence. The three local anomalous zones seem to belong to a single fault zone that traverses the line and lies within the Avacha depression; this is also borne out by the interpretations of aerial photographs as indicated in Fig. 1. It should be noted that the most stable part of the line (stations 18–28) occurs above the intrusive body inferred from geological and geophysical data.

Figure 3 shows the elevation changes at active and inactive leveling stations as compared to the seismicity that took place within 100 km of the line during the observation period. An active station is here defined as one where high-amplitude, antiphase changes in elevation between stations have taken place. Inactive stations exhibit in-phase behavior and low amplitudes of vertical movements.

Therefore, movements at active stations are in keeping with present-day superintensive ground deformations in fault zones [13].

It can be seen in Fig. 3 that the stations had periods of anomalous behavior, typically with three periods of an abnormal change for the active stations and only one for the inactive ones. The seismicity rate decreased during anomalous periods I and II, while anomalous period III, which is common to both the active and the inactive stations, involved a quasi-synchronous increase in strain rate and increasing seismicity rate, which culminated in the March 2, 1992, magnitude 7.1 earthquake. Assuming the anomalous movements at the active stations during periods I and II to have been due to the inherent dynamics of the associated faults, not directly related to seismicity [27], one can identify anomalous period III with the precursory process of this large earthquake. The precursory anomaly III varied from 4–8 cm ($(4\text{–}8)\times10^{-4}$) at the active stations situated in the fault zone to 4–8 mm ($(4\text{–}8)\times10^{-6}$) or less at the inactive stations outside of the fault. It is noteworthy that the strain precursor (III) had different durations at the stations in the fault zone and outside it (Figs 3, *a* and 3, *d*). The plots clearly show why the inherent dynamics of the fault increased during anomalous period II. It was caused by a moderate ($M = 5.8$) earthquake that occurred beyond Cape Shipunsky on March 1, 1990.

It can thus be stated that the anomalous precursory deformation that took place in the fault zone had amplitudes 1–2 orders above those observed outside it, the duration of precursory variations in the fault zone segments being considerably greater (by factors of 1.5–2) than for in the stable segments of the line.

The natural question arises as to the origin of this large precursory strain.

It follows from the literature that anomalous precursory deformation is at maximum in the vicinity of the future epicenter and decays away from it. There are several

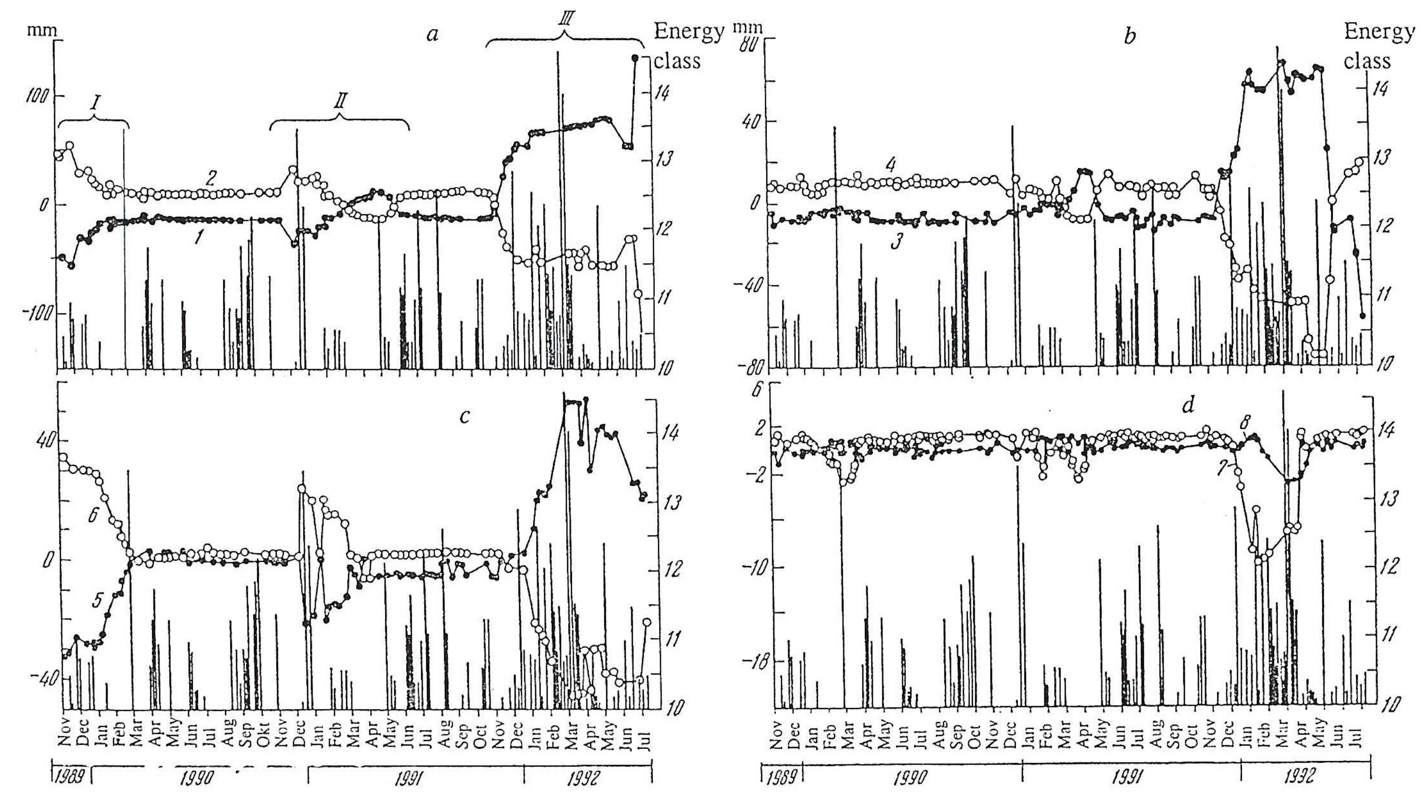

Figure 3 Elevation changes at active (*a–c*) and inactive (*d*) stations compared with seismicity. The horizontal axis represents the time of observation, the vertical axis shows elevation changes at the stations (in mm) and the energy classes of earthquakes that occurred within 150 km of the leveling line. Station numbers: *1* – 5; *2* – 6; *3* – 10; *4* – 11; *5* – 14; *6* – 15; *7* – 17; *8* – 19. I–III are periods of abnormal behavior.

quantitative models that describe the falloff of anomalous strain and tilt as a function of the distance from the earthquake source area depending on the earthquake energy class [3], [11], [16], [28]. I. P. Dobrovolskii's model, the most popular in Russia, provides relations for calculating so-called strain radii which are the greatest distances at which precursory effects can still be recorded.

It should however be remembered that this model is valid as a "point" approximation, so that it is effective only for cases in which the effects due to the shape and dimensions of the inclusion can be disregarded. This approach is very important in cases where an anomalous signal observed in a region should be compared with the region's seismicity. In that case I. P. Dobrovolskii's relations constrain the range of epicentral distances and magnitudes of earthquakes that are potentially capable of producing a precursory anomaly.

There are however situations when it is necessary to specify the inclusion's shape definitely enough. For instance, a retrospective analysis of a foreshock and aftershock activity shows that the source zone has a definite shape and position relative to the principal axes of regional tectonic stresses. When the shape of an inclusion is far from being spherical, and the precursors have been recorded in the "near" zone, one should take into account the concrete shape of the inclusion.

This becomes especially important when it is needed to compare precursory effects recorded by different strain-measuring systems (e.g., leveling and geodimeters, tiltmeters and strainmeters), because the character of the falloff of anomalous displacements, strain, and tilt with distance depends on the shape of the inclusion. In that case, when there are anomalous changes in parameters obtained simultaneously from leveling and geodimeter data, the shape is to some degree constrained by a relation between the maximum amplitudes of the respective precursors.

We used a model described in [13], [22] in order to incorporate the above factors for the quantitative analysis and modeling of the precursory situation before the March 2, 1992, earthquake. This model specifies the precursory process of an earthquake as the generation of a soft inclusion (mostly owing to dilatancy weakening) having a definite configuration in a field of specified subhorizontal stresses (compression or extension). The model gave analytical expressions for the cases in which the model analogue of a source zone is a sphere, an infinite horizontal circular cylinder, and a bounded horizontal circular cylinder. In addition, the distribution of displacements, tilts, and strain was calculated numerically (by the finite element method) for the case of an elliptic cylinder.

An elliptic configuration is usually believed to be the most natural shape of a source zone [20]. However, as was shown in [5] for the case in which the elliptic inclusion lies at a depth that is 1.5–2 times the smaller semiaxis (oriented vertically), and the distance to the observation site is 2–3 times the linear size of the source, the difference between the surface displacements due to an elliptic and a circular horizontal bounded cylinder may be as great as a few percent.

Zobin *et al.* [4] inferred the seismotectonic position of the March 2, 1992, earthquake source together with the dimensions and configuration of the source zone. Taking these results into account, the model analogue of the source zone can be a horizontal bounded circular cylinder with $r = 12.5$ km and $2l = 20$ km, where r is the radius of the cylinder and l, the half-width of its generatrix. The geodynamic and seismotectonic setting of this earthquake suggests the following model for the generation of the anomalous strain field.

The source zone of the March 2, 1992, MLH 7.1 earthquake was located within the axial part of the submarine extension of the Shipunskii Peninsula, which is the most active transverse feature in eastern Kamchatka, along the 600-m isobath as it intersects the main seismic dipping zone of Kamchatka. This earthquake continued the evolution of the October 6, 1987, MLH 6.6 earthquake source zone. The mechanisms of the main shock and the large aftershocks were similar, being reverse movements on high angle fault planes; this is in keeping with the orientation and dip angle of the Benioff zone, and indicates the orientation of the principal axis of the regional compression.

In this situation the subhorizontal regional compression was acting to maintain subduction and was oriented orthogonally to the trend of the Benioff zone. The part of lithosphere beneath which the Pacific plate is being subducted was in the state of bending; this means that the overall regional state of compression was transformed into a subhorizontal extension in the upper crust. Taking into account the relation between the duration of subduction (millions of years) and of the precursory strain events (a few months or years), it can be concluded that the principal regional compressive stress and the transformed regional extension must have been quasi-stationary compared with the duration of the precursory anomalies.

Therefore an anomalous uplift occurs in an environment of subhorizontal quasistationary compression around a cylindrical inclusion, and local subsidences take place in an environment of quasistationary extension in the fault zone.

Kuzmin [11] derived the following relations for horizontal U_2 and vertical U_3 displacements:

$$U_2 = \Phi \frac{r^2 x_2}{x_2^2 + h^2} \left[\frac{l + x_1}{(x_2^2 + (l + x_1)^2 + h^2)^{1/2}} + \frac{l - x_1}{(x_2^2 + (l - x_1)^2 + h^2)^{1/2}} \right];$$

$$U_3 = \Phi \frac{r^2 h}{x_2^2 + h^2} \left[\frac{l + x_1}{(x_2^2 + (l + x_1)^2 + h^2)^{1/2}} + \frac{l - x_1}{(x_2^2 + (l - x_1)^2 + h^2)^{1/2}} \right],$$

where Φ is a physical factor that describes the intensity of the associated strain anomaly; h, x_1, and x_2 are the depth and the coordinates of the source zone, respectively.

Assuming the typical values $\sigma = 100$ MPa, $\mu = 3 \times 10^5$ bars, $\nu = 0.25$, $\alpha = 0.4$, one can calculate the distribution of vertical and horizontal displacements around the source zone (Figs 4 and 5).

Vertical and horizontal displacements fall off differently. At first the vertical displacements dominate. Later, away from the source zone, both movements falloff, but the falloff of the horizontal displacement is slower than that of the vertical. The vertical displacement becomes equal to the horizontal at a distance equal to the source depth.

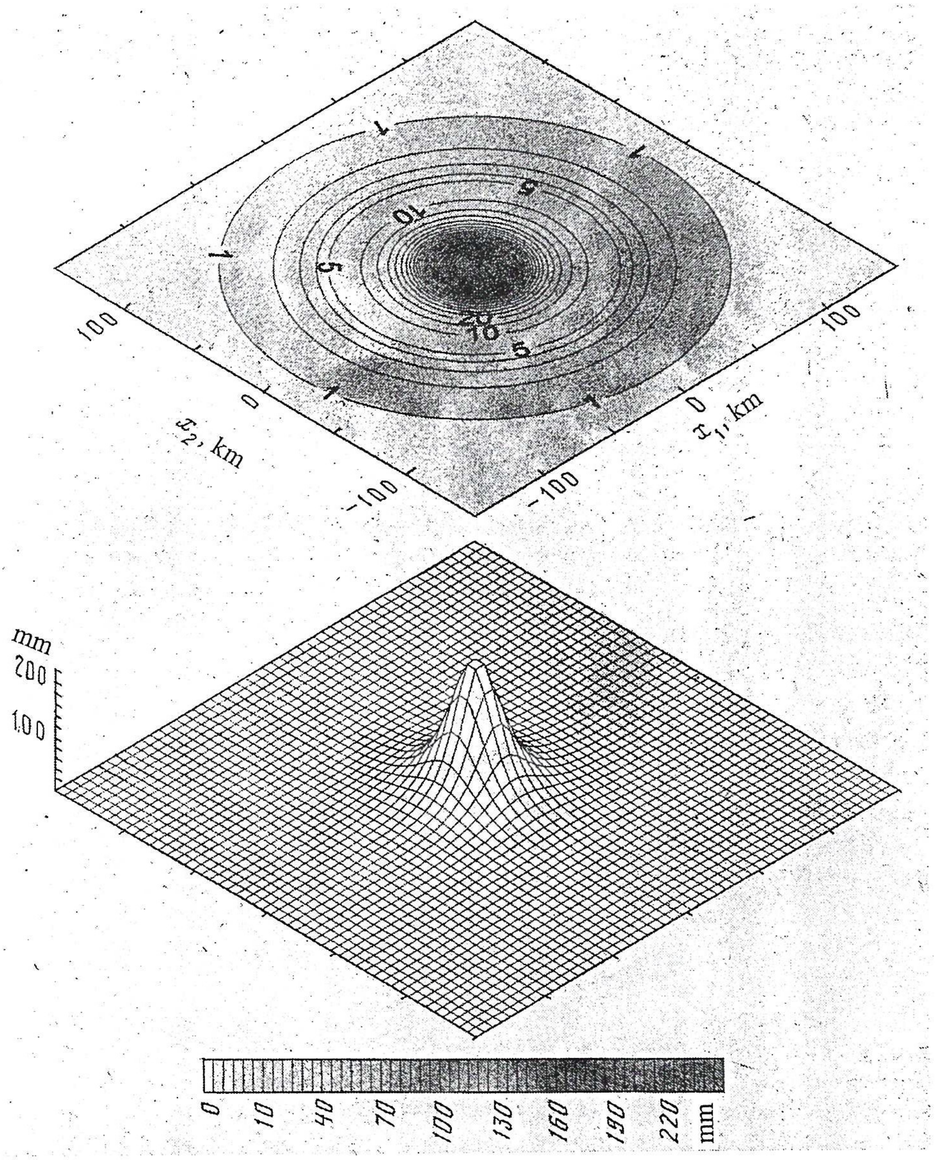

Figure 4 Distribution of vertical displacements around the source zone.

The model vertical (Fig. 6, *a*) and horizontal (Fig. 6, *b*) displacements were shifted to be located at the epicenter in order to compare them to the observations. Figure 6 shows the position of the March 2, 1992, epicentral zone in relation to the leveling line and to a sheaf of lines measured with a geodimeter installed at the Mishennaya

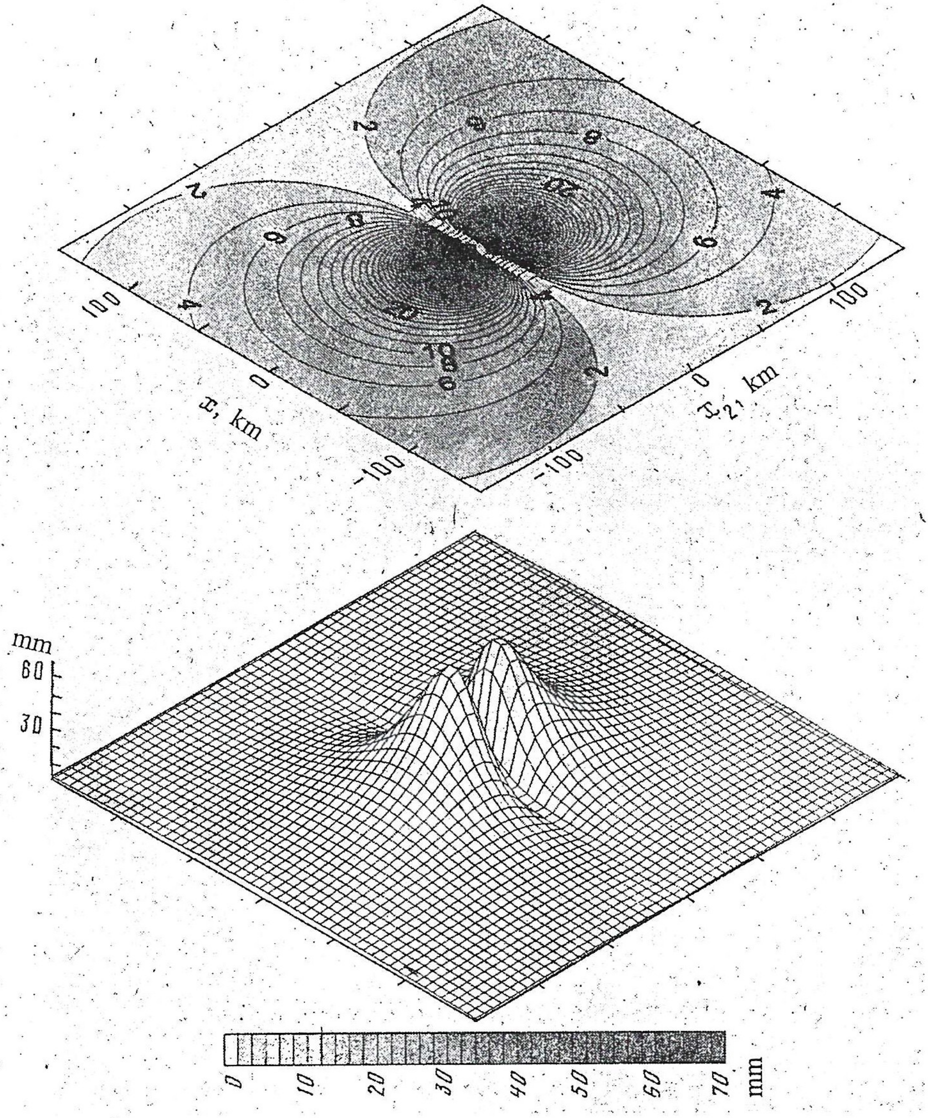

Figure 5 Distribution of horizontal displacements around the source zone.

Observatory (the sheaf is shown as in [4]). It appears from Fig. 6 that the leveling line falls into an area of vertical displacements about 2 mm in magnitude. This result is in good agreement with the measurements obtained along the stable segment of the line. The theoretical horizontal displacements also are in good agreement with the observations.

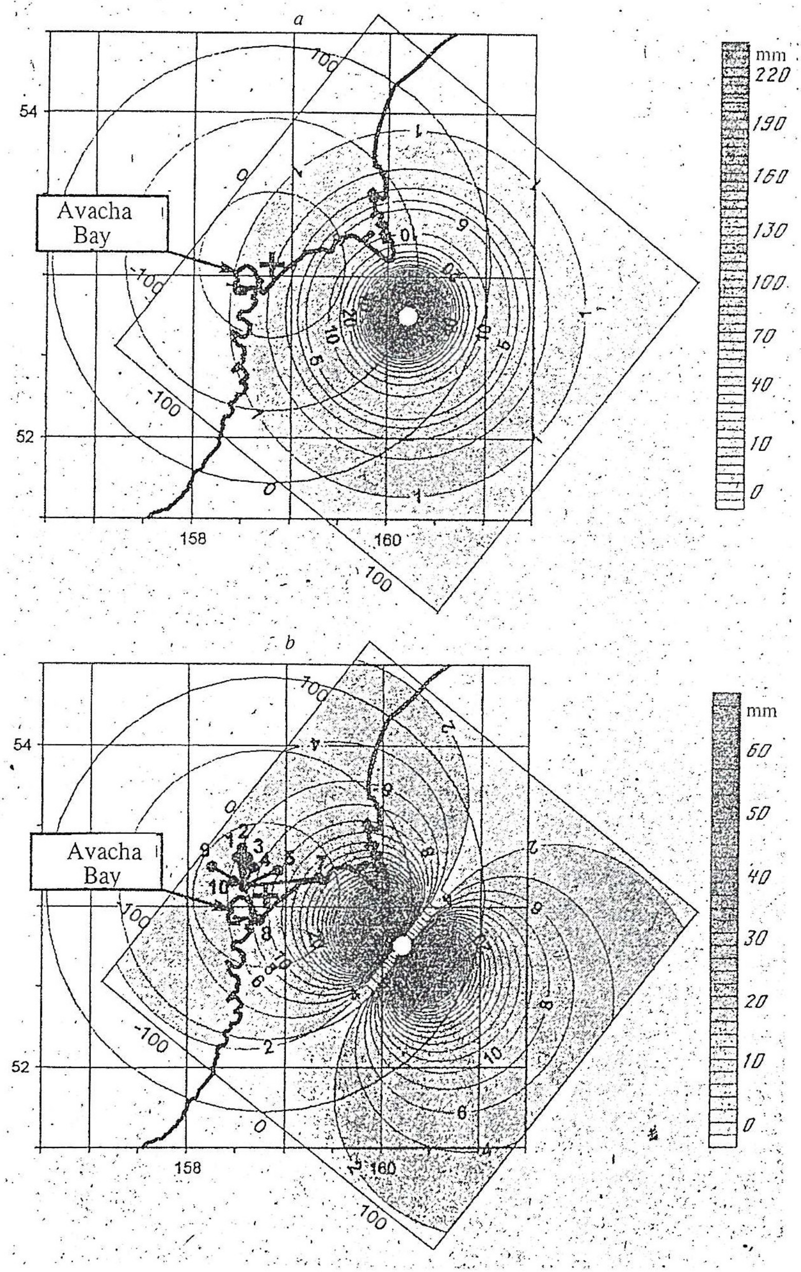

Figure 6 Comparison of the mathematical modeling results for vertical (*a*) and horizontal (*b*) displacements with the observations (for explanations see the text). The concentric circles have radii of 50, 100, and 150 km, the leveling line (marked by a cross) is at the center.

Similar calculations were carried out for a spherical model of the source zone (spherical inclusion), where the relation between horizontal and vertical displacements did not fit the observations.

According to our model calculations, the horizontal strain along the line might have reached about 4–5 × 10^{-6} with about 10^{-5} tilting for the March 2, 1992, earthquake. Taking each station to be a long-base tiltmeter (base of about 100 m), we converted the anomalies into dimensionless quantities and arrived at a satisfactory agreement between the model and observed data for the bench marks outside of the fault zones (stations 1–4 and 17–27, Figs 1 and 2). At the same time the tilts in the near-fault zones (in areas of local subsidence) were 10^{-3} to 10^{-4}, the values comparable with the strength limit of continuous solids. Two interpretations can be suggested to explain this paradox. One is that the sharp increase of the precursory anomaly amplitude results from the amplifying effect of the fault zone, which inflates the strain that reaches that zone owing to its anomalously low rigidity. The other interpretation implies that the increase of the precursory amplitude was caused by the parametric excitation of present-day geodynamic processes in the fault zone arising during the precursory period of an earthquake [7], [10] (Fig. 7).

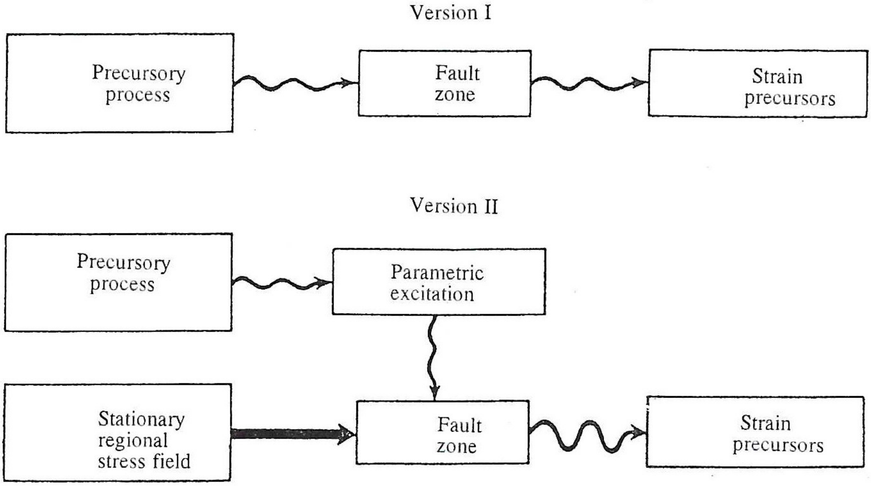

Figure 7 Chart showing the generation of superintensive strain precursors.

An analysis of the two interpretations shows however that the first of them requires the assumption of a short-lived decrease in the rigidity of the fault zone by two or three orders of magnitude during 5–6 months, while the second calls for a decrease of merely 20–30%. Hence the more likely mechanism for the generation of such intensive anomalies must have been the parametric excitation of deformation in the fault zones due to the precursory process of the earthquake.

This superintensive precursory deformation occurring in fault zones can thus be called a parametric precursor.

Sobolev [24] described three classes of earthquake precursors.

Our results suggest that two precursors out of his three classes appeared simultaneously on the leveling line during the precursory period of the March 2, 1992, earthquake.

Anomalous changes of 10^{-6} in vertical and horizontal displacements are fairly well consistent with our model estimates pointing to a direct proportionality between earthquake magnitude M and the distance R from the source to the site where the displacements were measured. Besides, the precursor duration fits the relation [11]

$$\log(T, \text{days}) = 0.19\mathrm{K} - 0.44,$$

which too shows a direct proportionality between the earthquake energy and the logarithm of the precursor time. As stated in [24], all of these features are characteristic of the precursors of the first class.

The superintensive precursory effects we identified were all confined to zones of active faults. Moreover, the relations connecting M, R, and T were not clear enough. These anomalies can thus be classified as precursors of the second class [23].

Two mechanisms can be invoked to account for the generation of parametric precursors.

One of them assumes the precursory deformation to affect the shape and size of the cracks that compose the activated fragment of the fault zone, leading to the extra "softening" of rocks in a fixed rock volume and to the appearance of a high amplitude anomaly.

In the other mechanism the activation of the fault zone (lower rigidity) can result from increased shaking in the fault zone during the foreshock period 3–4 months before the main shock (Fig. 3). It appears from Fig. 3 that the main shock of the March 2, 1992, earthquake was preceded by increased seismicity rate since about December 1991. This phenomenon is similar to an increase in the deformation of a jointed, fluid-saturated medium under vibration described in detail by Yu. P. Skovorodkin (see the section entitled "Methods of Exploration Geodynamics" in [21]).

The superintensive precursors observed before the March 2, 1992, earthquake were most likely produced by both mechanisms acting simultaneously.

It is important to point out that both cases involved changes in the internal rock parameters in some localized fragments of fault zones. This justifies the treatment of the observed precursory anomalies as parametric.

Here we offer some recommendations as to the choice of a network site to monitor vertical and horizontal movements of the ground surface associated with an impending large earthquake. The network should be located on a differential measurement basis, that is it should be deployed in such a way as to make measurements possible both in the stable and in the mobile part of the site. In other words, part of the network must cover (in part or completely, whenever this can be done) an active geodynamic feature, a fault or some other tectonic disturbance, and part of it must be in a zone of stationary ground surface. The meaning of this design consists in using the fault part of the network as a natural parametric amplifier of precursory processes, while its stable part can be used to monitor possible processes related to the inherent dynamics of fault zones not dependent on the precursory processes. This differential approach allows one to use a difference between the processes going on in the fault zone and outside of it in order to record time-dependent precursory processes before the expected seismic event and to issue intermediate-term forecasts.

CONCLUSIONS

1. A detailed analysis of deformation and seismicity changes yielded the following results: the parameters exhibited an in-phase behavior during the period of November 1991 to May 1992 and can be interpreted as a precursor of the March 2, 1992, magnitude 7.1 earthquake. The amplitude of this precursory anomaly ranged between 5–6 and 10–13 cm on various segments of the leveling line, depending on the position of the active fault.

2. A mechanism is proposed to explain the generation of superintensive precursory deformation in fault zones. These anomalies are suggested to be called parametric earthquake precursors.

3. Some recommendations are offered to use a differential measurement approach when choosing the location of a network for monitoring the vertical and horizontal displacements of the ground surface.

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