Responses to the preparation of strong Kamchatka earthquakes in the lithosphere–atmosphere–ionosphere system, based on new data from integrated ground and ionospheric monitoring

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Abstract. The experience of short-term forecasting of Kamchatka earthquakes based on complex well measurements at the Petropavlovsk-Kamchatsky geodynamic polygon (PGP) shows that, as a rule, the preparation of strong Kamchatka earthquakes is fairly reliable in the medium-term time scale (months or years before the earthquake). However the determination of the stage beginning immediately preceding an earthquake (weeks or days before the main event) is a very difficult task. At present time, the solution of this problem is largely associated with the involvement in the preparation of forecast conclusions of data from continuous monitoring of the ionosphere, carried out by ground-based means of vertical radiosounding and measurements of total electronic content (TEC) using the global navigation satellite system GLONASS and GPS. This is due to the fact that significant changes in a number of ionospheric parameters occur mainly 1-5 days before the Kamchatka earthquakes. The results of the comparison of the data of daily monitoring of the ionosphere, including information on TEC, with the data integrated downhole measurements showed a rather high correlation of occurrence of anomalies in the ionosphere before strong earthquakes with changes in the complex parameters in borehole measurements. As one example, the report presents the results of ionospheric and borehole monitoring obtained in the time neighborhood of the strong ($M_w = 7.5$) the earthquake that occurred on March 25, 2020 in the area of the Northern Kurils. The results show a high correlation between changes in the specific electrical resistivity of the Geospace in the area of the PGP with variations in the TEC and the formation of a number of other anomalies in the ionosphere a few days before the earthquake. These results indicate that it is possible to determine fairly reliably the beginning of the final stage of preparation for a strong earthquake. Currently, methods based on atmospheric parameters monitoring are used quite successfully for predictive estimates of the epicenter and magnitude of an earthquake: the method of chemical potential corrections for measurements at an altitude of ~ 100 m, as well as data from measurements of outgoing long-wave infrared radiation (OLR) at the level of the upper edge of clouds (heights of 10–15 km).

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1 Introduction

Modern research has established that the earth's crust in seismically active regions influences the physical processes occurring in the upper geospheric envelopes. Consequently, in these regions, any anomalous changes in the behavior of the ionospheric parameters, which are formed against the background of a regular daily change in the characteristics of the ionosphere, caused by the influence of the Sun, can provide information on the processes of earthquake preparation. In turn, each seismically active region is characterized by its own, the most informative features (anomalies) both in the behavior of the parameters of the stress-strain geoenvironment and the parameters of the atmosphere and ionosphere, which can be identified with earthquake precursors. This approach was the basis for the creation of a complex model of the lithosphere-atmospheric-ionospheric connections LAIC [1]. During the development of the model, it was shown that all the processes occurring in the upper geoshells of our planet above the earthquake preparation zone are themselves an integral part of this process and are genetically related to the processes of transformation of the earth's crust, in particular, the intensification of radon release from active tectonic faults coincides with the period the beginning of cracking and the formation of inhomogeneities (asperities) in the area of the earthquake source [2], a decrease in the value of the coefficient b in the Gutenberg – Richter ratio, and the onset of foreshock activity [3]. In fact, the appearance of atmospheric and ionospheric precursors indicates the beginning of the final stage of the earthquake preparation, which lasts no more than two weeks, and statistically, ionospheric precursors appear 1-5 days before the main shock (short-term forecast) [4]. Another important property of multiparameter monitoring is the synchronization in time and space of the appearance of all atmospheric and ionospheric precursors, which is typical for synergetic processes in open dissipative systems [5], which is a complex of generation of earthquake precursors at the final stage of their preparation. In turn, as shown in [6], the preparation of strong S earthquakes ($S=L/R_h*100\%$), where L is the linear size of the earthquake source approximated by an ellipse; R_h is the hypocentral distance), as a rule, begins to manifest itself in the data of borehole measurements at the Petropavlovsk-Kamchatskiy geodynamic test site (PGP) on a medium-term scale of time (months, years before the earthquake). A sufficiently accurate determination against the background of these processes of the beginning of the stage immediately preceding the earthquake (weeks, days before the moment of the main event), at the present stage of research, causes great difficulties and, in a short-term forecast, leads, as a rule, to unacceptably large values of the "alarming time". The authors associate a certain optimism with regard to solving this problem with the use of vertical radiosonde data of the ionosphere, carried out at the IKIR FEB RAS, as well as monitoring data for the total electron content (TEC) using the global navigation systems GLONASS and GPS (IKI RAS), in the preparation of forecast conclusions. The feasibility of these steps is associated with the fact that significant changes in a number of parameters of the ionosphere occur, mainly, 1-5 days before the Kamchatka earthquakes [7].

2 Ground-based observations of the atmosphere and ionosphere

2.1 Ground-based ionospheric observations

As shown by long-term studies of the dynamics of ionospheric parameters on the eve of an earthquake in the Kamchatka region, the features that can be attributed to the precursor signs are the following:

- 1) the precipitation of charged particles from the radiation belts into the ionosphere from several hours to several days before the earthquake (the formation of the K-layer);

2) the formation of a diffusion sporadic layer E_s (E_s -spread) 1-3 days before the earthquake;

3) the formation of a sporadic E_s layer of type r 1-5 days before the earthquake.

4) for 1-5 days against the background of the development of a magnetic storm (in autumn and spring periods) an anomalous increase in the critical frequency foF2 (an increase in the concentration of electrons), exceeding the median values (with the usual development of a magnetospheric storm in the ionosphere due to the vortex electric field, a drift occurs, which leads to displacement of electrons to great heights and to a decrease in their concentration).

5) the formation of a diffusion layer F2 (F2-spread) with a duration of several hours against the background of a quiet magnetosphere in 1-3 days.

6) in 1-3 days, stratification of the F2 layer in frequency and height (modes "H" and "V"), the so-called traveling ionospheric disturbances.

In this work, we used the data of radiophysical observations made by means of vertical radio sounding. Automatic ionospheric station (AIS "Parus") vertical radio sounding is located in the village Paratunka ($\varphi = 52.97^\circ N$, $\lambda = 158.24^\circ E$). Observations are carried out once every 15 minutes in a pulsed mode at frequencies from 1 to 15 MHz. As an example, Fig. 1 shows ionograms containing anomalies corresponding to features 3) (Fig. 1a) and 6) (Fig. 1b).

Figure 1. Examples of anomalous behavior of the ionospheric parameters: a) sporadic E_s layer of the r type; b) frequency stratification of the F2 layer (mode "V", traveling ionospheric disturbances).

The following parameters are used to assess the effectiveness of the prognostic indicator of ionospheric precursors: reliability, validity, efficiency, calculated according to known methods. The reliability of the ionospheric precursor is defined as the ratio of the number of earthquakes for which the precursor was identified to the number of all earthquakes [8]:

$$R = n(E_a)/n(E) \quad (1)$$

The validity of a precursor is defined as the ratio of the number of precursor anomalies to the total number of identified anomalies [8]:

$$V = n(A_E)/n(A) \quad (2)$$

The effectiveness of the prognostic indicator based on the methodology of A.A. Gusev [9] is calculated by the formula:

$$J_G = \frac{n/T_{alarm}}{N/T} \quad (3)$$

where T - is the total time of monitoring the seismic environment; n - the number of earthquakes corresponding to a successful forecast for the time T , N - the total number of earthquakes that occurred during the time T , T_{alarm} - the total alarm time (the total duration of

Table 1. Predictive efficiency of the complex of ionospheric precursors

N_+	N_-	N	$n(A_E)_+$	$n(A_E)_-$	$n(A_E)$	V	R	J_G	J_M
13	4	17	13	58	71	0.18	0.76	2.3	0.43

all time intervals in which the forecast was valid according to the estimated method during the monitoring time). In the absence of connection "earthquake-precursor", i.e. on guessing randomly, J_G 's efficiency is 1. The effectiveness of the prognostic sign based on the method of G.M. Molchan [10] is calculated by the formula:

$$J_M = 1 - \nu - \tau$$

(4)

where $\nu = 1 - \frac{n}{N}$ - percentage of missing targets, $\tau = \frac{T_{alarm}}{T}$ - relative volume of alarms.

In order to select the most effective ionospheric precursors, the parameters V, R, J_G, J_M were calculated using formulas (1 - 4) for seismic events of the predicted energy class $K_S \geq 13.5 (M \geq 6.0)$ that occurred at depths of up to $r = 100$ km at distances up to $r = 500$ km from the IKIR FEB RAS ionospheric observation point in Kamchatka. The observation period was chosen equal to $T = 01.01.2013 - 31.12.2018$ years, the waiting period for earthquakes with $K_S \geq 13.5$ was set equal to $T_{wait} = 5$ days. Calculations that are most informative, i.e. with the highest values of the parameters J_G and J_M , are the following ionospheric precursors (highlighted in green): the critical frequency foF2 of the ionospheric layer F2, K-layer, frequency stratification F2 (mode "V", "H") and sporadic layer E_s of type r.

Based on the selected most effective ionospheric precursors, an algorithm for short-term forecasting of earthquakes was constructed, in which a joint analysis of the considered ionospheric disturbances in a sliding time window with a width $\Delta T = 5$ days with a step $\Delta T = 1$ day is carried out. The condition for announcing the beginning of the waiting period for a seismic event was the execution on a time interval for at least three of the four considered ionospheric parameters numbered 1, 3, 4 and 5. The duration of the waiting period was chosen equal to $T_{wait} = 5$ days. For the algorithm, its predictive efficiency was assessed on the time interval 01.01.2013-31.12.2018. in spring and autumn seismic events occurring at depths of up to 100 km within a radius of 500 km from the registration point of ionospheric observations. The results of the assessment are presented in Table 1 and Fig. 2.

According to the results presented in Table 1, when predicting earthquakes with an energy class $K_S \geq 13.5$, the reliability is 0.76 (that is, 76% of earthquakes had a precursor), and the validity is 0.18 (that is, 18% of the detected anomalies are realized). The value of efficiency $J_G = 2.3$ shows that the forecast using this method is statistically significant and differs 2.3 times from random guessing. On the error diagram (Fig. 2), the values (τ, ν) , obtained for the range $K_S \geq 13.5$ lie below the lower boundary of the 99% confidence interval, which can be interpreted as a high degree of reliability of the revealed connection of the considered complex of ionospheric precursors with earthquakes of this range of energy class that occurred at distances of up to 500 km from the point observation.

Based on this algorithm, for the period 2018-2019, conclusions were prepared on the intensification of seismic activity for a period of 5 days in advance from the date of submission in the geographical area with coordinates $48^\circ - 58^\circ N$ and $154^\circ - 167^\circ E$ The frequency of submission of conclusions increased with the increase in the level of degassing noise in water during borehole measurements (more on this in section 3). This indicates an increase in gas emissions, including radon, which directly affects the anomalous behavior of ionospheric parameters on the eve of an earthquake.

Figure 3 shows the dynamics of the behavior of the ionosphere parameter's for the period from March 14 to March 25, 2020 (UT). During this time, all 4 prognostic ionospheric signs

Figure 2. Error diagram for the algorithm for the complex of ionospheric precursors for $K_S \geq 13.5$. The lower bounds of the confidence interval of the random forecast with the significance level and are marked $\alpha = 0.01$ and $\alpha = 0.05$.

were formed. The earthquake occurred on March 25, 2020 in the region of the northern Kuriles with $M_W = 7.5$. It can be seen in this figure that, starting from March 16, 2020 (Fig. 3a), a positive variation in the electron density ($n \sim (foF2)^2$) is observed in the daytime UT, which continues until March 22, 2020 (Fig. 3b, c).

Figure 4 shows in color the difference (%) of the current values of foF2 and the time median of Petropavlovsk-Kamchatsky (LT = UT + 12h). The figure also shows the appearance times of the K-layer, the "V", "H" and Es-r delamination. The red triangle marks the time of the earthquake. Figure 4 shows both the dynamics of changes in $\Delta foF2$ during ground-based radio sounding, and the time of formation of other prognostic signs from LT by day (from 12.00h 14.03.2020 to 12.00h 26.03.2020). The figure clearly shows an increase in the electron concentration in the night from March 16 to March 17, which continues until the night hours of March 22, 2020.

2.2 Satellite multiparameter monitoring technologies based on the LAIC model

Among the precursors described by the LAIC model [11], the parameters obtained with the help of remote sensing devices occupy a significant place. Their great advantage is the ability to monitor areas over the ocean and in coastal areas where it is impossible to install ground sensors. The combination of ground-based and satellite measurements increases the reliability of the forecast, because the advantages of both approaches are used: the continuity of measurements at ground stations and the large spatial coverage of satellite measurements. A special place in the series of precursors belongs to the correction of the chemical potential, indicating the intensity of the ionization process in the surface layer of the atmosphere, including over the ocean surface. At the moment of the phase transition (the act of condensation / evaporation), the chemical potential of a water molecule is equal to the value of the latent heat of evaporation, which allows calculations of the chemical potential using the thermodynamic parameters of the atmosphere - relative humidity and temperature. It turned out that the value of the latent heat during condensation on ions or aerosols is greater than the constant latent heat for water ($Q = 0.422$ eV per molecule). The excess is several percent of Q , i.e. 0.001 - 0.08 eV. The higher the ion production rate and the concentration of hydrated ions,

Figure 3a

Figure 3b

Figure 3c

Figure 3. Dynamics of daily values for a series of seismic events from March 14 to March 25, 2013 (UT). $\diamond$ - critical frequencies foF_2 ; $\times$ - sporadic foE_s layer, $\square$ - minimum frequencies f_{min} ; stratification mode "V", "H"; F - diffusion; 6 - diffusion, when the value of the foF_2 frequency can still be selected; Es-r - formation of a sporadic r-type layer; spread - diffusion f_{min} .

the higher the value of correction. Thus, the correction of the chemical potential is an integral parameter indicating the intensity of radon release and the number of formed ion clusters, and in a number of experiments it correlates with radon variations. The correction is calculated using the GEOS-FP quasi-real-time assimilative atmosphere model. The input parameters of the model contain the data from more than 20 remote sensing satellites, the global network of meteorological observations, meteo-sounding balloons , etc., and the delay is 10-15 hours in relation to real time. This allows continuous monitoring over any area on the Earth’s surface. Another advantage of our approach is that we use open data available on the web (hence the method is called multisensory web network monitoring), which makes it cheap and fast. And finally, the most important advantage of our approach is that we look at the precursors not as anomalies, but as a manifestation of a specific physical process, so their identification is based not on amplitude manipulations (deviations from the mean, etc.), but on the phenomenological features characteristic to variations in the atmosphere and ionosphere for a given process, i.e. on the recognition of the precursor image based on the physical mechanism of its generation determined by the LAIC model. We call this cognitive recognition [12]. In this paper, as stated, we will demonstrate a method of multivariable monitoring during the preparation of a strong earthquake using data on the state of the surface layer of the atmosphere (correction of the chemical potential), thermal radiation flux in the long-wave infrared range (OLR), varia-

Figure 4. Color diagram of the difference between the current values of foF2 and the median local time in Petropavlovsk-Kamchatsky (LT). The figure also shows the times of appearance of other precursors of the K-layer, the "V", "H" and Es-r layering.

tions in total electron content (GPS TEC). Ground monitoring data (borehole monitoring data and vertical sounding of the ionosphere) will serve as a bonus to these measurements.

2.3 Satellite multiparameter monitoring technologies based on the LAIC model

As shown by a long-term analysis of data on the chemical potential in the Kamchatka region [3], this parameter allows one to estimate both the position of the epicenter and the magnitude of the impending earthquake. However, in this case, the picture was strongly disturbed by constantly incipient cyclones, with a center near the epicenter of the future earthquake (Fig. 5). In this regard, it turned out to be difficult to identify the usually observed maximum near the epicenter. On the other hand, you can see increased values of the chemical potential over a huge area. According to [13], the radius of the earthquake preparation zone is $R(km) = 10^{0.43M}$, which for a magnitude of 7.5 will be 1679 km. The highlighted zones in the figures just indicate the size of the preparation zone for the impending earthquake.

If linear zones of increased stress appear in the preparation zone [14], a linear cloud structure or a linear structure in the spatial distribution of the chemical potential may appear above this area. This situation was observed 2 days before the earthquake, and the end of this structure indicates the position of the earthquake epicenter (Fig. 6).

The time series of the chemical potential correction obtained for the point inside the shown linearly anomalous structure confirms the presence of a local maximum in the 1 month time interval from March 1 to March 31 (Fig. 7, top panel).

Figure 5. Spatial distribution of the correction of the chemical potential in the Kamchatka region on March 17 and 20, 2020 during the preparation of the M7.5 earthquake near the Kuril Islands

Figure 6. Distribution of the correction of the chemical potential in the region of Kamchatka and the Kuril Islands on March 23, 2020. The white star marks the position of the epicenter of the M7.5 earthquake on March 25, 2020

It is characteristic that for the same date the absolute maximum of the outgoing flux of low-frequency infrared radiation OLR was observed, which was recorded independently by two remote sensing satellites NOAA-15 (dark shading) and NOAA-18 (gray shading), Fig. 7, bottom panel.

The dynamics of the spatial distribution of the observed OLR flow anomalies is shown in Fig. 8. It can be seen from the figures that anomalies appear mainly near the boundaries of tectonic plates, marked in the figures with burgundy lines. Their "dance" testifies the dynamic changes in the earth's crust before the earthquake.

Another unexpected feature of this earthquake was that, in contrast to most cases, ionospheric precursors appeared earlier than OLR anomalies and chemical potential anomalies. In this case, the ionospheric anomalies in time coincided with the period of a decrease in the conductivity of the earth's crust, which gives grounds to propose a mechanism for the generation of these anomalies that is different from the ionization one (see Fig. 9).

Figure 7. Upper panel - a graph of changes in the correction of the chemical potential within the linear anomaly for the period from March 1 to March 31, 2020; bottom panel - daily values of the gradient of the outgoing long-wave infrared radiation flux according to the data of the NOAA-15 (dark shaded) and NOAA-18 (gray shaded) satellites for March 2020.

For clarity, ionospheric variations are shown in the form of so-called "masks" that allows to see how the variations behave in local time during the entire interval from March 06 to March 30, 2020 (65-90 DOY) [11]. It can be seen that from days 75 to 83 for the critical frequency and from 76 to 80 days for GPS TEC, a positive variation in the electron density is observed, as described in the model [11], with the solar terminator serving as the cutoff time for this anomaly.

3 Boreholes measurements

3.1 Petropavlovsk-Kamchatskiy geodynamic polygon

At present, the network of complex borehole measurements of PGP (a zone with a radius of about 100 km from the center of Petropavlovsk-Kamchatsky) consists of five radio telemetry points and the Center for collection and processing of information located in the building of

Figure 8. Spatial distribution of OLR anomalies in the Kamchatka region for the period from March 20 to March 24, 2020.

IV&S FEB RAS (Fig. 10). The work on short-term forecasting of earthquakes carried out by the IV&S FEB RAS is currently based primarily on methods for monitoring changes in the stress-strain state (SSS) of the geoenvironment in the PGP region, which allow one to control the intensification of the processes of dilatancy and fluidization of the geomedium in the Avacha Bay area. The basic measurements are continuous geoacoustic measurements at depths up to 1012 m and electromagnetic measurements with underground electric antennas. The basis of geoacoustic methods for monitoring the stress-strain state of the geoenvironment is the effect of modulation of the GAE amplitude by an alternating electric field, discovered during long-term complex borehole measurements at the PGP [6, 15–18]. The method of continuous monitoring of the stress-strain state of the geoenvironment, based on measurement data with underground electric antennas, makes it possible to monitor changes in the resistivity of the geoenvironment in the area of the well to a depth of about 2200 m [6].

In addition to basic measurements, the network provides:

- measurement of specific electrical conductivity of water in wells (wells G-1 and GK-1);
- monitoring of changes in the permeability of the geomedium (wells GK-1 and P -2);
- measuring the water temperature of the well at different depths (wells P -2 and GK-1);
- measurement of the water level of the well (well P -2).

To measure the specific conductivity of water in wells, a conductometric liquid analyzer AZHK-3130 with an inductive proximity sensor is used. The sensor installation depth in well G-1 is 41 m, in the self-flowing well GK-1 the sensor is installed at a depth of 1 m.

The method for monitoring the permeability of the geoenvironment used in measurements at the well GK-1 is based on measurements of degassing noise in the water of the well. Since April 2018, these measurements have been carried out in a continuous mode using a G61N hydrophone installed in a well at a depth of 280 m. The results obtained so far indicate that this method is promising in the system of medium-term and short-term forecasting of Kamchatka earthquakes [19].

The main idea behind the method for monitoring changes in the permeability of the geoenvironment, which has been used since November 2005 at well P -2, is that, provided the temperature of the water in the well is stable, significant changes in its specific gravity (density) should be associated with changes in gas volumes entering the well water per unit of time. In turn, changes in gas volumes should be primarily determined by changes in the permeability of the geoenvironment in the well area. The technical details of the method are presented in [20].

Figure 9. From top to bottom - Mask of the critical frequency, the graph of the deviation of the critical frequency; GPS TEC mask, GPS TEC deviation graph; variations in the resistivity of the geoenvironment to a depth of about 1000 m in the area of well. G-1 on the eve of a strong ($M_W = 7.5$) earthquake on 25.03. 2020 in the region of the northern Kuriles

The data of the water level in the well R-2 is obtained by calculation using the results of measuring the water pressure in the well at a depth of 3 m and the data of measurements of atmospheric pressure.

Figure 10. Configuration of the network of integrated borehole measurements Petropavlovsk - Kamchatka geodynamic test site.

3.2 Comparison of data from complex borehole measurements with the results of ionospheric monitoring

The first results of the joint analysis of data from the network of complex borehole measurements of PGP and the results of vertical radio sounding of the ionosphere (IKIR FEB RAS) showed (Fig. 11) that, before strong Kamchatka earthquakes, there is a fairly high correlation between the occurrence of anomalies in the ionosphere with changes in the complex of parameters in the data of the borehole measurement network.

This conclusion is confirmed by comparing the results of changes in the resistivity of the geoenvironment in the PGP region with changes in the total electron content (TEC) and the formation of a number of other anomalies in the ionosphere a few days before a strong ($M_w = 7.5$) earthquake that occurred on March 25, 2020 in the northern region Kuril (fig. 9). These results show that carrying out a joint multivariate analysis of borehole geophysical monitoring data and monitoring data of the state of the ionosphere in the PGP zone can significantly improve the reliability of determining the beginning of the final stage of earthquake preparation and significantly reduce the “alarming time” in short-term forecasting of strong Kamchatka earthquakes.

Figure 11. Results of integrated borehole measurements at GWP in comparison with the intervals of occurrence of anomalies in the ionosphere: a) - anomalies in the ionosphere (red rectangles) according to the data of the Parus ionospheric station of the IKIR FEB RAS; b) - changes in the level of degassing noise in the water of the GK-1; c) - changes in the specific electrical conductivity of the water of the GK-1; d) - changes in the resistivity of the geoenvironment in the area of G-1 to a depth of about 1000 m; e) - changes in the amplitudes of responses of geoacoustic emission to the effect of an external electromagnetic field in the zone of the G-1.

4 Conclusions

This paper presents the results of an integrated approach to studying the preparation of strong Kamchatka earthquakes in the lithosphere-atmosphere-ionosphere system by means of ground-based and satellite monitoring. A number of features typical of the Kamchatka earthquake that occurred on March 25, 2020 ($M = 7.7$) have been identified. According to Fig. 1, Fig. 3 and Fig. 4, during the period from 14.03.-25.03.2020 (UT), features are observed on ground-based ionograms of vertical sounding: the critical frequency $foF2$ of the ionospheric layer F2, K-layer, frequency stratification F2 (mode "V") and a sporadic Es layer of the r type, characterizing the precursor period for earthquakes in the Kamchatka region. At the same time, surprising is the fact that this period coincides with the time of the decrease in the conductivity of the earth's crust (Fig. 9, lower panel), which suggests that this phenomenon is involved in the generation of ionospheric precursors. In addition, an interesting feature of the earthquake of 03.25.2020 is that ionospheric precursors appeared earlier than OLR anomalies and chemical potential anomalies, in contrast to most cases of ionospheric precursors. In turn, it is known that the main transmitter of the effect of earthquake preparation in the ionosphere is the Global Electric Circuit (GEC) [21], and a decrease in the conductivity in the earthquake preparation zone is equivalent to an increase in the vertical electric field, which can cause the formation of a positive anomaly of electron concentration above this zone. This idea requires verification using modeling, but how a working hypothesis can be used and should be tested in future cases of simultaneous recording of the Earth's crustal

conductivity and variations in the ionosphere during the preparation of strong earthquakes in the Kamchatka region.

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