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# KAMCHATKA MEGAEARTHQUAKE ON JULY 29, 2025: REFLECTION OF THE PREPARATION PROCESS IN THE RESULTS OF MULTI-INSTRUMENTAL GEOPHYSICAL MEASUREMENTS IN THE AVACHA BAY AREA

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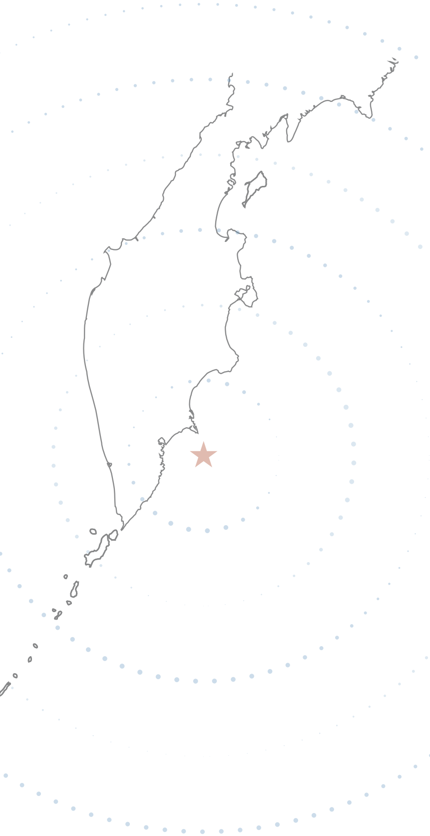
**Abstract:** This article discusses the results of long-term multi-instrumental geophysical measurements in the Avacha Bay area (the eastern coast of Kamchatka), conducted for the purpose of medium- and short-term seismic hazard prediction for the Petropavlovsk-Kamchatsky region. The most important results, reflecting the starting process of the Kamchatka megaearthquake (July 29, 2025, $M_W = 8.8$), were obtained using data from the Multi-Instrumental Borehole Measurement Network, as well as data from monitoring changes in the total electron content of the ionosphere. Data obtained from six types of borehole measurements are used to monitor the initial processes of large earthquakes in the Avacha Bay area. The basic types of monitoring are two original methods developed by the authors: a method for monitoring changes in the specific electrical resistance (SER) of the geoenvironment using underground electrical antennas, and a method for monitoring changes in the geoenvironment moisture based on borehole geoacoustic measurement data. It is shown that a record-breaking SER anomaly (amplitude, duration) formed in the Avacha Bay area on the eve of the Kamchatka megaearthquake. This anomaly was reflected in SER monitoring data for a monitoring depth of 2200 m beginning in mid-2018, and in data for a depth of 950 m in early 2021. Since January 2014, the Laboratory for Multi-Instrumental Monitoring of Seismically Active Environments at the Institute of Volcanology and Seismology of the Far Eastern Branch of the Russian Academy of Sciences (IVS FEB RAS) has been regularly (usually every two weeks) preparing conclusions with seismic hazard assessments for the Petropavlovsk-Kamchatsky agglomeration area based on the current results of geophysical measurements in the Avacha Bay area. The research focused not on accurately predicting the timing and parameters of a strong earthquake (which is inherently impossible) but on probabilistically assessing the current seismic hazard for the Petropavlovsk-Kamchatsky agglomeration. This approach enabled the authors to successfully predict two strong foreshocks of the Kamchatka megaearthquake – the Shipunskoye-1 earthquake (August 17, 2024; $M_W = 7.0$) and the Shipunskoye-2 earthquake (July 20, 2025, $M_W = 7.4$), which caused tremors of up to points 6.0 in Petropavlovsk-Kamchatsky.



**RESEARCH ARTICLE**

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## 1. Introduction

The powerful ($M_W = 8.8$) shallow earthquake (hereinafter referred to as the Kamchatka megaearthquake) that occurred off the eastern coast of Kamchatka on July 29, 2025, confirmed Kamchatka's status as the most seismically active region in Russia and one of the most seismically active regions in the world. In terms of its parameters, the Kamchatka megaearthquake is a unique seismic event.

At the same time, according to data from various sources, at least seven shallow earthquakes with a magnitude of $M \geq 8.0$ (1737, 1792, 1841, 1917, 1923, 1952, 2025) have occurred off the eastern coast of Kamchatka from 1737 to the present day, as well as a powerful series of three earthquakes in 1904 with a magnitude of about 8, second in the 20th century only to the Chilean earthquakes of 1960 [*Godzikovskaya*, 2010]. Thus, the average recurrence rate of the strongest earthquakes in the area of the eastern coast of Kamchatka is very high – less than 40 years on average.

The previous strongest earthquake, the Great Kamchatka Earthquake with a magnitude of $M = 8.5$ (or 9.0 according to USGS), which caused a catastrophic tsunami in the south of Kamchatka, occurred in 1952. The Kamchatka megaearthquake of 2025 confirmed the long-term five-year forecasts of Academician S. A. Fedotov and colleagues, which indicated, starting in 2001, the most likely location of the next strongest earthquake ($M \geq 7.7$) as the area from the northern border of Avacha Bay to the southern tip of Kamchatka, possibly encompassing the area of the source of the Great Kamchatka Earthquake of 1952 [*Fedotov and Chernyshev*, 2002]. This forecast, with a refined magnitude of the expected earthquake up to $M \geq 8.3$, was also confirmed in [*Fedotov and Solomatin*, 2017, 2019]. Moreover, the overall probability of a 7–9 magnitude earthquake occurring in Petropavlovsk-Kamchatsky over the specified five-year period was estimated at 47.7%, while the probability that the strongest earthquake would occur in the coastal part of Avacha Bay and would have a magnitude of 9 on the Richter scale in Petropavlovsk-Kamchatsky, with corresponding catastrophic consequences, was estimated at 14.2% [*Fedotov and Solomatin*, 2019]. These long-term seismic predictions served as the basis for the timely adoption by the Russian Government of a whole range of important measures to improve the seismic stability of residential buildings, key facilities, and life support systems in Kamchatka Krai.

At the same time, such forecasts highlighted the need to develop research aimed at effectively predicting medium- and short-term seismic hazards for the Avacha Bay area. Since the late 1990s, this task has become a key focus for the Laboratory for Multi-Instrumental Monitoring of Seismically Active Environments at the IVS FEB RAS, and subsequently for the Laboratory for Research of Extreme Phenomena of Kamchatka at the Vitus Bering Kamchatka State University.

During the first stage of addressing this challenge, the primary focus was on establishing a geophysical measurement network in the Petropavlovsk-Kamchatsky agglomeration area capable of continuously monitoring the preparatory processes of strong earthquakes in the Avacha Bay area. Emphasis was placed on organizing multi-instrumental geophysical measurements in sufficiently deep (at least 300 m) boreholes. It was anticipated that measurements in such boreholes, by significantly reducing the influence of surface noise and conducting measurements directly in the geoenvironment (in situ), could yield important scientific results unattainable with surface measurements. The very first results obtained from combined geoacoustic and electromagnetic measurements confirmed the potential of borehole measurements for solving problems related to seismic hazard prediction [*Gavrilov et al.*, 2006].

At present, the Network of Multi-Instrumental Borehole Measurements (hereinafter referred to as the Network) has actually become the information basis for the system of medium- and short-term seismic hazard prediction for the Petropavlovsk-Kamchatsky agglomeration area [*Gavrilov et al.*, 2022]. In addition to borehole measurements, additional data from third-party organizations conducting observations in the same area (primarily from the Kamchatka Branch of the Federal Research Center “Geophysical Survey of the Russian Academy of Sciences” (KB FRC GS RAS)) is used to analyze the results of integrated geophysical monitoring. In recent years, ionospheric total electron content (TEC) monitoring data has been actively used in multivariate analysis of the Network’s data.

Since January 2014, the Laboratory for Multi-Instrumental Monitoring of Seismically Active Environments at the IVS FEB RAS has been regularly submitting reports on the current seismic hazard ("prediction conclusions") for the Petropavlovsk-Kamchatsky agglomeration to the Kamchatka branch of the Russian Expert Council for Earthquake Prediction, Seismic Hazard and Risk Assessment (KB REC), as well as to the Council for the Prediction of Earthquakes and Volcanic Eruptions of the IVS FEB RAS. As a rule, reports are prepared every two weeks. If data is received indicating a sharp increase in seismic hazard for the Petropavlovsk-Kamchatsky area, unscheduled reports are prepared. It should be emphasized that the laboratory's transition to the mode of issuing regular prediction conclusions was preceded by a long (approximately 14 years) stage of research, which was associated with the creation of a network of multi-instrumental borehole measurements, the study of possible physical causes and mechanisms capable of explaining the appearance of precursor anomalies on the eve of strong Kamchatka earthquakes, as well as the development and implementation of new methods for monitoring the processes of earthquake preparation [*Gavrilov*, 2017]. In addition, at this stage of research, we released a number of successful forecasts of strong Kamchatka earthquakes [*Gavrilov*, 2017; *Gavrilov et al.*, 2020; *Strong…*, 2014].

We should also emphasize the importance of the authors' 2014 decision to have the laboratory regularly issue prediction reports. Despite the significant organizational and financial challenges associated with it, it forced the need to find solutions to support the continuous operation of a unique network of multi-instrumental borehole measurements, as well as to develop approaches to sufficiently reliable short-term seismic hazard prediction. This significantly contributed to a number of important results, including those presented in this article, which reflect the initial stages of evolution of the Kamchatka megaearthquake of July 29, 2025.

## 2. Multi-Instrumental Borehole Measurement Network

The key features of the Multi-Instrumental Borehole Measurement Network created at the IVS FEB RAS are the ability to conduct observations in relatively deep boreholes and their comprehensive nature. Overall, data received daily via telemetry channels from four measuring sites within the Network for six types of borehole measurements is currently used to monitor earthquake preparatory processes (Figure 1). In fact, the range of measurements carried out at the sites is somewhat broader, since some of the Network's measurement sites are used jointly with researchers of the KB FRC GS RAS, who carry out their own observations. Some of these observations are also used to supplement data from the Borehole Measurement Network of the IVS FEB RAS. Given that each site continuously conducts a range of geophysical measurements, such a site in the Network is effectively a mini-observatory. The set of measurements is selected for each site individually based on borehole parameters, the geological structure of the near-borehole zone, and a number of other factors.

It can be seen that borehole measurement sites are confined to developed fault structures associated with the active seismogenic area of Avacha Bay. This factor was given particular attention when selecting boreholes for the Network, as these zones are characterized by highly dynamic filtration processes during the final stages of earthquake preparation [*Kissin*, 2009]. In this regard, it is also no coincidence that most of the borehole measurements used in the Network focus on monitoring changes in the nature of geological fluidization, as the results obtained are capable of accurately reflecting the process of evolution of large earthquakes in the Avacha Bay area. The composition of borehole measurements currently conducted at Network sites is presented in Table 1.

The first measuring site of the Network, created on the basis of the deep (2542 m) borehole G-1 (see Figure 1), began to function in continuous mode in August 2000. At the initial stage, geoacoustic measurements were carried out using a borehole three-component geophone of the MAG-3S type [*Belyakov*, 2004], installed at a depth of 1035 m. In 2003, electromagnetic measurements using an underground electric antenna began at the site to elucidate the physical causes of diurnal variations in geoacoustic emission (GAE) intensity. The Network subsequently expanded continuously, primarily through the introduction of

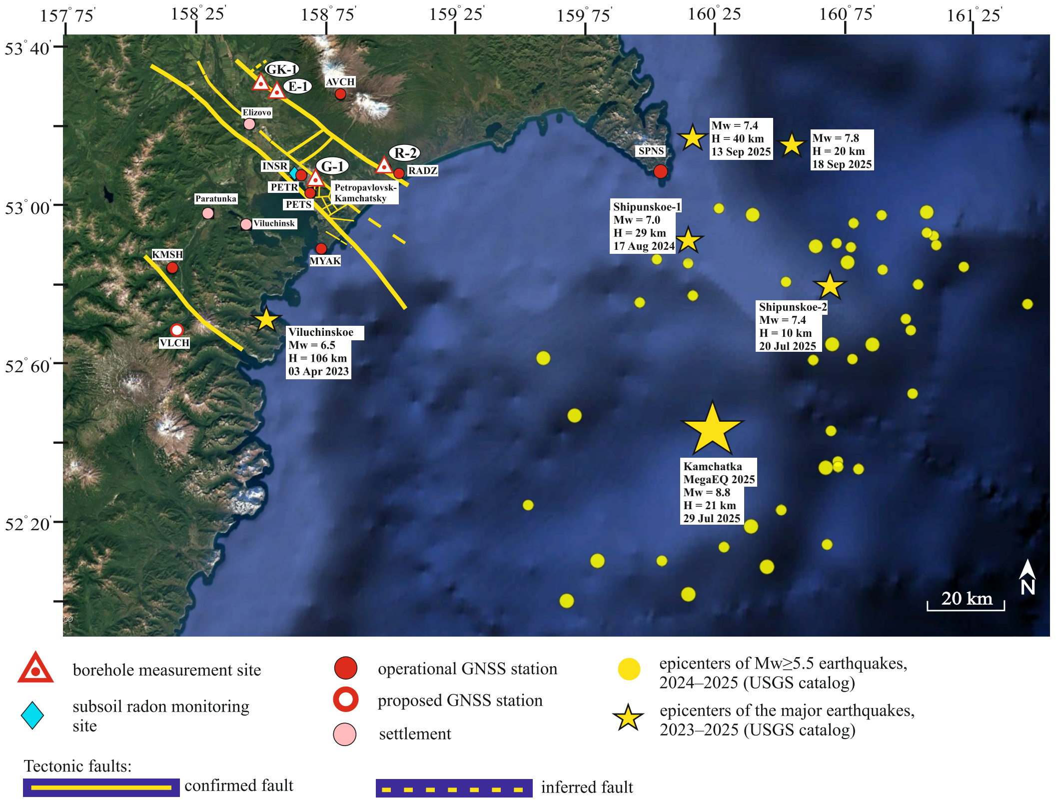

**Figure 1.** Multi-instrumental geophysical measurement sites in the Petropavlovsk-Kamchatsky agglomeration area.

observation methods promising for monitoring the stress-strain state (SSS) of the geoenvironment.

Currently, the basic methods of monitoring the processes of development of large earthquakes in the Avacha Bay area are the method of monitoring changes in the specific electrical resistance (SER) using underground electrical antennas (the "EMR method"), and the method of monitoring changes in the geomedium moisture based on borehole geoacoustic measurements (the "GAE method") [*Gavrilov*, 2017; *Gavrilov et al.*, 2022; *Gavrilov and Naumov*, 2017]. The results obtained using these methods reflect changes in the nature of geological fluidization processes. Under certain conditions, the results of such measurements are actually indicators of the final stages of preparation of major earthquakes [*Kissin*, 2009, 2011]. In this regard, when selecting measuring boreholes for the Network, preference was given to deep boreholes with hydraulic connections to fault structures in the Avacha Bay area – the most likely location for earthquakes capable of causing high-magnitude tremors in the Petropavlovsk-Kamchatsky agglomeration.

**The Key Points of the EMR Method for Monitoring Changes in the Specific Electrical Resistance of the Geoenvironment.** The key points of the EMR monitoring method include the following.

1. Monitoring is carried out at a site equipped with a sufficiently deep (more than 300 m) borehole with a metal casing used as a linear element of an underground vertical electric antenna [*Gavrilov*, 2013, 2017; *Gavrilov et al.*, 2022].
2. To obtain data for constructing time series of changes in the SER of the geoenvironment, continuous recording of external background electromagnetic radiation (EMR) in the ultra-low frequency (ULF) range of the first Hz to the first kHz, of man-made (50 Hz) or natural (atmospheric) origin, transmitted through the geoenvironment in the measurement zone, is performed. Ground-based antennas are used to monitor changes in the amplitude of external EMR strength.

**Table 1.** Types of measurements at the sites of the Multi-Instrumental Borehole Geophysical Measurement Network

| Borehole name, coordinates, depth, start date of continuous measurements | Type of measurement; start date of measurements |
|---|---|
| G-1, 53°03′N 158°37′48″E, 2540 m, August 2000 | 1. Geoacoustic, three components, at depths exceeding 1000 m – since August 2000;<br>2. Geoacoustic ($Z$-component) at a depth of 270 m – since July 2010;<br>3. Electromagnetic with underground electric antenna – since May 2003;<br>4. Electromagnetic with ground-based antenna – since December 2016;<br>5. Specific conductivity of water at a depth of 41 m – since May 2020 |
| R-2, 53°05′25″N 158°54′20″E, 1504 m, July 2005 | 1. Geoacoustic measurements at depths from 215 m to 730 m – since July 2006;<br>2. Electromagnetic with underground electric antenna – since October 2010;<br>3. Electromagnetic with ground-based electric antenna – since July 2019;<br>4. Water column pressure at depths of 3 m and 53 m – since November 2005;<br>5. Water temperature at depths of 3 m and 53 m – since April 2014;<br>6. Borehole water level – since October 2006;<br>7. Atmospheric pressure – since October 2006 |
| E-1, 53°16′N 158°29′E, 3003 m, August 2011 | 1. Geoacoustic (three components) at a depth of 600 m – since August 2011;<br>2. Electromagnetic with underground electric antenna – since August 2011 |
| GK-1, (self-flowing, with a water flow rate of about 0.1 l/s), 53°17′6.45″N 158°24′33.75″E, 1261 m, February 2016 | 1. Monitoring changes in gas saturation of borehole water – since April 2018;<br>2. Measurements of the specific electrical conductivity of borehole water at a depth of 1.5 m – since April 2018;<br>3. Measurements of daylight surface noise at a depth of 0.5 m (geophone, vertical component) – since August 2018;<br>4. Borehole water temperature measurements at depths of 5 cm and 7.5 m – since May 2021 |

3. Monitoring the changes in SER of the geoenvironment is conducted simultaneously at several depths. For this purpose, the broadband signal coming from the underground antenna output is divided into several frequency channels by narrowband filters. Then, analog and digital processing of the output signals for each frequency channel is performed in on-line mode, which allows obtaining results reflecting changes in SER for different depths of the upper part of the Earth's crust in the area of the Petropavlovsk-Kamchatsky geodynamic test site (PGS) [*Gavrilov*, 2013, 2017; *Gavrilov et al.*, 2022].
4. SER of rocks depends little on the resistance of the mineral skeleton, but is determined primarily by the moisture content of the rock [*King and Smith*, 1981; *Parkhomenko*, 1965]. Absorption in the geoenvironment, caused by thermal losses of electromagnetic energy, is determined by the exponential factor $e^{-\delta h}$, where $\delta$ is the absorption coefficient for depth $h$. As shown in [*Gavrilov*, 2017], for EMR of the ULF range $60\lambda\sigma \gg \varepsilon$, in this case the values of the absorption coefficient $\delta$ can be calculated using a simplified formula: $\delta = 2\pi\sqrt{\frac{30}{\rho\lambda}}, \quad \text{m}^{-1}$, where $\lambda$ is the length of the electromagnetic wave in the air; $\rho$ is the specific electrical resistance of the geoenvironment.
   For this reason, a comparative analysis of time series of data on SER of the geoenvironment obtained through different frequency channels allows us to obtain information on the dynamics of pore fluid filtration in the measurement zone.
5. As noted in numerous publications (see, for example, [*Sidorin*, 1992; *Sobolev and Ponomarev*, 2003]), the values of the coefficient of strain sensitivity of SER of rocks can reach values of the order of $10^3$–$10^5$. Moreover, according to laboratory studies, the highest sensitivity of SER to changes in the stress-strain state of the geological environment occurs at values of rock moisture not exceeding 1.5% [*Parkhomenko*, 1965]. The high strain sensitivity of SER of rocks is confirmed by significant SER anomalies before strong nearby Kamchatka earthquakes. The results presented in

[*Gavrilov et al.*, 2020] show that all strong earthquakes with the parameter $S \geq 19\%$ were preceded by significant (up to 750%) changes in SER of the geoenvironment in the PGS area, where $S = L/R_h \times 100$, %, $L = 10^{0.44M-1.29}$ is the length of the earthquake source [*Riznichenko*, 1976], $R_h$ is the hypocentral distance, $M$ is the moment magnitude. Using the $S$ value allows us to take into account the influence of magnitude and hypocentral distance on the intensity of shocks.

It should also be noted that the underground antennas used in the PGS zone are vertical electric antennas, for which changes in the antenna output signal are determined primarily by changes in the *vertical* electrical component of the electromagnetic radiation. For this reason, the use of such antennas significantly reduces interference caused by eddy currents flowing horizontally through the geoenvironment, including interference associated with magnetic storms [*Fujinawa et al.*, 1992].

**GAE Method for Monitoring Changes in the Geomedium Moisture.** The physical basis of the GAE method is the effect of modulation of the intensity of geoacoustic emission (GAE) by a weak alternating electric field of the ULF range, discovered by the authors during many years of research [*Gavrilov*, 2017]. The proposed physical mechanism of this effect is described in [*Gavrilov*, 2017; *Gavrilov and Naumov*, 2017], where it is shown that the amplitude of the GAE responses to the impact of weak electromagnetic radiation in the ULF range (first Hz – first kHz) is determined by the amplitude of the EMR intensity and the total area of contact between the liquid and solid phases in the volume of the geoenvironment monitored by a geophone. If the geoenvironment is sufficiently humid, the impact of external EMR in the ULF range with a slowly varying electric field amplitude on geoacoustic processes will cause corresponding changes in the GAE amplitude. For example, diurnal variations in the EMR amplitude affecting the geoenvironment lead to corresponding diurnal variations in the GAE amplitude – the GAE responses to EMR. Intensification of filtration processes during the active preparation phase of a nearby strong earthquake leads to changes in the contact area between the liquid and solid phases for significant volumes of the geoenvironment and corresponding changes in the amplitudes of the GAE responses. Calculations and measurements at the PGS show that when used for geoacoustic measurements in deep boreholes, the GAE method enables monitoring changes in the geomedium moisture caused by earthquake preparatory processes within a radius of approximately 3 km.

**Monitoring Gas Saturation of Borehole Water.** The effectiveness of the method developed by the authors for continuously monitoring changes in the gas saturation of borehole water should also be noted [*Gavrilov et al.*, 2022]. The method consists of recording degassing noise, which occurs when gas bubbles (primarily methane) escape from the borehole water into the atmosphere, using a hydrophone installed in a measuring borehole at a depth of approximately 200–300 m. The strain gauge sensitivity of such measurements depends on many factors and can only be assessed through long-term measurements. Since April 2018, this method has been used as part of a multi-instrumental borehole measurement program at the GK-1 flowing borehole, located 35 km from Petropavlovsk-Kamchatsky (see Figure 1). The borehole's depth is 1,261 m, with the main thermal water inflow concentrated in the 1,140–1,261 m depth range. The average gas saturation of the borehole water is 50 ml/l. Methane predominates, accounting for up to 90% of the gas. A hydrophone installed at a depth of 280 m is used for measurements. The results obtained to date (see Section 4) indicate high strain sensitivity of the method, given the appropriate location of the measuring borehole.

In recent years, global navigation satellite system (GNSS) observations have been actively used in multivariate analysis of the Borehole Measurement Network data. These include variations in deformation characteristics calculated using GNSS station displacement data, as well as ionospheric TEC monitoring data. To date, this approach has yielded a number of important scientific results, significantly improving the effectiveness of ongoing research.

**Deformation Monitoring.** The feasibility of incorporating deformation observation data into the analysis of borehole monitoring results for the stress-strain state of the geoenvironment was substantiated in [*Gavrilov et al.*, 2023b]. It demonstrated that a combined analysis of borehole and deformation monitoring data allows for a refinement of the time boundaries of the stages of change in the stress-strain state of the geoenvironment, eliminates ambiguities in the interpretation of electromagnetic and geoacoustic borehole measurements in the final stages of earthquake evolution, and improves the reliability of seismic hazard assessments. These results stimulated the development of a GNSS network in the Avacha Bay area, and GNSS observation data began to be used to refine the interpretation of borehole measurement results.

Sufficiently detailed information on the GNSS network at the PGS, the data from which are used to analyze the borehole monitoring results, is contained in [*Gavrilov et al.*, 2023b]. The location of the GNSS network sites is shown in Figure 1. When analyzing the monitoring results, the time series of complex borehole measurements in the PGS area are compared with a series of flat dilatation reflecting seismic deformation processes in the Avacha Bay area. The plane dilation series is calculated based on the average daily displacements in the horizontal plane of the PETS, MYAK, RADZ sites (see Figure 1) as the sum of the elements on the main diagonal of the plane strain tensor. To reduce the values of the standard deviation of the obtained time series, the original displacement series first undergo mandatory processing, which includes the elimination of rough outliers and coseismic jumps, smoothing with a 25-day window, and the elimination of the subduction trend and seasonal variations. The displacement series processed in this way form a dilation series characterized by an error rate of $0.1 \times 10^{-7}$, which is about 10% of the minimum changes of $1 \times 10^{-7}$ considered significant. For example, during the two months preceding the Zhupanovsky earthquake (January 30, 2016, $M_W = 7.2$), the amplitude of dilation changes was approximately $2 \times 10^{-7}$ [*Gavrilov et al.*, 2023b], which exceeded tidal deformations by 20 times and corresponded in magnitude to the observed changes in borehole measurement data.

**Monitoring Changes in the Ionospheric Total Electron Content.** Data on ionospheric TEC changes over Avacha Bay, compared with changes in the SER of the geoenvironment at various depths based on borehole monitoring data, provide additional information on changes in the SSS of large volumes of geoenvironment in the subionospheric region. In certain cases, this makes it possible to detect the location of the future near-epicentral region of an impending major seismic event [*Gavrilov et al.*, 2025b]. In the course of the studies conducted by the authors, it was shown that changes in the ionospheric TEC at the final stages of preparation of large earthquakes are mainly due to changes in SER of the geoenvironment of the upper part of the Earth's crust in the corresponding subionospheric zone [*Gavrilov et al.*, 2025b]. These results are consistent with the concept of a possible significant role of changes in SER of the geoenvironment in the formation of ionospheric TEC anomalies before strong earthquakes [*Pulinets and Davidenko*, 2014], which is of great scientific importance both for refining the theoretical basis of lithosphere–atmosphere–ionosphere interaction processes and for developing methods for short-term seismic hazard forecasting for seismically active regions. For this reason, in recent years, ionospheric TEC monitoring data have been consistently used to prepare regular laboratory conclusions on seismic hazard for Kamchatka Krai (see below).

## 3. Approaches to Short-Term Seismic Hazard Forecasting in the Avacha Bay Area

The Network has made it possible to obtain a number of important scientific results related to the establishment of physical causes and mechanisms that determine changes in the nature of time series at the final stages in the process of generation of strong earthquakes in the Avacha Bay area, as well as to establish new highly sensitive methods for monitoring the preparatory stages of strong Kamchatka earthquakes. These results include, among other things, the discovery of the effect of the modulating influence of weak electromagnetic ULF fields on the intensity of geoacoustic emission of rocks [*Gavrilov et al.*, 2008, 2006], as well as the establishment and description of the mechanism of this effect [*Gavrilov*, 2017; *Gavrilov and Naumov*, 2017]. It is also worth noting the development of a number of new methods for monitoring changes in the parameters of the geoenvironment during the preparation of strong earthquakes, which have no analogues at domestic and foreign seismic forecasting sites [*Gavrilov*, 2017; *Gavrilov et al.*, 2022].

In addition, data from the Multi-Instrumental Borehole Measurement Network made it possible to make a number of correct short-term forecasts of the strongest Kamchatka earthquakes in 2005–2024, which caused tremors of up to 5–6 points in the Petropavlovsk-Kamchatsky agglomeration area [*Gavrilov et al.*, 2025a]. Among these results is a short-term (9 days before the earthquake) successful forecast of the Shipunskoye-1 earthquake (August 17, 2024; $M_W = 7.0$). In June 2025, a short-term (24-day) forecast was made that was confirmed for the Shipunskoye-2 earthquake (July 20, 2025; $M_W = 7.4$) – the foreshock of the Kamchatka megaearthquake that occurred on July 29, 2025.

The presented results indicate the feasibility of successful short-term forecasting of strong Kamchatka earthquakes with "soft", i.e., less stringent, requirements for the accuracy of earthquake parameter forecasts and with a qualitative assessment of the probability of the predicted event.

The aforementioned successful forecasts of strong Kamchatka earthquakes serve as definitive confirmation of the effectiveness of the authors' fundamentally new approach to seismic hazard forecasting for the Petropavlovsk-Kamchatsky agglomeration. This approach is described in detail in [*Gavrilov et al.*, 2025a]. Its key points are as follows.

1. Accurate short-term forecasts of time (error ±3 days), earthquake magnitude (error ±0.1), as well as achieving a high degree of forecast success (at least 85–90%), which a number of researchers insist on (see, for example, [*Koronovskii et al.*, 2021]), are impossible. Meanwhile, such demands for high-precision short-term earthquake forecasting are essentially unfounded, since residents, as well as government officials and emergency services, are primarily interested not in the precise parameters of the predicted earthquake, but in the severity of possible shaking in the coming days and weeks for a specific area. For this reason, the main goal of short-term forecasting should be a qualitative assessment of the current seismic hazard for the controlled zone, rather than a highly accurate (obviously impossible!) forecast of the parameters of the expected earthquake. In this case, seismic hazard assessments should be based on current monitoring results for the preparation of strong earthquakes in the Avacha Bay area, which could cause significant (at least magnitude 6) tremors in the Petropavlovsk-Kamchatsky agglomeration. At the initial stage, high-quality three-stage assessments ("low", "elevated", and "significantly elevated") are sufficient. This makes it possible to promptly inform authorities and the Ministry of Emergency Situations if there is a significant likelihood of tremors of at least point 6 in a given area within the next 2–4 weeks. Clearly, in this case, we are also essentially talking about short-term earthquake forecasting; however, as the authors' many years of research have shown, in such cases, the requirements for estimating the predicted earthquake's parameters may be limited to an estimate of the $S$ value – the percentage ratio of the earthquake's focal length to the hypocentral distance.
2. Global experience from many years of research shows that relying solely on "precursors" cannot guarantee reliable short-term earthquake forecasting. Analysis of current geophysical and seismic measurements conducted for short-term forecasting purposes must be conducted within the framework of key principles and a soundly selected underlying physical model (concept) of earthquake preparation. The Multi-Instrumental Geophysical Observation Network allows us to focus not on searching for "precursors", but on the timely detection, within the framework of the basic

model, of the onset of changes in the nature of the results of monitoring the stress-strain state of the geoenvironment, indicating the preparation of a major earthquake. According to [*Gavrilov et al.*, 2025a], in many cases, large Kamchatka earthquakes are preceded by an "active phase" of preparation several months in advance (see below). Understanding the physical causes of the active phase indicates a real opportunity to significantly improve the effectiveness of medium- and short-term seismic hazard forecasting.

We emphasize that the types of geophysical observations used for geoenvironment monitoring must be consistent in their information capabilities with the selected baseline physical model. If this is not the case, it will likely be crucial to make the necessary changes to the measurements performed by the monitoring network, recognizing that this is much easier to accomplish than selecting a different baseline model.

**On the Selection of a Basic Physical Model for Earthquake Preparation for the Avacha Bay Area.** Currently, the authors use the consolidation model of I. P. Dobrovolsky [*Dobrovolsky*, 2009] as a basic physical model for the preparation of strong earthquakes in the Avacha Bay area. The basis for choosing this particular model was the results obtained in the course of many years of research, which showed that the nature of changes in the time series of data from complex geophysical measurements (primarily data from monitoring changes in SER of the geoenvironment) at the final stages of earthquake preparation corresponds to the consolidation model [*Gavrilov et al.*, 2025a].

Analysis of current multi-instrumental borehole monitoring data, conducted within the framework of the consolidation model, allows, in most cases, for the reliable and rapid identification of the onset of the final stage of earthquake preparation. This is a significant advantage compared to most other earthquake preparation models. For example, reliably identifying the onset of the final preparatory stage of an earthquake within the dilatant-diffusion model [*Nur*, 1972; *Sholz et al.*, 1973] proved impossible.

According to [*Dobrovolsky*, 2009], the consolidation model distinguishes two main stages preceding a tectonic earthquake: the consolidation stage and the disintegration stage of the heterogeneity. During the consolidation stage, the formation and growth of the rigid heterogeneity occurs, with a corresponding accumulation of potential energy. The heterogeneity disintegration stage is the most important for short-term earthquake forecasting, as it is during this stage that the main rupture's position is established and short-term precursors appear. Its duration is significantly shorter than the consolidation stage, as the heterogeneity decay process proceeds intensively due to the potential energy accumulated during the previous stage.

**Active Phase of Earthquake Preparation.** Analysis of multi-instrumental borehole measurement data, conducted within the framework of a consolidation model, allowed us to elucidate the physical basis of the so-called "active phase of earthquake preparation". As shown in [*Gavrilov et al.*, 2023a], the active phase in many cases precedes large Kamchatka earthquakes by several months. ”,sign of the onset of the active phase is the nearly simultaneous appearance of high-amplitude short-term precursor anomalies in various types of measurements, corresponding in their physical meaning to the selected basic earthquake preparation model. As shown in [*Gavrilov et al.*, 2025a], within the framework of the key concepts of the consolidation model, the active preparatory phase of an earthquake is physically explained as a response to the decay of a rigid heterogeneity. This is an important scientific result, since the manifestation of the onset of the active phase in monitoring data indicates that the decay of the heterogeneity has already begun. Given that the process of heterogeneity decay is well-energized, the probability of a subsequent main rupture (a strong earthquake) is very high. Early detection of the onset of an active phase through analysis of current results of multi-instrumental borehole measurements enables significant improvements in the effectiveness of medium-term (up to one year) seismic hazard forecasting. Clearly, this approach can also significantly improve the reliability of short-term seismic hazard forecasting.

## 4. Reflection of the Preparatory Process of the Kamchatka Megaearthquake of July 29, 2025 in the Results of Multi-Instrumental Geophysical Measurements in the Avacha Bay Area

**Monitoring the Specific Resistance of the Geomedium.** Given the high strain sensitivity of the EMR method for monitoring SER of the geomedium and the 20-year duration of the SER time series, the results of the resistance monitoring most fully reflect the processes leading up to the Kamchatka megaearthquake in the Avacha Bay area. Figure 2 shows two time series of the changes in SER of the geomedium, constructed using the same initial data but with significantly different smoothing windows.

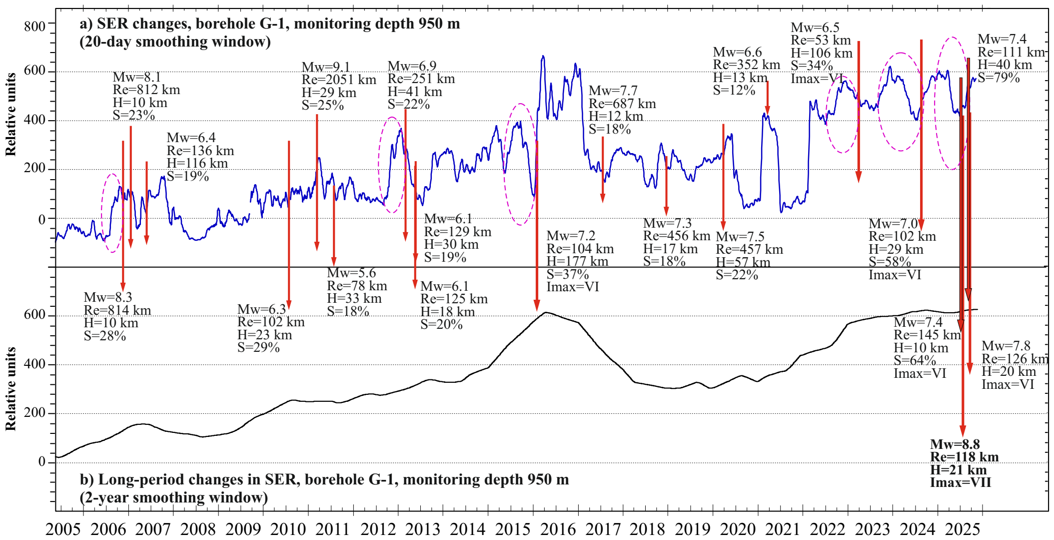

Figure 2. Changes in SER of the geoenvironment before earthquakes with a depth of $H \leq 200$ km and $S$ value $\geq 18\%$ based on measurements at the G-1 borehole using an underground electric antenna. The monitoring depth of SER is 950 m: (a) changes in SER of the geoenvironment, smoothing window is 20 days; (b) changes in SER of the geoenvironment, smoothing window is 2 years. The explanations are in the text.

The series presented in Figure 2a was constructed using a 20-day smoothing window. This provides a more detailed understanding of changes in the nature of SER of the geoenvironment before earthquakes. A two-year smoothing window was used to construct the series presented in Figure 2b, allowing us to assess the nature of changes in the trend component of long-term SER changes.

The data presented in Figure 2a show that all earthquakes with the $S$ parameter value of at least 22% were preceded by short-term changes in SER of the geoenvironment. A detailed analysis of the data allows us to conclude that the nature of these changes is consistent with the consolidation model [*Gavrilov et al.*, 2025a]. In Figure 2a, such time intervals are marked with dashed ovals.

The data presented in Figure 2b show that all of the most powerful seismic events with $S \geq 23\%$ were preceded by prolonged (up to several years) intervals of increased growth in SER of the geoenvironment. These results indicate that the nature of long-term changes in SER of the geoenvironment in the PGS area is determined by changes in the regional stress field.

Figure 2 shows that, on the eve of the 2025 Kamchatka megaearthquake, a record-breaking SER anomaly (amplitude, duration) formed at a monitoring depth of 950 m. A similar anomaly was also recorded in the SER monitoring data at a depth of 2200 m (Figure 3). Moreover, the increase in SER of the geoenvironment at a depth of 2200 m began much earlier – approximately in September 2018. Previously, over 20 years of multi-instrumental borehole measurements in the PGS area, the formation of similar SER anomalies had not been observed.

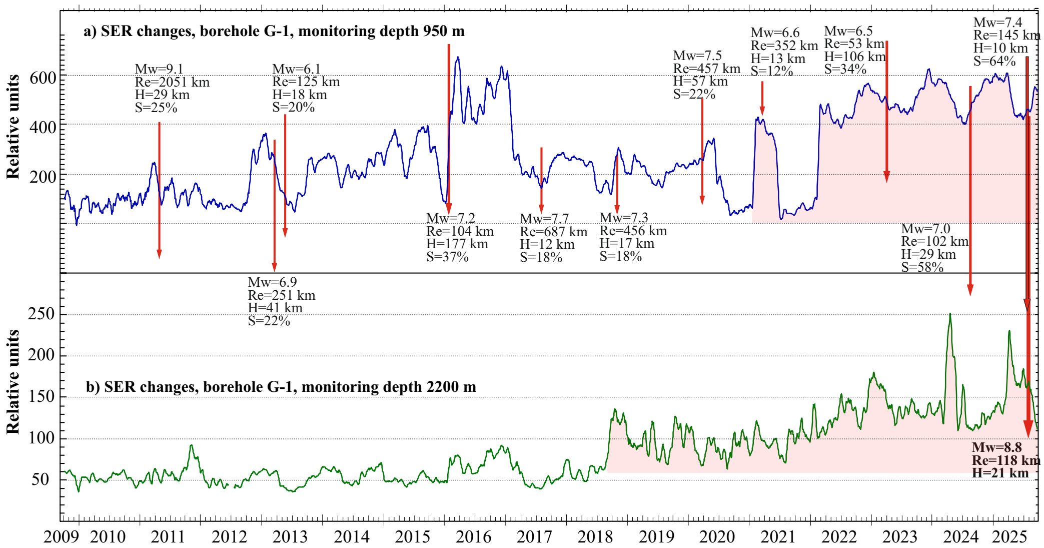

**Figure 3.** Anomalies of SER of the geoenvironment in the Avacha Bay zone according to monitoring data at depths of up to 950 m and 2200 m.

Within the consolidation model [*Dobrovolsky*, 2009], the record duration of SER anomalies signifies the formation of a three-dimensional consolidated heterogeneity of the geoenvironment of very large dimensions. The heterogeneity reaches its maximum size before an earthquake, with the dimensions of the heterogeneity on the eve of an earthquake being close to the dimensions of the future source. In this case, the relationship between the heterogeneity dimensions and the earthquake magnitude can be estimated, as indicated previously, by the expression $L = 10^{0.44M-1.29}$, where $M$ is the moment magnitude [*Riznichenko*, 1976].

Following the Kamchatka megaearthquake of July 29, 2025, it became clear that the aforementioned SER anomalies in the geoenvironment were directly related to the preparation of this unique, powerful seismic event. Assessing the possible physical causes of these SER anomalies (see Figures 2 and 3), it can be assumed that they are largely related to the strongest ($M_W = 7.7$, $R_e = 687$ km, $H = 12$ km, $S = 18\%$) Near Islands Aleutian earthquake that occurred on July 17, 2017. The mechanism for transmitting disturbances in the geoenvironment stress-strain state associated with the Near Islands Aleutian earthquake to the Avacha Bay area, in our opinion, can be explained from the standpoint of the concept of deformation waves [*Bykov*, 2005, 2023].

**About the Foreshocks of the Kamchatka Megaearthquake.** In 2023–2025, in Avacha Bay (see Figure 1), on the eve of the Kamchatka megaearthquake, three strong earthquakes occurred: Vilyuchinskoye (April 3, 2023, $M_W = 6.5$), Shipunskoye-1 (August 17, 2024, $M_W = 7.0$) and Shipunskoye-2 (July 20, 2025, $M_W = 7.4$), which caused six-point tremors in the city of Petropavlovsk-Kamchatsky.

The Shipunskoye-2 earthquake, which occurred in the Avacha Bay area nine days before the Kamchatka megaearthquake, can be considered its foreshock. The Shipunskoye-1 and Vilyuchinskoye earthquakes occurred much earlier – 11 and 17 months before the Kamchatka megaearthquake, respectively. Therefore, the grounds for considering them foreshocks were initially unclear. However, in terms of their preparation and the nature of the postseismic stage, Shipunskoye-2 and Shipunskoye-1 are virtually identical (Figures 4c, d), allowing both earthquakes to be considered foreshocks of the Kamchatka megaearthquake. The Vilyuchinskoye earthquake's preparatory stage is also fundamentally no different from the preparatory stages of the Shipunskoye-1 and Shipunskoye-2 earthquakes (see Figure 3). Thus, all three earthquakes share similarities, both in their preparation and in the nature of their postseismic stages. It should be noted that the time intervals between the earthquakes were too short for such large seismic events. Furthermore, during the postseismic stages of these earthquakes, only a slight decrease in SER occurred, while the main SER anomaly in the Avacha Bay area remained anomalously high. This indicates that these were not “independent” seismic events, but rather markers of the final phase of the preparation of a much more powerful seismic event – i.e., they were foreshocks of the Kamchatka megaearthquake.

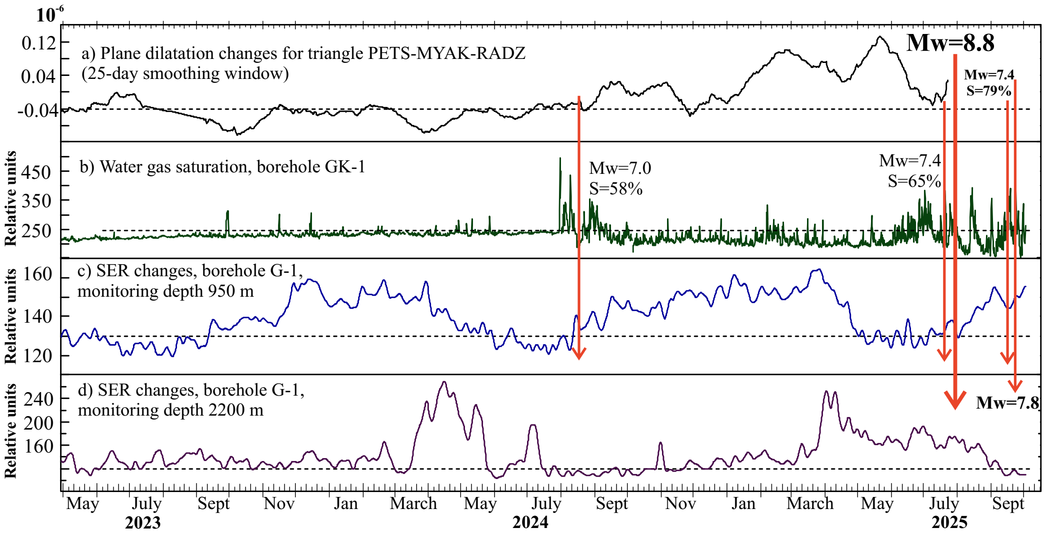

**Figure 4.** Reflection of the final preparatory stage of the Kamchatka megaearthquake in the results of multi-instrumental borehole measurements and deformation monitoring.

Figure 4 shows the results of deformation monitoring reflecting the preparation of the Kamchatka megaearthquake. A flat dilation series was constructed using data from the PETS, MYAK, and RADZ stations of the Kamchatka GNSS observation network (see Figure 1). Significant changes in dilation can be seen immediately after the Shipunskoye-1 earthquake. During a short period from January to June 2025, dilation increased by $2\times10^{-6}$, and then, approximately 60 days before the Shipunskoye-2 earthquake, extension processes abruptly gave way to intense compression of the geoenvironment. Similar significant changes in the dilation series, both in amplitude and in the nature of the changes, were previously observed before another major Kamchatka seismic event – the Zhupanovsky earthquake ($M_W = 7.2$), which occurred in January 2016 [*Gavrilov et al.*, 2023b].

Furthermore, anomalous changes in gas saturation in the GK-1 borehole (Figure 4b) are noteworthy. These changes occurred just before both earthquakes. We observe that the emergence of these anomalies just before the Shipunskoye-1 and Shipunskoye-2 earthquakes allowed for the correct short-term forecasts of these earthquakes (see below). These results also provide grounds for considering the Shipunskoye-2 earthquake to be the foreshock of the Kamchatka megaearthquake.

**Short-Term Earthquake Forecasts for Shipunskoye-1 and Shipunskoye-2.** [**sec:03**] mentioned that, within the framework of the authors’ approach to seismic hazard forecasting for the Petropavlovsk-Kamchatsky region, the requirements for estimating predicted earthquake parameters can be limited to an estimate of the $S$ value – the percentage ratio of the earthquake focal length to the hypocentral distance. It was also noted that, at the initial stage, high-quality three-stage seismic hazard assessments (“low”, “elevated”, and “significantly elevated”) are sufficient.

The effectiveness of this approach can be confirmed by the successful short-term forecasts of the Shipunskoye-1 (August 17, 2024; $M_W = 7.0$) and Shipunskoye-2 (July 20, 2025, $M_W = 7.4$) earthquakes, which caused tremors of up to points 6 in Petropavlovsk-Kamchatsky. As shown above, these earthquakes are foreshocks of the Kamchatka megaearthquake. Figure 5 explains the specific results of the current multi-instrumental borehole monitoring of the geoenvironment in the Avacha Bay area that served as the basis for the forecast conclusions.

The first forecast report related to the preparation for the Shipunskoye-1 earthquake was sent on December 19, 2023, to the KB REC and the Council for the Prediction of Earthquakes and Volcanic Eruptions of the IVS FEB RAS. It reported an "**increased** probability of an earthquake with an $S$ parameter of $\geq 18\%$ over the next 10 days". The $R_h$ parameter for the report was calculated relative to the location of borehole G-1.

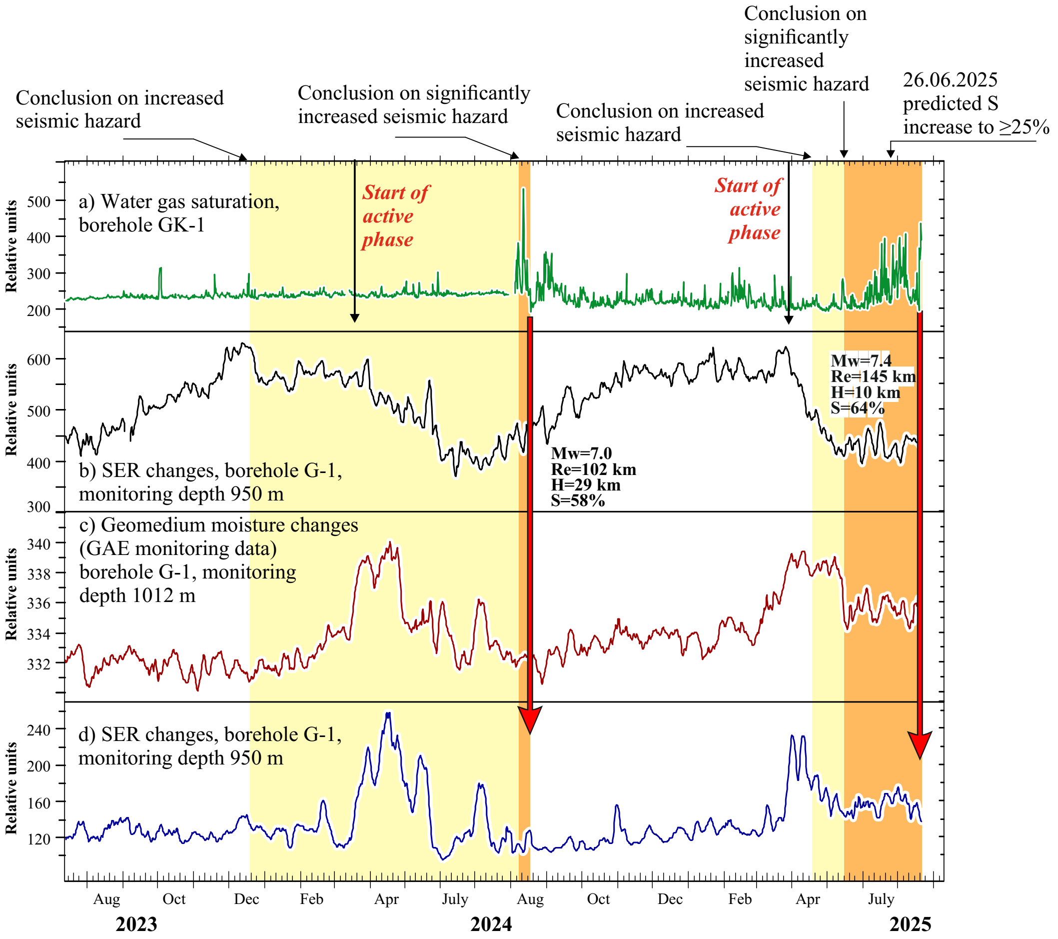

**Figure 5.** Chronology of submission of forecast conclusions on seismic hazard on the eve of the Shipunskoye-1 and Shipunskoye-2 earthquakes.

The basis for this conclusion was changes in the nature of SER monitoring data for the geoenvironment (Figure 5b), as well as borehole geoacoustic measurement data (Figure 5c). Within the framework of the consolidation model, such data allowed for the conclusion of a transition from the consolidation stage to the heterogeneity disintegration stage. This conclusion was then confirmed every two weeks until August 8, 2024, since, until that point, current data from multi-instrumental borehole monitoring of changes in the SSS of the geoenvironment in the Avacha Bay area, received via daily telemetry channels, did not provide a serious basis for changing the wording of the conclusion.

On August 8, 2024, a Conclusion was made regarding "**a significantly increased** probability of a strong earthquake with an $S$ parameter value of at least 18% for the period from August 8 to August 22, 2024". The basis for this Conclusion was, first of all, a sharp and significant increase in the gas saturation of water in the GK-1 borehole, which began on August 1, 2024 (Figure 5a). Earlier, the monitoring data on the specific electrical conductivity of water in the GK-1 borehole and the geomedium SER at a depth of 950 m in the G-1 borehole changed to the opposite (Figure 5b). The earthquake corresponding to the parameters specified in the report – the Shipunskoye-1 earthquake – occurred on August 17, 2024, i.e., nine days after the report on the significant probability of a strong earthquake in the Petropavlovsk-Kamchatsky area was submitted.

The short-term forecasting of the Shipunskoye-2 earthquake went through similar stages, but with some additions and clarifications. The first conclusion related to the preparation of the Shipunskoye-2 earthquake was submitted by the authors on April 17, 2025. It reported "an **increased** probability of an earthquake with an $S$ parameter of $\geq 18\%$ over the next two weeks". The basis for this conclusion, as in the previous case, was the changes in the nature of the data from monitoring SER of the geoenvironment and the data from borehole geoacoustic measurements. This conclusion was then also confirmed every two weeks until May 16, 2025, and then a report was sent to the KB REC and to the Council for the Prediction of Earthquakes and Volcanic Eruptions of the IVS FEB RAS on "a **significantly increased** probability of a strong earthquake with a parameter $S$ value of at least 18% over the next two weeks". This assessment of seismic hazard was based, first of all, on the changes in the nature of the time series of data on SER of the geoenvironment and borehole geoacoustic measurements (see Figure 5).

It is necessary to clarify the following. During the analysis of the data from monitoring changes in SER at a depth of 950 m, reflecting the processes occurring before the Shipunskoye-2 earthquake during the heterogeneity decay stage (March–April 2025 interval, Figure 5b), a significantly higher rate of decrease in SER values was noted compared to the data obtained for the Shipunskoye-1 earthquake (March–April 2024 interval, Figure 5b). The data obtained in the subsequent interval (May–June 2025 interval, Figure 5b) indicated even more significant differences with the data obtained on the eve of the Shipunskoye-1 earthquake, which made it difficult to reliably and correctly interpret them in real time.

In this situation, the results related to the moment of identification of the beginning of the active phase of preparation of the Shipunskoye-1 earthquake, presented in [*Gavrilov et al.*, 2025a], helped to draw correct conclusions regarding the interpretation of monitoring data for the interval of May–June 2025. This moment of the beginning of the active phase of preparation of the Shipunskoye-1 earthquake (mid-March 2025) is shown in Figure 5a. Based on the similarity of the preparation processes of the Shipunskoye-1 and Shipunskoye-2 earthquakes, a conclusion was made (later confirmed) about the beginning of the active phase of preparation for the Shipunskoye-2 earthquake in early April 2025.

Section 3 emphasizes that the onset of the active phase in the monitoring data, consistent with the consolidation model, indicates that heterogeneity decay has already begun. Considering also that the heterogeneity decay process is well-energized, the probability of a subsequent main rupture (a strong earthquake) in this case is very high. In this regard, a clarification was made to the conclusion of May 16, 2025, regarding the significantly increased probability of a strong earthquake. In the new conclusion of June 26, 2025, based on the higher magnitude of the expected earthquake, the predicted value of the $S$ parameter was increased to $S \geq 25\%$. The Shipunskoye-2 earthquake, corresponding to the parameters specified in the Conclusion of June 26, 2025, occurred on July 20, 2025.

**Monitoring Changes in the Ionospheric Total Electron Content.** As shown in Section 2, in recent years, the authors have been actively incorporating ionospheric TEC monitoring data into their multivariate analysis of the Borehole Measurement Network data. To date, this has yielded a number of important scientific results, significantly improving the effectiveness of ongoing research. This includes results related to the preparation of the Kamchatka megaearthquake.

Figure 6 shows the changes in the minimum level of vertical TEC (VTEC) of the ionosphere based on the data from the PETT and SPNS GNSS stations in comparison with the data from monitoring SER of the geoenvironment in the R-2 borehole zone (see Figure 1). The synchronous increase in SER of the geoenvironment and the TECU values

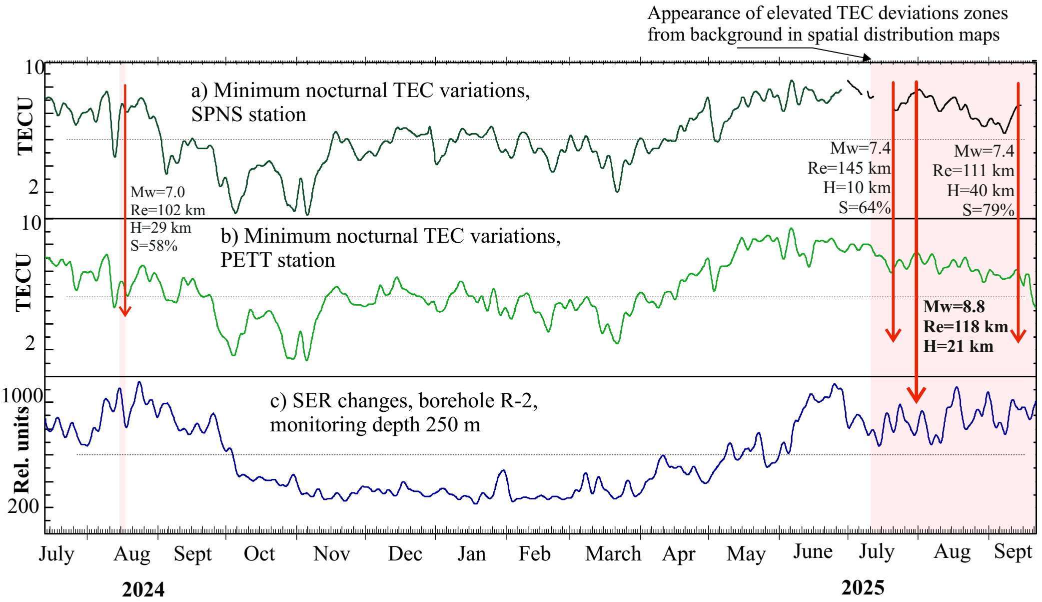

**Figure 6.** Comparison of minimum night variations in ionospheric TEC based on data from PETT and SPNS GNSS stations and data on changes in SER of the surface layer of the geoenvironment at borehole R-2.

in the presented series since the beginning of June 2025 is noteworthy. Similar results were observed before the strong Zhupanovsky earthquake (January 30, 2016, $M_W = 7.2$). It is shown in [*Gavrilov et al.*, 2025b] that synchronous variations in the data series of the ionospheric TEC and SER of the upper layers of the Earth's crust may indicate the restructuring of very large volumes of the geoenvironment, which caused changes in SER of the upper layer of the Earth's crust in the observed subionospheric territory.

Two-dimensional maps, constructed as percentage deviations from selected geomagnetically quiet days (Figure 7), provide insight into the spatial distribution of ionospheric TEC disturbances during the final stages of preparation for the Kamchatka megaearthquake. The maps in Figure 7 show that, starting approximately in mid-July 2025, areas with significant (up to 80%) deviations from the background VTEC level emerged in the Avacha Bay area. Moreover, these areas were located close to the future epicentral zones of the Shipunskoye-2 earthquake and the Kamchatka megaearthquake.

It should be mentioned that the geomagnetic environment for all days shown in Figure 7 was calm, with the *Dst* index not falling below −10. It should be noted that spatial maps largely reflect changes in maximum nighttime ionospheric TEC values. The anomalously high areas highlighted in these maps could potentially be due to the residual influence of solar radiation at times close to sunrise and sunset. For this reason, the calculated values undergo mandatory smoothing during the interpolation process. Nevertheless, even after this processing, areas with significant deviations from the background VTEC level are clearly visible, as can be seen in Figure 7.

As shown in [*Gavrilov et al.*, 2025b], the appearance of such regions on spatial maps of TEC disturbances, combined with a simultaneous increase in the upper crustal SER in the Avacha Bay area, indicates the epicentral zone of a future major earthquake, the preparation of which is in its final stages. In this case, we suggest that the appearance of such regions since mid-July 2025 in the Avacha Bay area is associated with the preparation of the Shipunskoye-2 earthquake and the Kamchatka megaearthquake.

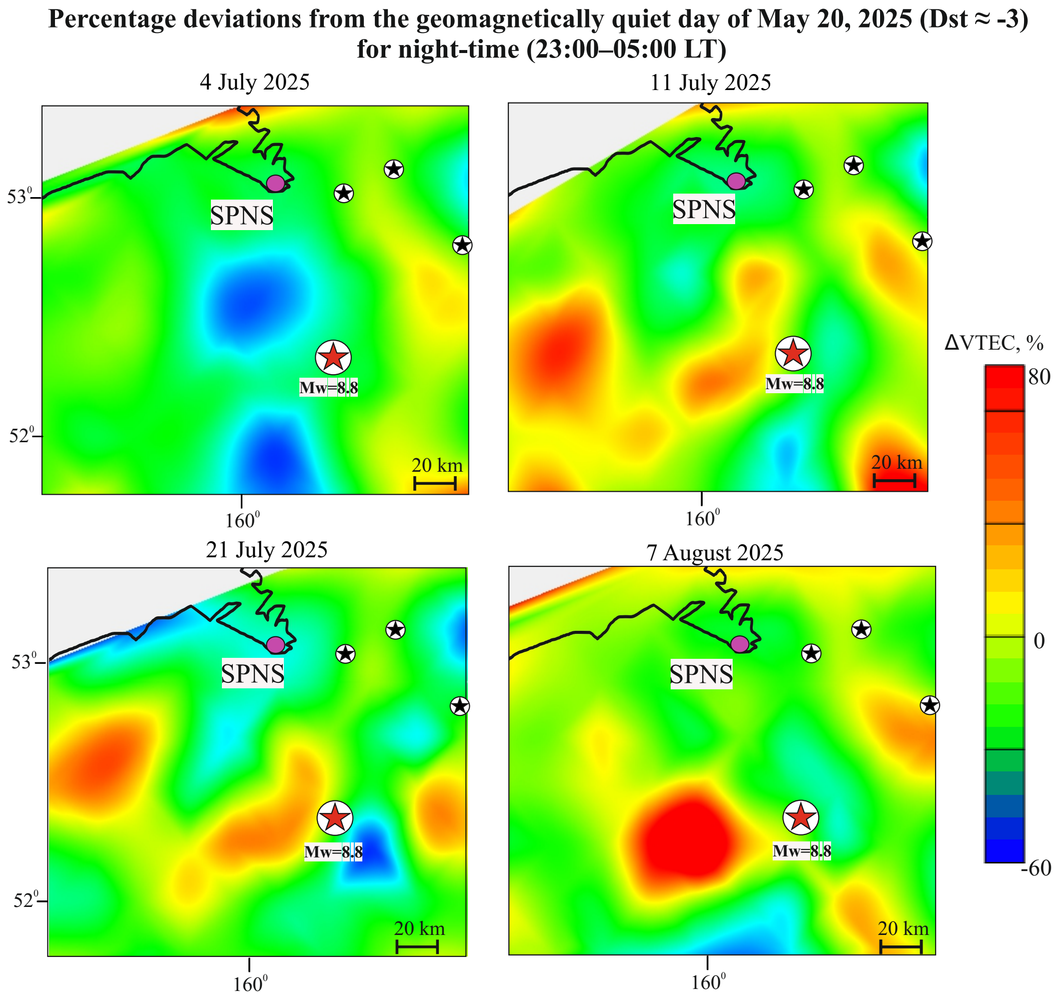

**Figure 7.** Spatial distribution of ionospheric TEC disturbances based on data from the PETT and SPNS GNSS stations in July–August 2025, plotted as a percentage deviation from selected geomagnetically quiet days. Mapped ionospheric TEC values are filtered for high elevation angles and darkness (UTC+12).

## 5. Conclusion

The most important scientific results reflecting the preparatory stage of the 2025 Kamchatka megaearthquake were obtained using data from the Multi-Instrumental Borehole Measurement Network, specifically created for continuous monitoring of the preparation processes of strong earthquakes in the Avacha Bay area. According to the results of SER monitoring, a record-breaking resistance anomaly (amplitude and duration) formed in the Avacha Bay area on the eve of the Kamchatka megaearthquake. This anomaly was reflected in SER monitoring data for a monitoring depth of 2200 m, starting in mid-2018, and in the data for a depth of 950 m – since the beginning of 2021. The Vilyuchinskoye, Shipunskoye-1, and Shipunskoye-2 earthquakes that occurred against the backdrop of this SER anomaly were not "independent" seismic events, but were markers of the final phase of preparation of a much more powerful seismic event, i.e., they were foreshocks of the Kamchatka megaearthquake. The authors' fundamentally new approach to medium- and short-term seismic hazard forecasting enabled successful short-term forecasts of the Shipunskoye-1 and Shipunskoye-2 earthquakes, which caused tremors of up to points 6 in Petropavlovsk-Kamchatsky. Overall, the results presented in this article highlight the need for further development of the existing framework for medium- and short-term seismic hazard forecasting for the Petropavlovsk-Kamchatsky agglomeration. Given the positive experience of such research, it is imperative to develop similar systems in other areas of the eastern coast of Kamchatka.

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