Reaction in the field of subsoil gases to the preparation of the earthquake on March 16, 2021 with MW = 6.6 (Kamchatka, Russia)

Pavel Firstov¹,² and Evgenii Makarov¹,²,³
¹ Kamchatka Branch of Federal Research Center, Geophysical Survey RAS, Petropavlovsk-Kamchatsky, Russia
² Kamchatka State University named after Vitus Bering, Petropavlovsk-Kamchatsky, Russia
³ E-mail: ice@emsd.ru

Abstract. The paper presents the data of monitoring of subsoil gases on Kamchatka peninsula. Before the earthquake with MW=6.6 on March 16, 2021 near Kamchatka, anomalous variations were revealed in the field of subsoil gases, which are probably associated with the passage in the earth's crust of solitary deformation pulses, called deformation waves. Such deformation pulses can affect the permeability of rocks and cause changes in the radon flux to the surface at the locations of the sensors. Based on the complex of emanation data, the earthquake of March 16, 2021 with MW=6.6 was successfully predicted.

1. Introduction
Radon (²²²Rn) is formed as a result of radium decay and technologically available for continuous recording in subsoil air. It is often used to explore the response of the stress-strain state of the geomedium from external influences [1, 2]. Searches for anomalies in the field of subsoil radon have been widely conducted in recent decades in many seismically active regions of the world. In review works [3, 4, 5] provides facts on the information content of the radon emanation method for the purposes of forecasting strong earthquakes. Short-term precursor anomalies in the field of subsoil radon before earthquakes with a magnitude of MW> 4.5 and with a lead time of up to 15 days were registered in many regions of the world [6, 7, 8, 9]. However, descriptions of medium- and long-term precursors of strong earthquakes in the field of subsoil radon are rather rare. So, before the Izu Oshima earthquake on January 14, 1978 with MW=7.0 an anomaly in the concentration of subsoil Rn was observed at a distance of 30 km from the epicenter for 2.5 months [10]. In the water of an artesian well, 4.5 months before the Tohoku mega-earthquake (Japan) on March 11, 2011, with MW=9.1, an increase in the radon volumetric activity (RVA) began, which continued after the earthquake [11].

Meteorological quantities (air temperature, atmospheric pressure, precipitation) make a significant contribution to the dynamics of the field of subsoil radon. They cause a significant amount of noise in the initial data, which makes it difficult to identify the precursor anomalies. This forces the use of special methods for identifying precursor anomalies [8, 12, 13].
2. Methods
At the Petropavlovsk-Kamchatsky geodynamic test site (PGTS), a network of monitoring stations of the subsoil RVA and molecular hydrogen with digital signal recording has been operating since 2000 (figure 1). The network includes five stations equipped with complexes for registering subsoil gases. In the context of the need to ensure continuous monitoring of the Rn concentration for a long time, the most reliable and metrologically simple method was to register the radon concentration in the air of subsoils by the $\beta$-radiation of its daughter decay products using gas-discharge counters (GDC). The work [8] describes in detail the principles of organizing this network, the arrangement of points and the equipment used.

![Figure 1](image-url)  
**Figure 1.** Map of the boundaries of areas within which the preparation process for earthquakes of corresponding magnitudes can cause anomalies in the field of subsoil radon with a relative amplitude $\delta_{\text{min}} \geq 20$ minus the lower boundary of the 95% confidence corridor [8]. The star shows the epicenter of the earthquake on March 16, 2021 with $M_W = 6.6$.

Based on long-term observations at the PGTS in the field of subsoil radon two types of precursor anomalies have been identified for subduction earthquakes with $M > 5$. Type A - are distinguished in the data at several registration points in the form of in-phase bay-like variations lasting from 3 to 12 days [8] and reflects a large-scale manifestation of geodeformational processes at the last stage of earthquake preparation. It is this type of anomalies preceding earthquakes that is supposed to be associated with the passage of solitary deformation waves in the geomedium, arising due to the quasi-plastic or cataclastic flow of mountain masses at the last stage of the earthquake preparation. Type B - is registered at a single observation point and is associated with a special state of the hydrogeological system of the registration point. As shown in [8], the type B precursor mechanism is in good agreement with the theoretical model of Rn transfer in an aqueous medium with complete transverse mixing.
3. Results
An earthquake with $M_W = 6.6$ occurred in the Pacific Ocean on the traverse of the Kronotsky Peninsula (Kamchatka) on March 16, 2021, at a distance of 350 km from INSR at a depth of 65 km (figure 1). This earthquake was preceded by in-phase, identified at several points of the network, bay-like RVA anomalies of positive polarity (points INSR, MRZR) and negative polarity (point PRTR) lasting ~ 6–18 days. In amplitude, they exceeded similar variations associated with abrupt changes in atmospheric pressure.

![Figure 2](image.png)

**Figure 2.** RVA dynamics at points INSR (a), MRZR and PRTR (b), concentration of molecular hydrogen at INSR point (c), variations in atmospheric pressure and a time series constructed using the "eigenoscopy" method (d) for the period January 01- March 24, 2021. The moment of the earthquake is shown by a red vertical line, anomalies are highlighted in light gray, forecast periods are shown by light blue rectangles.

The relative amplitude of the RVA anomalies ($\delta = \frac{A_{\text{anom}} - A_{\text{backg}}}{A_{\text{backg}}} \cdot 100\%$) was 180% and 46% on two sensors at INSR, 20% at MRZR, and ~69% at PRTR1 (figure 2a, b). The lead time was ~60 days.
It was shown in [8, 14] that before some earthquakes in Kamchatka, hydrogen anomalies are recorded at the PGTS, which have the character of short bursts or bipolar pulses. In a number of cases, such anomalies occurred in a temporary vicinity with radon ones and preceded strong earthquakes [8]. At the INSR station, a molecular hydrogen sensor located in the wellbore of the NIS-1 well at a depth of ~5 m from the head, before the earthquake on March 16, 2021, recorded two anomalous bursts with a duration of ~2-4 days (figure 2c), exceeding by amplitude the variations in associated with daily fluctuations in atmospheric pressure in the bunker, arising in connection with the peculiarities of the organization of this observation point [8].

In addition, using the developed technique for identifying in-phase variations in the time series of the RVA using the "eigenoscopy" method, which makes it possible to identify moments of collective behavior in multidimensional series [8], the identified radon anomaly was formalized and identified as a possible precursor of a strong earthquake (figure 2d).

The work [15] presents the results of a three-year instrumental monitoring of deformation of rocks at the South Baikal geodynamic test site, in which the authors of [15] identified two types of deformation waves. The first type of waves is expressed in time series of data by single impulses passing through all monitoring points. Their sources are located outside the monitoring points. The appearance of such a deformation pulse is initiated by a tremor-like displacement along a seismically active fault, which preceded the main seismogenic displacement [15]. The pulse migration rate was ~1-2 m/s.

The distinguished deformation waves of the second type appear more often than the first and are represented by symmetric or asymmetric pulses with amplitudes smaller by an order of magnitude than those of waves of the first type. Their origin, as suggested in [15], is associated with the redistribution of stresses in the fault-block structure of the upper part of the earth's crust within the monitoring points, and the frequency of their manifestation significantly increases before nearby earthquakes. The migration rate of deformation waves of the second type sharply increases a few days before the earthquake (from ~5 to ~50 km/day), then decreases [15].

Based on the works [8, 15], it can be assumed that the anomalous radon variations recorded at the PGTS before the earthquake of March 16, 2021 with $M_W=6.6$ are associated with the impact on the geomedium of several deformation impulses that passed through all registration points, causing changes in soil permeability, which led to a change in the radon flux at the locations of the GDC. The probable region of generation of such pulses is associated with the spatial location of the future source, and the occurrence of deformations in it, similar to the processes of inelastic deformation (creep) [16, 17], indicates the final stage of the earthquake preparation. The rather long times of the anomaly (up to 18 days) and the lead times also indicate that the processes of the final stage of the preparation of this earthquake were extended in time and are probably associated with the creep of rocks.

4. Conclusion
Based on the weekly analysis of data coming from the network of observation points to the Kamchatka branch of the Russian Expert Council on earthquake prediction, assessment seismic hazard and risk, on March 11, 2021, a conclusion on the seismic hazard for the Kamchatka territory was submitted. This conclusion made on the basis of the emanation method described in [8]. According to the conclusion made, during the next week, it was possible that earthquakes with magnitudes greater than those indicated in the corresponding regions marked in figure. 1, or earthquakes with $M>6.5$ in a band limited in latitude 49.5°–56° N and the axis of the deep-sea trough. The forecast made on March 11 was preceded by conclusions on seismic hazard, submitted earlier and also containing forecast estimates. The periods of these forecasts are shown in figure 2 light blue rectangles. All submitted forecasts were based on an expert assessment of the development of the identified anomaly, but the final one, submitted on March 11 and completing the series of forecasts, was additionally substantiated using the "eigenoscopy" method. The earthquake with $M_W=6.6$ that occurred in the region of the Kronotsky Peninsula on March 16, 2021 is considered by the authors as successfully predicted.
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