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From retrospective to real-time system – LURR earthquake prediction on Sakhalin (2019–2022)

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Abstract. The results of an experiment on the implementation of operational analysis of Sakhalin seismicity by the LURR method of medium-term earthquake prediction are presented. Monitoring began in 2022 on the basis of the LURR parameter calculations based on 2019–2021 seismic data. The island territory is divided into 36 calculated areas, which evenly cover it in increments of 0.5 degree in latitude and longitude. Prediction zones for this period are constructed, including those calculated areas in which anomalies of the LURR parameter have been detected. During 2022, information about new anomalies and prediction zones was added quarterly. The main objective of the experiment is to test the work with data in quasi-real time mode and to check the quality of solving the procedural issues related to prediction from the approval stage to the completion one. In the period of 2019–2022, 25 anomalies of the prediction parameter were detected. In the retrospective database (from 2019 to 2021), two prediction zones were identified in 2020 (consisting of 9 and 4 calculation areas, respectively). Two more prediction zones were formed in 2022 (3 and 6 calculation areas). Predictions with the definition of time, place and strength were approved for three prediction zones at the meetings of the Sakhalin Branch of the Russian Expert Council on Emergency Situations (SB REC). During 2022, two out of three predictions were recognized as realized. In the fourth zone, the prediction was realized, but an earthquake with the required parameters has occurred after the definition of the zone within a quarter, i.e. both the prediction zone and its implementation were simultaneously recorded, already

after the fact (data processing is carried out once a quarter). In this case, the forecast is not recognized as either a missed goal or realized in real time (retrospectively, this is a successful forecast), but it is procedurally defined as a technical omission. As of the beginning of 2023, there is one active prediction zone in the north of the island. The experiment continues.

Keywords: seismicity, seismic events, LURR method, earthquakes catalog, anomaly, monitoring

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Introduction

Since 2015, the employees of the Institute of Marine Geology and Geophysics of the FEB RAS (IMGG FEB RAS) have obtained interesting results in the field of medium-term earthquake prediction on Sakhalin using the LURR method (load-unload response ratio). Methods for applying the LURR algorithm have been developed, which are characterized by the versatility in the choice of processing parameters, which provides the possibility of repeating the obtained results and impossibility of their «fitting». Indeed, in the works of Chinese scientists [1] who had first proposed the LURR method, the calculation parameters changed for each prediction (this makes an operational prediction impossible). In the case of our calculations, these parameters have fixed values. Thus, the range of magnitudes in the working sample (from 3.3 to 5.0), the size of the sliding window (360 days) and the shift (30 days), the type and size of the calculation area (circle-ellipse with a radius of 1°) were determined. Very convincing results [2, 3] were obtained for different parts of Sakhalin Island using the above parameters in the LURR calculations. 15 prediction zones (which are the calculated areas with anomalies of the LURR parameter) were identified in Sakhalin for the period from 1997 to 2019 by means of the developed approach in the latest large retrospective study [4], in 11 of which then (within a period not exceeding 2 years) earthquakes occurred with magnitudes >5.0 . 16 earthquakes out of 19 with $M \geq 5.0$ (as it occurred in Sakhalin from 1997 to 2019) fell into the identified prediction zones. The statistics on strong earthquakes (Neftegorsk 1995, Uglegorsk 2000, Nevelsk 2007, Uanga 2010, Onor 2016) is especially convincing in terms of predictions. It is noteworthy, that some predictions were made in real time. The predictions for two earthquakes (Onor 2016, Krylon 2017) were considered at the meetings of the Sakhalin Branch of the Russian Expert Council on Emergency

Situations (SB REC, protocol no. 3 of 11.05.2016 and protocol no. 2 of 16.03.2017). Both predictions were considered realized.

The obtained results showed the readiness of seismologists of IMGG FEB RAS and Sakhalin Branch of the Federal Research Center «United Geophysical Survey of RAS» (SB FRC UGS RAS) to move on to the next stage of the work – detection of anomalies in prediction parameter in real time in the mode of continuous calculation with sufficient discretization. In fact, there are not many examples of this kind of experiment in the open access. One of these in Russian practice is a long-term experiment in real time with the M8 and MSc methods [5]. According to the author [5], the data of the world network were processed every 6 months. The results were published on the internal website of the Institute of Earthquake Prediction Theory and Mathematical Geophysics of the Russian Academy of Sciences. At the same time, even with the relatively modest statistics of target earthquakes (17 earthquakes with magnitudes > 8.0) from 1992 to 2010, there are no data on all earthquakes in the work [5], only examples are given. Judging by the final results of this experiment presented in the «Natural hazards» journal [6], which, in fact, had already been published in Russia two years earlier [5], the Chile (2010) and Tohoku (2011) earthquakes were the last in a chain of successful predictions. The experiment is known to be ongoing.

The LURR real-time earthquake prediction experiment for the Island of Sakhalin was started in 2022. The main objective of the experiment is to test the work with data in a quasi-real-time mode and to check the quality of solving the procedural issues related to prediction from the approval stage to the completion one. This article presents the results of the first year (prediction statistics) and discusses the aspects that will improve the quality of work in subsequent periods of the study.

Experiment methodology

The experiment involves the acquisition and analysis of data in an operational (quarterly update, delay no more than a month from the current time) mode.

The project is primarily focused on the medium-term assessments that the LURR method provides, in fact. According to earlier data [4], more than 85% of cases of successful predictions had a waiting period between 0.5 and 2 years. Rare cases give shorter or longer time frames [4], so quarterly updates should be sufficient to prevent omissions.

The LURR method uses the operational catalog from the database of the «Yuzhno-Sakhalinsk» Regional Data Processing Centre (RDPC) to analyze the seismicity of Sakhalin. Each event is processed by a group of stations to clarify coordinates and magnitudes. After additional data processing, a new catalog is created, which contains the events that meet the criteria of the working sample. The resulting catalog is converted into the format required for calculating the LURR parameter.

The methodology for the LURR parameter calculation, including the principles of calculated areas identifying, detection of anomalies and determination of prediction zones, is fully consistent with those tested in the large-scale seismic survey of Sakhalin in the period of 1997–2019 [4]. Recall that the basis for calculating LURR is the square root of seismic energy (Benioff deformation). The main principles of the methodology are the following: sufficiently dense coverage of the territory by the calculated areas (these are circles with a radius of one degree, which are located at 0.5° ; thus, the island is divided into 36 areas); fixed parameters of mathematical processing (sliding window of 360 days); working sample of earthquakes within the magnitude range from 3.3 to 5); waiting period of 2 years. All these values have been tested by numerous experimental studies and proved to be valid [2–4]. The principles of identifying anomalies have also been determined, in particular, one of the main parameters – is a threshold (equal to 3), when exceeding, the parameter goes into the area of anomalous values.

For the experiment to which this work is devoted, the catalog is updated with new seismic events on a quarterly basis, and the parameter LURR is again calculated in each of the 36 calculated areas with a starting point in 2019.

The choice of 2019 as the starting point of the experiment is based on the fact that the latest calculations for Sakhalin were completed before 2019 [4], and it is a sufficient backstory of 2 years or more in order to have enough accumulated data. If anomalies are detected, they are added into the database and prediction zone is recorded (geometrically it is a set of calculated areas). If there is a simultaneous (with a duration of maximum 6 months) concentration of anomalies in the adjacent areas, the larger prediction zones are formed.

The obtained data for 36 calculated areas are stored on a special service of the SB REC in the form of a demonstration of the identified anomalies and the hazard zones formed by them on Sakhalin Island. When such zones are defined, they are monitored and the reports are submitted to the REC meetings every 3 months during the entire set alarm period (2 years). If a seismic event with a magnitude of $M > 5$ occurs in the prediction zone during the alarm period, the prediction is removed and considered realized. The alarm period ends and monitoring of the zone stops. The experiment has begun in 2022 and is conducted together by IMGG FEB RAS and SB FRC UGS RAS within the framework of the Sakhalin Branch of the Russian Expert Council on Emergency Situations (SB REC).

Results

According to the results of data processing for the period from 2019 to 2022 on the territory of Sakhalin Island and adjacent waters, we identified four zones with medium-term earthquake prediction.

The first information after the catalog data processing from 2019 to 2021 was submitted to the SB REC with a request for medium-term prediction of an earthquake with a magnitude of $M \geq 5.0 (\pm 0.1)$ for two zones: in the northern (9 calculated areas) and the southern (4 calculated areas) parts of Sakhalin Island and adjacent waters or territories (Fig. 1 and 2). Geometrically, prediction zones were determined by the boundaries of the calculated areas that make up the prediction zones: 1) $51.5\text{--}54^\circ \text{ N}$, $141\text{--}144^\circ \text{ E}$; 2) $45\text{--}47.5^\circ \text{ N}$, $141\text{--}144^\circ \text{ E}$.

Taking into account the fact that anomalies in the calculated regions completed in 2021 in both prediction zones (LURR parameter changed to the background level), the alarm period was set un-

til the end of 2023 (protocol no.1 of the SB REC from 25.01.2022). The decision of the Council was as follows: announce prediction of earthquakes with $M \geq 5.0$ for the northern and southern parts of Sakhalin Island (in the given coordinates) and approve their action from February 1, 2022, to December 31, 2023.

Prediction no. 1. The first of the predictions has realized on 05.02.2022 at 21:18:52 UTC (06.02.2022 at 08:18:52 Sakhalin time). 23 km east of the village of Val and 48 km northeast of the village of Goryachiye Kluchi (Nogliksky District) an earthquake with $M_L = 5.3$ occurred. The coordinates of the epicenter are 52.47° N and 143.53° E, depth 22 km. Parameters of the earthquake according to the results of processing by Russian and international seismological centers are given in the Table 1.

The predicted intensity according to the accelerometers in Nogliki and Okha was 4 points, and it was also 4 points according to the questionnaires in Okha, the urban-type settlement of Nogliki, the villages of Tungor, Nekrasovka, Moscalvo, and Val (the survey was carried out among employees of the administrations of villages, schools, communication departments, shops). Over the next two days, there were 20 aftershocks with M_L from 2.1 to 3.6. Information about the epicenter of the earthquake and its aftershocks is presented on the map (Fig. 1).

The earthquake has occurred on the eastern shelf of Northern Sakhalin. Structurally, the shelf is a system of sub-meridional alternating uplifts and depressions. The depressions are almost completely compensated with sedimentation. According to the seismic studies, the following structural elements are identified in the west-east direction: Piltun Depression, Odoptinsk Uplift and East Odoptinsk Uplift. East Sakhalin Trough and its starved part Deryugin Closed Bathyal Depression are located seaward [7]. Odoptinsk and East Odoptinsk uplifts are separated with a very narrow trough. These two structures are combined into a single uplift, which is bounded on the western side by the West Odoptinsk Fault, to which the Piltun Depression adjoins. From the east, this uplift is bounded by the East Sakhalin Fault adjacent to the East Sakhalin Trough [7]. The seismicity of the East Sakhalin fault system is represented by the following earthquakes: at the boundary of the Deryugin Depression ($M = 5.5$) 1944, Okha-Piltun 1932, 1939, 1942 and 1953 ($M = 5.0-5.5$) [8], as well as the June 12, 2005 Mw 5.6 Piltun earthquake.

On the totality of features, the prediction was recognized as realized, and the monitoring of the zone within the specified coordinates was stopped (protocol no. 2 of the SB REC from 15.04.2022).

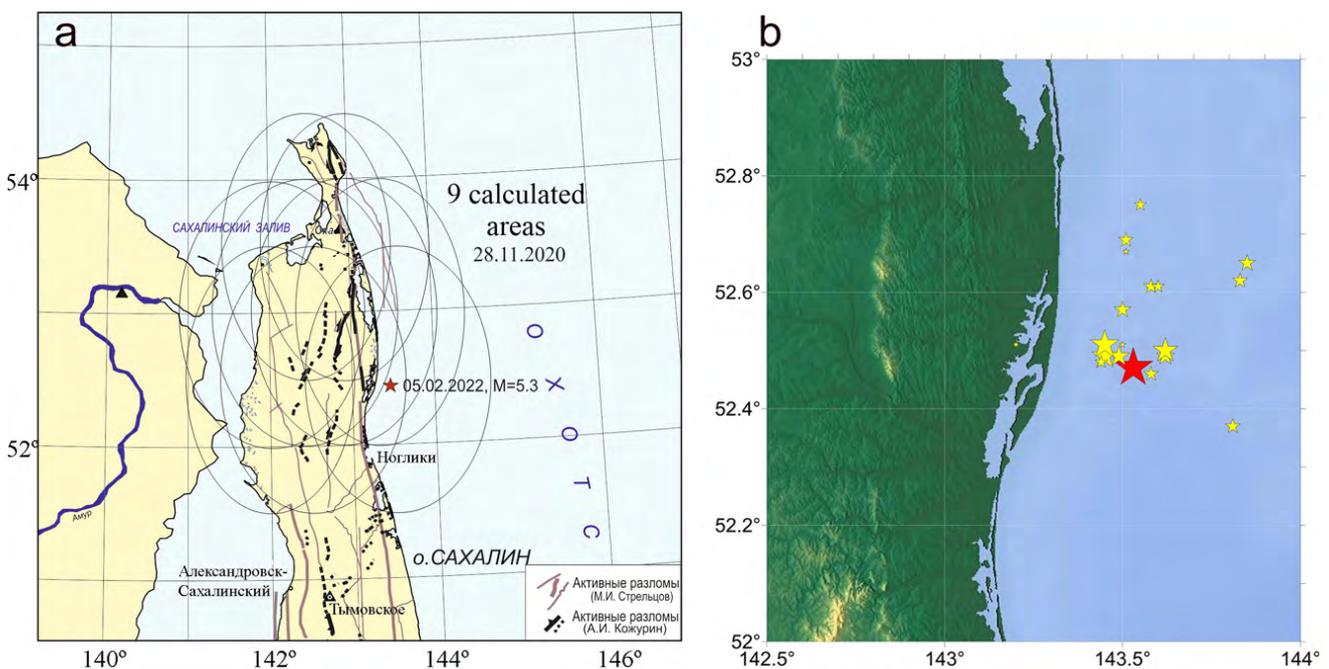


Fig. 1. Map of prediction zone no.1, indicating the date of alarm period beginning, epicenter location (marked with an asterisk) and earthquake date (Sakhalin time) – prediction realization (a) and map of aftershocks of the 05.02.2022 earthquake ($M_L = 5.3$) (b).

Prediction no. 2. By the second prediction in the south of Sakhalin (4 calculated areas with the LURR anomalies, Fig. 2) in August 2022, the data testified to its implementation in the north of Hokkaido Island have been obtained.

An earthquake with $M_L = 5.2$ occurred on August 10, 2022, at 15:52:59 UTC in the northwestmost tip of Hokkaido Island (Japan). The epicenter was located in close proximity to the village of Nakagawa (Kamikawa District, Hokkaido Circuit). The earthquake parameters according to the results of processing of Russian and international seismological centers are given in the Table 2.

By means of various processing software, it was found that the discrepancies in determining the parameters of the hypocenter and energy assessments of the earthquake on August 10, 2022, by different seismological agencies are minimal. The data from the regional network of seismic stations of the Sakhalin Branch of FRC UGS RAS, stations of the Institute of Volcanology and Seismology of Hokkaido University and stations of the FEB RAS were used in determin-

ing the earthquake parameters. As of August 20, 2022, 43 aftershocks with magnitudes from 1.0 to 4.5 were registered by the network of stations (Fig. 2).

According to the identification of the epicenter by various agencies, the earthquake has occurred at the boundary of the prediction zone (Fig. 2) at a latitude of about 45° N. Since there are no calculated areas outside Sakhalin Island below 45° N according to the terms of the experiment, the 10.08.2022 earthquake does not reach the prediction zone and its epicenter is about 13 km away from the zone boundary. Taking into account the fact, that the calculated prediction zone can be continued south of Sakhalin, and the deviation of the epicenter from the zone boundary relative to the linear size of the prediction zone (275 km) is less than 5%, the prediction can be considered realized. But we decided to calculate the parameter LURR in the fifth area, additional to our four, with a center located in 44° N and 142° E (Fig. 3). The catalog we use does not cover the area below 45° N, so the data from the

Table 1. Parameters of the earthquake on February 5, 2022, with the epicenter in the Nogliksky District

Data source	Time in the source, t_0 , h:min:s	Epicenter coordinates		Depth h , km	Magnitude		
		φ° , N	λ° , E		Mw	mb	M_L
“Yuzhno-Sakhalinsk” RDPC	21:18:52.0	52.47	143.53	22	–	–	5.3
AS SB FRC UGS RAS	21:18:52.0	52.61	143.36	20	–	5.7	–
EMSC	21:18:51.8	52.57	143.29	17	5.2	–	–
GEOFON	21:18:52.1	52.55	143.34	15	5.3	–	–
USGS	21:18:52.0	52.59	143.28	10	5.2	–	–

Note. Mw – Kanamori magnitude, mb – body wave magnitude, M_L – local magnitude. “Yuzhno-Sakhalinsk” RDPC – “Yuzhno-Sakhalinsk” Regional Data Processing Centre; AS SB FRC UGS RAS – Alert Service SB FRC, Obninsk, Russia; EMSC – European seismological centre (<http://www.emsc-csem.org/Earthquake/earthquake.php?id=324605>); GEOFON – Helmholtz Centre Potsdam (<http://geofon.gfz-potsdam.de/eqinfo/form.php>); USGS – United States Geological Survey (<https://earthquake.usgs.gov/>).

Table 2. Parameters of the earthquake on August 10, 2022, with the epicenter at the northwestmost tip of Hokkaido Island (Japan)

Data source	Time in the source, t_0 , h:min:s	Epicenter coordinates		Depth h , km	Magnitude		
		φ° , N	λ° , E		Mw	mb	M_L
“Yuzhno-Sakhalinsk” RDPC	15:52:59	44.86	142.04	11	–	–	5.2
AS SB FRC UGS RAS	15:52:59	45.06	142.04	10	–	5.1	–
EMSC	15:52:59	45.03	142.07	10	5.1	–	–
GEOFON	15:53:04	44.98	141.99	42	–	4.9	–
JMA	15:51:00	44.90	142.06	10	–	–	5.1

Note. JMA – Japan Meteorological Agency (<https://www.jma.go.jp/jma/en/menu.html/>). See the Table 1 for other acronyms.

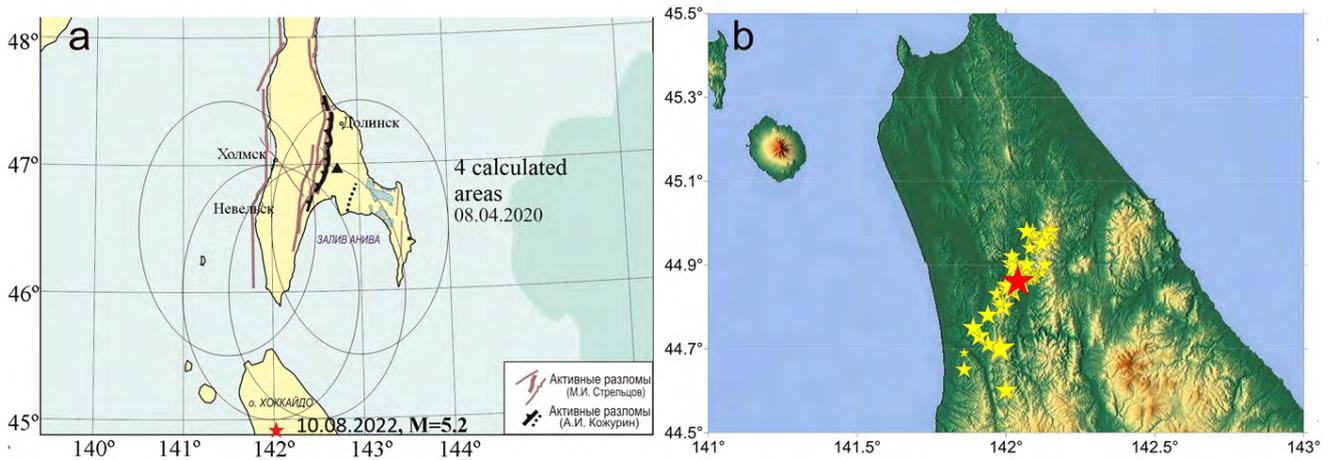


Fig. 2. Map of the zone of the prediction no. 2 with indication of date of the alarm period beginning, epicenter (shown with an asterisk) and the earthquake date (Sakhalin time) – the prediction realization (a) and the map of the aftershocks of the August 10, 2022 ($M_L = 5.2$) earthquake (b).

catalogs of the United States Geological Survey (USGS) (<https://earthquakeusgs.gov/>) have been used for the calculation.

According to the results of the checking calculation from 2016 to 2022, the LURR anomaly is detected in this region in July 2020 (Fig. 3). This indicates the unity of all 5 areas for the formed prediction zone (by 4 Sakhalin areas the anomalies have appeared in April 2020). Thus, the zone initially formed in the southern part of Sakhalin Island in April 2020, then was expanded farther south and covered the northernmost tip of Hokkaido Island. This calculation is a pure check-up, and there will be no increase in the number of calculated areas in the future to cover Hokkaido Island. The reason for this is that the US Geological

Survey catalogs used are not fully applicable for LURR calculations because they contain earthquake information starting at a magnitude of 4.0, but we use a sample starting at $M = 3.3$. But just in this case, the calculation has probative value.

The 10.08.2022 earthquake has probably occurred at the joint of the tectonic structures. On the western side of the epicenter there are the Moneron and the Rebut-Kobato zones, which together extend a little north of Moneron Island. The central part of Hokkaido Island is formed by the formations of the Kamukotan zone and the adjacent Susunay one, which is its northern continuation [8].

This earthquake had a much higher level of macroseismic manifestations than the seismic

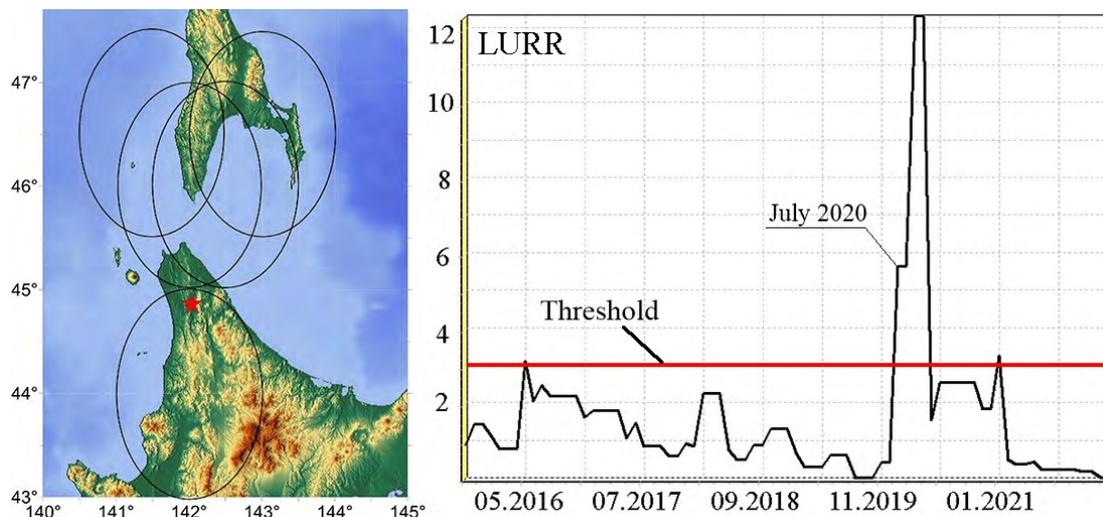


Fig. 3. Additional calculation area on Hokkaido Island (left) and calculation of the LURR parameter here in the period from 2016 to 2022 according to the USGS data.

event of February 5, 2022, due to the significant development of the northern part of Hokkaido Island (compared to the north of Sakhalin Island). According to the Japanese Meteorological Agency (JMA) (<https://www.data.jma.go.jp/svd/eqdb/data/shindo/#20220811005300>), earthquake intensity in the village of Nakagawa scored 5+ on the JMA scale (JMA. Tables explaining the JMA Seismic Intensity Scale, <http://ww.j.jma.go.jp/jma/en/Activities/inttable.html>), which corresponds to 6 [9] on the MSK-64 scale and characterizes strong earthquakes. In other localities of the northern Hokkaido, particularly in Sōya and Rumoi districts, the intensity was 3-4 scores on the JMA scale. On the territory of the Sakhalin Region, due to the significant distance of the nearest settlements from the earthquake source, this seismic event was not felt. According to the instrumental data from the records of the seismic station in Nevelsk closest to the source (200 km from the epicenter), the intensity was 1 point on the MSK-64 scale.

Thus, both prediction zones, from which the project started, were removed from monitoring in 2022 with satisfactory realization performance indicators.

However, the year did not pass without the appearance of new anomalies, which, as a result, formed two new prediction zones (Fig. 4, 5).

Prediction no. 3. Unfortunately, one of the predictions, the third in succession, is qualified

as «technical omission». As already mentioned in the methodological section, quarterly updates should have been sufficient to prevent omissions. However, in the first months of the experiment, such a case has occurred. At the end of January 2022, the anomalies have appeared in three calculated zones (Fig. 4), which were recorded after data processing in April 2022 (with the update of data for the first quarter). Then it was found out that the prediction zone formed of these three calculated areas was «worked out» on February 9, i.e. two weeks after the appearance of anomalies.

The earthquake with $M_L = 5.0$ has occurred on February 8, 2022, at 22:29:00.7 UTC (09.02.2022, 09:29:00.7 Sakhalin time) 21 km southwest of the village of Porechye, Makarovsky District and 32 km northeast of the village of Krasnogorsk (Tomarinsky District). The coordinates of the epicenter are 48.54° N and 142.48° E, depth 13.7 km. Earthquake parameters are given in Table 3.

Earthquake intensity in the Vostochnoye village, Makarovsky District is estimated at 5 points, in the village of Krasnogorsk, Tomarinsky District at 4-5 points, in the city of Makarov at 4 points, in the village of Porechye, Makarovsky District, in the city of Tomari, the Ilyinskoye village, Tomarinsky District, the city of Ulegorsk, the village of Krasnopolye, Ulegorsky District – at 3-4 points, in the urban-type settlement of Shakhtyorsk, Ulegorsky District – at 3 points according to the questionnaires. The calculated

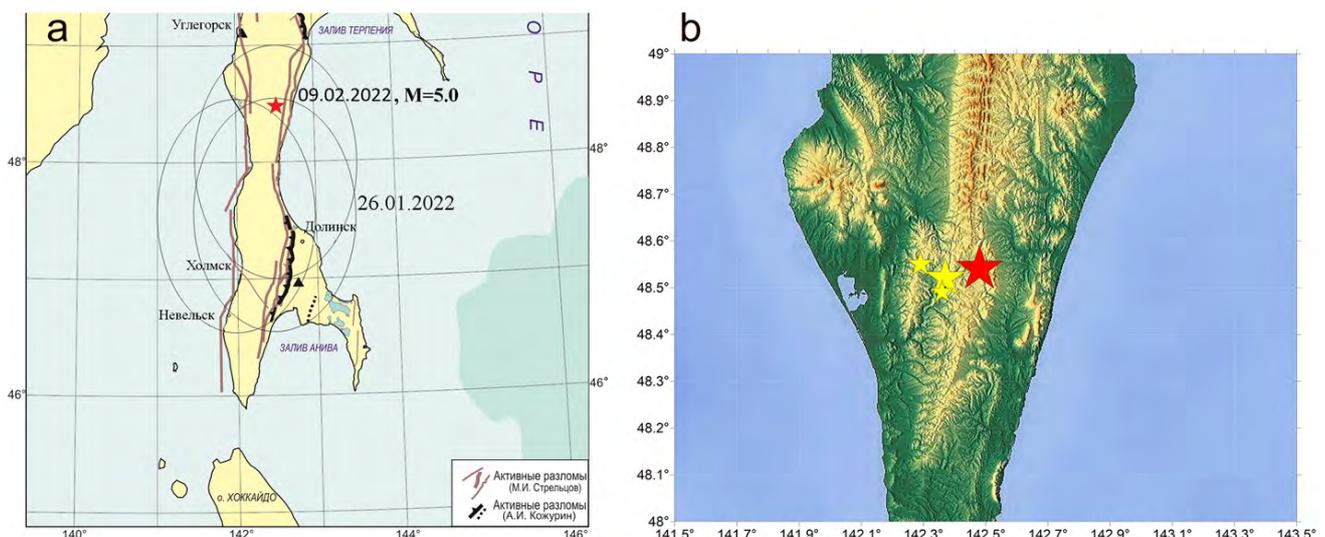


Fig. 4. Map of the zone of the prediction no. 3 with indication of date of the alarm period beginning, epicenter (shown with an asterisk) and the earthquake date (Sakhalin time) – the prediction realization (a) and the map of the aftershocks of the February 9, 2022 ($M_L = 5.0$) earthquake (b).

Table 3. Parameters of the February 8, 2022 earthquake with an epicenter southwest of the village of Porechye, Makarovsky District, Sakhalin Region

Data source	Time in the source, t_0 , h:min:s	Epicenter coordinates		Depth h , km	Magnitude		
		φ° , N	λ° , E		Mw	mb	M_L
“Yuzhno-Sakhalinsk” RDPC	22:29:00.7	48.54	142.48	13.7	–	–	5.0
AS SB FRC UGS RAS	22:29:03.0	48.52	142.42	10	–	5.0	–
EMSC	22:29:02.6	48.52	142.44	10	5.0	–	–
GEOFON	22:29:03.7	48.48	142.47	10	–	4.8	–
USGS	22:29:02.0	48.51	142.37	10	4.9	–	–

Note. See Table 1 for the acronyms.

intensity according to the data of accelerometers was 2.5 points in the city of Uglegorsk, the village of Ilyinskoye – 3.3 points, in the city of Dolinsk – 2.6 points, in the city of Holmsk – 1.5 points; and by the data of velocimeters it was 2.9 points in the city of Uglegorsk, in the village of Krasnopolye – 4.0 points, at the Cape of Hokui, Uglegorsky District – 2.3 points.

The February 8, 2022 earthquake is confined to the areas of intersection of the Central Sakhalin (Tym-Poronai) Fault with diagonal faults of the West Sakhalin one. And although the Central Sakhalin Fault is inferior in seismic activity to the West Sakhalin Fault, such earthquakes as the 1923 $M = 5.2$ Tomarinskoye and the 1957 $M = 4.9$ Leonidovskoye can be noted [10].

Prediction no. 4. The prediction for the fourth zone has been officially approved and is actual as of January 2023. It has been compiled according to the data of 2–4 quarters of 2022. In the first stage, from March to May 2022, the LURR anomaly was singly found in 3 calculated areas in the north of the island (Fig. 5). Then, three months later, the anomalies have recurred in the original three areas, the new ones have first appeared in the neighbouring three new areas. Thus, the prediction zone has been formed from March to August 2022 and is represented by 6 anomalies in 6 calculated areas. SB REC announced the mid-term pre-

dition of a seismic event with a magnitude of $M \geq 5.0 (\pm 0.1)$ (protocol no. 3 from 14.10.2022) till the May 2024 for the northern part of Sakhalin Island within the boundaries of 52.0 to 54.5 N, 141.5 to 144° E, i.e. practically within the same boundaries that the prediction zone no. 1.

The situation when anomalies are detected again in the area, where only less than 2 years ago they have been already detected, is non-trivial. Technically, if the earthquake in February 2022 did not occur (Fig. 1), the prediction in the territory could be prolonged, and, in general, this practice is not new for SB REC when working with other methods (long-term predictions). But it has occurred, and then the prediction is

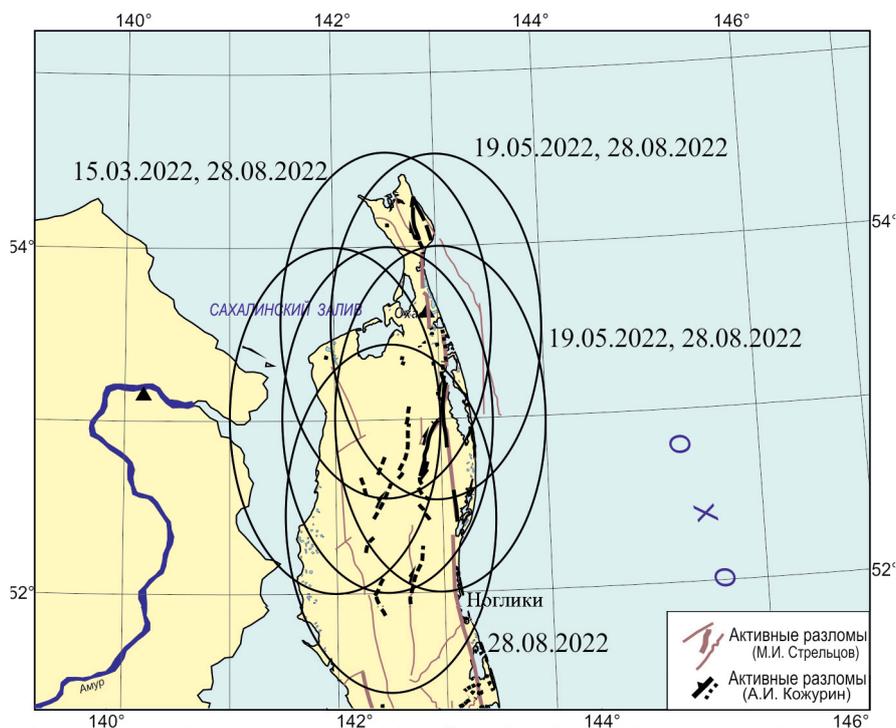


Fig. 5. Map of the zone of the registered prediction no. 4.

removed. Note that the alarm period parameter in the LURR methodology is the most uncertain (we have up to two or three years, and the Chinese scientists have even more). In this case, one prediction was removed, and the other was announced a month later.

We will learn about the consequences of such frequency of anomaly occurrence in the north of Sakhalin in a few years, but now it is interesting to discuss the potential of seismic generating zones that fall in the zone of the current prediction period.

All six calculated areas are located within the East Sakhalin fault zone. The East Sakhalin zone is not homogeneous in structure. In the eastern coastal zone of the northern part of the island, it is represented by the Piltun and Garomai faults. It is assumed [11], that the first fault is characterized primarily by dextral strike-slip displacements and the second fault is characterized by thrust ones. To the west of the Piltun and Garomai faults, the dextral strike-slip Upper Piltun Fault (1995 Neftegorsk seismic rupture) extends with a maximum movement of 8.1 m [12]. It is possible that a similar fault extends south of Neftegorsk in the axial part of the Darginsky Uplift. The fault is quite distinctly distinguished in space images of different resolutions and in topography. Several sub-meridional breaks have been identified to the west of the Upper Piltun and Darginsky faults, but there is no data for them except for the clearness on the space images of medium resolution [11]. The nonrecurrent displacements on the strike-slips, except for the Neftegorsk Fault, were not directly measured anywhere. Data on the Piltun Fault presented in the article [11], are estimative and based on a number of assumptions. The northernmost elements of the zone are the active dextral Kheyton and Longri (less strike-slip) faults of Schmidt Peninsula. The Kheyton Fault, the main of these two, extends north to the coastline and most likely continues underwater into the shelf. The southern continuation of the fault and its possible connection to the Piltun Fault are unclear. It seems that the spatial independence of these two faults is possible.

As it is indicated in [7], instrumental observations tell us only about three significant events in this area (East Sakhalin zone). In addition to the Neftegorsk earthquake, the following events

occurred there: the 1935 $M = 5.6$ Katangli earthquake; the 1964 $M = 5.8$ Nogliki earthquake, and the 1967 $M = 5.5$ North Sakhalin one. As noted in [12], the mismatch with the palaeodata indicates only a small period of observation, and the potential of the zone is much higher, of course.

The most reliable estimates are based on the M_{\max} maximum magnitude. Individual faults generate earthquakes of approximately the same (within half a unit) magnitude close to their M_{\max} known as characteristic earthquakes. The M_{\max} is estimated by the length of the fault or the size of the nonrecurrent movement (with or without displacement). At present, only the length of the Piltun Fault, which is approximately 50 km (including its western branch in the north along the west coast of Torokh), is more or less reliable. The Garomai, Kheyton, and Longri faults can extend over some unknown distance under water, i.e. only minimal estimates of their length are available (~ 21 , 37–40 and ~ 30 km respectively). Based on the above approximate estimates, and using the dependencies from [13], we obtain $M_{w_{\max}} \approx 7.1 (\pm 0.23)$ for $L \sim 50$ km (Piltun Fault). In general, it is possible to accept M_{\max} equal to 7–7.2 for the entire East Sakhalin zone. In view of the above, the prediction, which is currently actual for this zone, can have an upper threshold $M = 7.2$ by the size of the characteristic level.

It is useful to recall the recurrence of characteristic earthquakes in addition to assessing their magnitudes. On the basis of the generalizations by A.I. Kozhurin on the Piltun Fault, the conservative estimate ranges from 700 to 2 600 years, and it is about 5 000 years for the Garomai one. But these are estimates of recent events by several trenches, and, in general, with segmentation and consolidation of segments, the Piltun-Garomai fault system with a length of about 600 km allows estimating the recurrence intervals of about 370 years [12].

Conclusion

Summing up the results of the first year of the experiment on the use of the LURR method for medium-term real-time prediction, we tabulate the information into the final table (Table 4). It demonstrates that the parameters of the declared and realized predictions are mainly the same (including the retrospective prediction on a technical omission).

Table 4. Summary table of predictions for the period of the experiment according to the data of 2019–2022

Prediction, no.	Number of calculated areas	Zone boundaries		Period or date of the prediction zone formation	Document official status	Realization date; magnitude; coordinates	Alarm period prior the realization
		N	E				
1	9	51.5°–54.5°	141.5°–144.5°	28.11.2020	Approved, removed	05.02.2022; $M_L = 5.3$; 52.47° N, 143.53° E	15 mos.
2	4	45°–47.5°	140.5°–144°	08.04.2020	Approved, removed	10.08.2022; $M_L = 5.2$; 45.06° N, 142.04° E	26 mos.
3	3	46.5°–49°	141°–143.5°	26.01.2022	Technical omission	05.02.2022; $M_L = 5$; 48.54° N, 142.48° E	10 days
4	6	51.5°–54.5°	141°–144°	15.03.2022– 28.08.2022	Approved, actual	Not applicable	Not applicable

The target events in our experimental predictions are earthquakes with $M \geq 5.0$. Three such earthquakes have occurred in the experimental zone from January 2019 to December 2022: in the northern part of Sakhalin Island, 23 km east of the village of Val and 48 km northeast of the village of Goryachiye Kluchi (Nogliksky District), south of Sakhalin Island, on the northwestmost tip of Hokkaido Island (Japan) and in the Central Sakhalin, in Makarovskiy District.

These three earthquakes with $M \geq 5.0$ became the realizations for the prediction zones no. 1–3: two in on-line mode and one retrospectively (technical omission).

25 anomalies were detected from 2019 to 2022 by the LURR parameter calculation, which were grouped by time and space into four prediction zones (from 9, 4, 3 and 6 calculated areas). At the meetings of the Sakhalin Branch of the Russian Expert Council on Emergency Situations, the predictions were approved for three zones, for which all the necessary attributes of earthquakes – time, place and energy indicator – were identified. For two registered zones, as well as the zone, where the technical omission is registered, we have a successful prediction realization. The prediction for the fourth zone has been approved in 2022, and it is valid at the time of article publication, the monitoring is going on. We will report on the development of events in this zone in the next publication based on the results of continuous operational analysis of seismicity of Sakhalin Island using the LURR medium-term earthquake prediction method.

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