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On the possible relationship between magnetic storms and earthquakes in certain tectonic conditions (using the example of Sakhalin)*

Aleksander S. Zakupin[@], *Artem I. Kazakov*, *Nikolai S. Stovbun*, *Sergei A. Gulyakov*, *Marina Yu. Andreeva*, *Olga A. Zherdeva*

[@]*E-mail: a.zakupin@imgg.ru*

Institute of Marine Geology and Geophysics, FEB RAS, Yuzhno-Sakhalinsk, Russia

Abstract. The paper considers topical issues of geophysics related to the possible influence of disturbances in the magnetosphere on seismicity. The study was conducted based on a detailed catalog of seismic events in southern Sakhalin for the period from 2003 to 2023. The paper aims to test the assumption that such an influence can manifest itself in individual seismogenic zones during their proximity to discharge. The testing was carried out in randomly selected segments of the West Sakhalin (WSF) and Central Sakhalin (CSF) faults. The coincidence of the moments of some seismic events (with M > 2.7) and magnetic storms with a high index (G1 and higher) was revealed in these segments. The LURR (load-unload response ratio) method was used to identify periods when fault segments were in a subcritical stress-strain state. It was shown that the main part of the coincidences occurred during the periods of increased abnormal activity of the LURR parameter.

Keywords: earthquake, magnetic storm, LURR, correlation, fault segment

О возможной связи между магнитными бурями и землетрясениями в определенных тектонических условиях (на примере о. Сахалин)**

А. С. Закупин[@], *А. И. Казаков*, *Н. С. Стовбун*, *С. А. Гуляков*, *М. Ю. Андреева*, *О. А. Жердева*

[@]*E-mail: a.zakupin@imgg.ru*

Институт морской геологии и геофизики ДВО РАН, Южно-Сахалинск, Россия

Резюме. В работе рассмотрены актуальные вопросы геофизики, связанные с возможным влиянием возмущений в магнитосфере на сейсмичность. Исследование проведено на детальном каталоге сейсмических событий южного Сахалина для периода с 2003 по 2023 г. В работе поставлена задача проверить предположение о том, что такое влияние может проявиться в отдельных сейсмогенных зонах в период их близости к разрядке. Проверка осуществлена в произвольно взятых сегментах Западно-Сахалинского (ЗСР) и Центрально-Сахалинского (ЦСР) разломов. В них выявлены совпадения моментов некоторых сейсмических событий (с $M > 2.7$) и магнитных бурь с высоким индексом (G1 и выше). Для выделения периодов, когда сегменты разломов находятся в субкритическом напряженно-деформированном состоянии, используется метод LURR (load-unload response ratio). Показано, что основная часть совпадений выпала на периоды повышенной аномальной активности параметра LURR.

Ключевые слова: землетрясение, магнитная буря, LURR, корреляция, сегмент разлома

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Introduction

The question of the relationship between the magnetosphere and the Earth's elastic field, changes in which lead to the destruction of the geosphere and movements occurring in the form of seismic vibrations, has always been on the agenda and has not lost its relevance to this day. The result of such studies is mostly determined by the quality and sampling size of seismic events. We shall address the state of this field by analyzing recent publications.

An interesting result was obtained in the study [1]. The authors tested the hypothesis about the existence of a relationship between earthquakes (M = 4–4.9) and solar activity for the period from 2006 to 2012. The earthquake data were taken from the ANNS database (California), and the daily solar activity and magnetospheric data were taken from OMNIWeb (https://omniweb.gsfc.nasa.gov/). The authors constructed generalized autoregressive models with exogenous variables (GARX), with exogenous variables being the parameters reflecting potential triggers of earthquakes (interplanetary magnetic field, Dst index, solar wind speed, sunspot number, and Earth's electric field) to find the relationship. As a result of a mathematical algorithm, the coefficient of determination and the Schwarz criterion were obtained, the parameters of which indicate a relationship between solar activity and earthquakes with magnitude M = 4–4.9. However, the authors note that the results of this algorithm in the processing of earthquakes with magnitude $M > 5$ give the opposite result, i.e., no connection with solar activity.

Guglielmi et al. [2] studied earthquakes all over the planet from 1973 to 2010 with magnitudes $M \geq 5$ based on the data from the catalog of the National Earthquake Information Center of the U.S. Geological Survey (USGS). (We would like to note that we consider the decision to use such old data on earthquakes with small magnitudes unobvious.) A total of 405 earthquakes were analyzed, which occurred within 1 h before and 1 h after 1113 magnetic storms with a sudden commencement (SSC, storm sudden commencement, a sudden increase in the H component of the geomagnetic field that occurs almost simultaneously over the entire Earth). The active phase of the geomagnetic storms themselves was not analyzed in this paper. As a result, an empirical confirmation of the connection between earthquakes and SSC was found, specifically, a decrease in global seismicity after SSC. The authors claim, however, that there is no theoretical interpretation of the relationship between SSC and earthquakes.

In the study [3], the authors searched for the relationship between geomagnetic disturbances (Dst index, absolute value of the field disturbance |ΔX|, and absolute value of the field variability |dX/dt|) and earthquakes for the Alaska region (geomagnetic station "College") in the period from 2014 to 2016. The U.S. Geological Survey catalog of seismic events was used as the basis of the study. Firstly, the statistics of geomagnetic variations before and after earthquakes of different classes – strong ($M > 5$), weak minor ($3 < M < 5$, H < 5 km), weak near-surface ($3 < M < 5$, H = 5–10 km), and weak shallow ($3 < M < 5$, H > 10 km) – were studied, as well as randomly selected earthquakes. Another approach was to study the number of earthquakes of different classes before and after substorm onset. Both approaches did not confirm the hypothesis about the trigger effect of magnetic storms on earthquakes. It was also noted that such an effect can occur only with a combination of unique favorable factors, which are difficult to identify in statistics. Regarding unique factors, it should be added that the article was published in 2020, and the authors simply did not know that in 2021 there would be a megathrust earthquake with $M = 8.2$ in Alaska. Moreover, the trigger seismicity (e.g., from geomagnetic activity), which is of such interest to the authors [3], could occur during the period of unstable development of the seismic process, and according to our data (using the LURR method) obtained in [4], this period has only occurred since August 2019.

In the study [5], a relationship between Dst index and earthquakes with $M \geq 7$ (USGC) was found using a superposed epoch analysis and a Z-test. The result showed a higher number of geomagnetic storms before seismic events than after them, and a stronger correlation with shallow earthquakes was observed. Yet there is no precise explanation for such a phenomenon. This may be due to the special aspects of the manifestation of the inverse piezoelectric effect in the near-surface layer.

The authors [6] claim that they were able to find a correlation between the solar wind and strong earthquakes with $M > 5.6$. The ISC-GEM catalog was used for the earthquakes, and the solar wind data were taken from the SOHO (Solar and Heliospheric Observatory) catalog. During the analysis, it was found that solar activity triggers high-intensity seismic events when structures are critically stressed or when other effects, such as inverse piezoelectric effects, co-occur.

In the paper [7], the strongest magnetic storms (Kp > 7, Ap index) and all 935 earthquakes ($M \geq 6.5$) in the world in the period from 1994 to 2017 (USGS) were compared. Out of the 49 strongest storms during this period, 17 cases were identified in which seismic events occurred at the same time as the storm or the following day. Of these, 14 occurred near Japan and in the southwest Pacific, but were almost absent in continental Asia, North America, and South America. The authors suggest that this may be related to the less stable lithosphere of the eastern hemisphere.

Another study [8] confirms the absence of a correlation between solar activity (Dst index) and global seismicity ($M \geq 4$) from 1996 to 2016 (USGS). Having found no correlation over a longer period, the authors [8] analyzed shallow earthquakes ($M \geq 4$, H ≤ 70 km) and Dst index level separately for 2004, where no correlation was also found. On the other hand, a sample of seismically active periods in different local zones (southeastern Indonesia, Taiwan, eastern Japan, southern Alaska, western Mexico, and western Chile) shows a drastic change in the Dst index level in periods of increased earthquakes. The biggest change was recorded in Indonesia during the period of seismic activity on November 9–13, 2004: the Dst index level fell to –373 μT. The weakest change (–124 μT) was found during the sudden increase in the number of earthquakes on September 8, 2007, in Mexico.

Thus, numerous examples from the literature indicate the absence of correlation rather than its presence. However, we can also see that the considered studies have different sampling approaches, and the comparison of the results will not necessarily provide an objective evaluation. There is a general tendency towards globalization (covering a longer period and larger regions), but it should be taken into account that the paradigm “the larger the sample of earthquakes, the more significant the statistics” may not work here. It is obvious that magnetic storms can act as triggers for earthquakes but in no way generate them. Most publications only statistically analyze the relationship between geomagnetic activity and seismic events, while the mechanism of impact remains unresolved.

The authors [9, 10] presented a theoretical model and calculations of electric field disturbance, electric current, and heat generation in the lithosphere. It was found that the density of telluric currents generated by solar flares is comparable to the current density from artificial sources (MHD generator “Pamir-2,” ERGU-600) [11], which impacted the seismicity of the Pamir Mountains and Northern Tian Shan [12]. It was also noted that the trigger effect depends not only on the stress-strain state of the earthquake formation area but also on the time of growth of the flare front as well as the level of conductivity in the lithosphere layer. To confirm such an idea (of the trigger effect on seismicity) in the case of solar flares, a statistical analysis of global (USGS catalog, $M \geq 4$) and regional (Greece, EMCS catalog, $M \geq 3$) seismicity during the X9.3 solar flare on September 6, 2017, was performed [13]. The number of earthquakes (±10 days from the solar flare) increased relative to the baseline by 68 % for global seismicity and by 120 % for regional seismicity. An important question about the state of the geosphere and the degree of its preparation for effective interaction with an external source for the dissipation of previously accumulated energy arises. It was shown in the study [14] that in the interaction of electromagnetic and elastic fields, trigger effects in rocks are only possible in the region of inelastic deformation at levels of about 85 % and higher of the maximum level of resistance to the applied load. In the same range (beyond the point of proportionality), the trigger response of the medium to an external impact is assumed for the scale of the Earth's crust in general. For example, such an approach is implemented in the method of identifying areas with near-critical stress state and intermediate-term LURR earthquake prediction. Moreover, the hypothesis about the zones that are in the subcritical stress-strain state and sensitive to the influence of geomagnetic field pulsations has already been expressed earlier and partially confirmed in the study [15]. This study shows the response of seismicity in the aftershock zones of strong earthquakes, where subcritical stress zones constantly appear due to the rearrangement of the stress-strain state of the crust after the main shock.

At different scales (planetary or regional), a single sample may contain earthquakes that occur simultaneously but in different zones: in relaxing zones (with significant aftershock activity), neutral zones (moderate seismicity in foci at the stage of stress accumulation), and, finally, in focal zones that are in an unstable state (near-critical stress levels). In a single sample, the presence of all these different stages of earthquakes is possible, but only in an evolutionary form when one state replaces another, and this requires working in separate seismogenic zones. However, a problem is that it is not always easy to perfectly isolate such zones geometrically. It is also impossible to tell whether a focal zone is completely independent. Fault zones can be not only extended up to hundreds of kilometers but can also be physically in contact with other faults along their length. Yet there are areas with the largest number of earthquakes on seismic activity maps ("dark" spots), so they can be considered "almost" independent focal areas. In our recent paper [16], we conducted a study within such a separate seismogenic zone. It was found that in one of the segments of the Aprelovsky fault (south of Sakhalin Island), all earthquakes (two out of two) with $M > 3$ in almost three months (from July to October 2023) occurred during periods of magnetic storms of G1 and above or after X-class flares. In total, geomagnetic disturbances only occurred on 9 days out of 80, and it is clear that the statistics here are definitely in favor of the existence of a connection. Moreover, in the study [17], we also showed how the formation of one of these two earthquakes is manifested in the changes in the electrotelluric potentials. Therefore, it is of interest to identify possible connections between geomagnetic activity and earthquakes under certain conditions. To this end, it is proposed, among other things, to use methods for identifying time periods in which the focal zone could be in a state sensitive to external influences.

Methods

The LURR method is proposed as a basis for evaluating the stress-strain state in the seismogenic zone. The LURR (Load/Unload Response Ratio) method was developed by Chinese seismologists in the 1990s [18]. The method is based on consistent models of the theory of elasticity (model of an absolutely rigid Earth) and fracture mechanics (Mohr–Coulomb criterion). The key point is that beyond the elastic deformation of the medium, the load response does not correspond to the unload response (and the relative response ratio becomes different from one). With time, this discrepancy only intensifies up to the loss of stability of the collapsing object. The method suggests solving the elasticity theory equations to determine the components of the stress tensor at the site where the slip vector is located. Calculations are performed for each earthquake in the catalog. The displacements from tidal influence at a given point (the earthquake epicenter) are calculated. The use of lunar-solar tides in the method is justified by the fact that it is impossible to find another such perfect calibrated load/unload indicator in the geoenvironment. Tectonic and lithostatic components are not taken into account because their rates of change differ significantly from the tidal ones. To divide earthquakes into "loading" and "unloading" earthquakes, the Mohr–Coulomb criterion is calculated. The earthquake occurring during the increasing value of this criterion is defined as "positive," otherwise "negative". The studied parameter (LURR) is identified with the ratio of the total Benioff strain of all positive earthquakes to the same parameter of negative earthquakes for a certain period of time (in mathematical processing, it is the sliding window value). In elastic-plastic media, before fracture, a phenomenon of fluidity is observed when, under constant stresses, the strain continues to grow. Clearly, in such circumstances, the calculation of the ratio of the load response to the unload response makes no sense (there is no response as such), and mathematically, the LURR parameter again becomes close to one. In the area of transition from elastic to inelastic deformation, this parameter starts to grow and reaches its maximum values near the fracture of the medium. That is why in the medium where brittle fracture is realized, the main (predicted) event can be expected after the curve reaches its maximum values, and in the medium where plastic effects are possible, the parameter returns to the background level and some delay (time lag from the moment of determination of the predicted feature, LURR variation) in time occurs. It is obvious that this delay depends on geologic conditions. The LURR method is described in great detail in the original papers [18], so we have limited ourselves to a qualitative description. It should be noted that our studies allow us to positively evaluate the possibilities of this method (refer, for example, to the review [19]).

Before studying the relationships in separate seismogenic zones (which is the main goal of this paper), we present a general analysis of seismicity for southern Sakhalin in comparison with geomagnetic activity. Recognizing that in this case the seismogenic zones of the two main lineaments (West Sakhalin fault (WSF) and Central Sakhalin fault (CSF)) will be in the same sample, we will not search for relationships with geomagnetic activity for specific earthquakes. It would be appropriate here to simply note characteristic points in the change in the series and to identify (if any) trends. Geomagnetic activity in space will be constant for any seismic sample, and we will estimate it by the intensity (Kp index). The geomagnetic index (Kp) is provided on the website of the Laboratory of solar astronomy of the Space Research Institute of the Russian Academy of Sciences and the Institute of Solar-Terrestrial Physics of the Siberian Branch of the Russian Academy of Sciences (https://xras.ru/magnetic_storms.html). The histograms given there contain information on the dynamics of changes in the planetary Kp index. Based on this index, the G scale of the geomagnetic storm intensity is also calculated.

To study separate seismogenic zones, we used the areas of the WSF and CSF as objects, which are depicted as rectangles on the fault map in Fig. 1. The study was carried out in the following order: First, a curve characterizing the periods of instability was constructed using the LURR method, and then the correlation of significant levels of the Kp index with earthquakes in time was checked. We considered it evidence of a connection if the earthquake occurred at the time of the storm or a day later. One day is a conventional period for the expected trigger effect (which should manifest itself in the shortest time possible). We chose this period, despite the probability of a delay from several days to several weeks (as estimated by various authors), primarily because these delays are only a product of statistics in certain studies and have no confirmed physical mechanisms behind them. In the LURR method, which, however, has not escaped criticism [21], a direct transition is used (all within the scope of mechanical phenomena), and the evaluation of the trigger effect from the tidal factor is made de facto at the moment of displacement, which, at least, does not make our choice completely unreasonable.

Now, to the question of sampling, i.e., earthquakes with which characteristics should be taken into account. It would be logical to select earthquakes with minimum magnitude according to the level of representativeness of the catalog (to improve statistics), but it only reflects the network capabilities. We would like to have a physical justification for the choice of threshold. If we assume that the influence of storms is only significant at the stage of unstable focus (with a high level of internal energy), we can also follow the analogy with the LURR methodology, where the parameter correlated well with the formation of strong earthquakes ($M > 5$). Applying this method, we used moderate seismicity with $M = 3.3$–5 for calculations, and in most cases the lowering of the threshold to $M = 3$ did not worsen the result. Therefore, there are several possible options for the evaluation of storms and earthquakes, and the

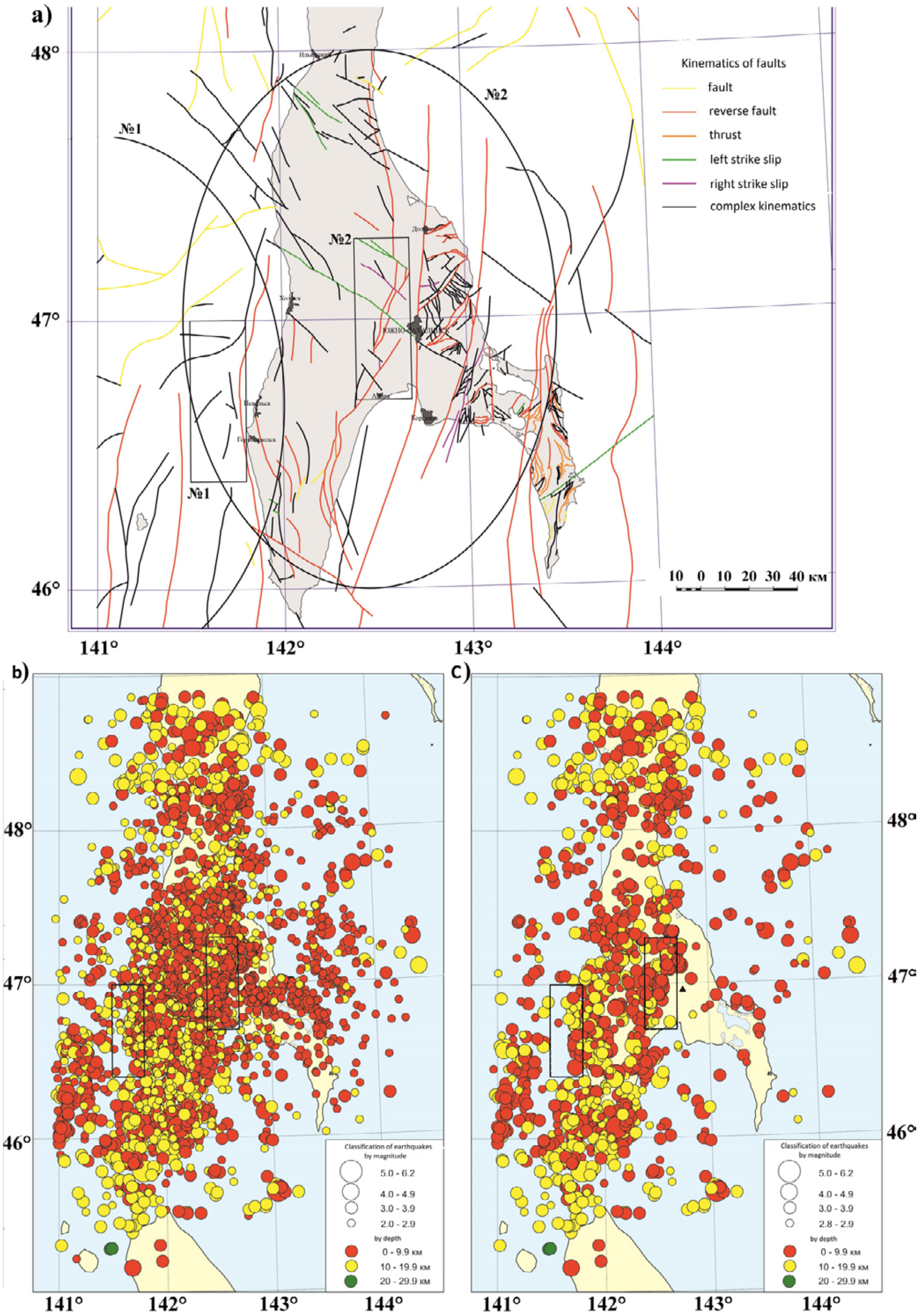

Fig. 1. a) Map of faults according to [20] indicating study zones (No. 1, segment of the WSF; No. 2, Aprelovsky fault of the CSF); circles (one partially) indicate LURR calculation areas in accordance with the zone index; b), c) earthquakes in the south of Sakhalin from 2003 to 2023 from the full catalog (b), with $M > 2.7$) (c). Rectangles indicate study zones. Zone coordinates (corners of rectangles): No. 1, 46.7N, 142.4E – 47.3N, 142.7E; No. 2, 46.4N, 141.5E – 47N, 141.8E.

lower threshold can be taken with a margin (several options with $M < 3$). In the study we considered five options, where the samples included earthquakes with magnitudes $M \geq 2.7/2.8/2.9/3/3.1$.

To analyze the correlations between seismicity and geomagnetic activity, we used the catalog of earthquakes in the south of Sakhalin from 2003 to 2023, which is compiled at the Institute of Geology and Geophysics of the Far Eastern Branch of the Russian Academy of Sciences on the basis of the official annual collections of the Geophysical Survey of the Russian Academy of Sciences. In this study, we also declustered the catalog using the program described in the paper [22]. The local intensity ratio (LIR) method [23] is incorporated in the program algorithm. In the declustered catalog, 6179 events remained out of 10 771 events.

Results and discussion

It is of interest to plot seismic activity graphs for the entire period for the entire sample, i.e., for all of southern Sakhalin, and then compare it with the activity graph of the geomagnetic Kp index. Over a twenty-year period, there were at least two 11-year maximums of solar activity and, of course, seismicity activation (there were 4 earthquakes with $M > 5$ on southern Sakhalin from 2003 to 2023). The seismic activity graphs were plotted for the original and declustered catalogs.

The seismic activity tends to increase after the geomagnetic activity peaks on a decreasing trend. The strongest seismic event for this period (the Nevelsk earthquake of August 2, 2007, $M = 6.2$) occurred after the strongest activation of the magnetosphere in 2004–2005, when 138 magnetic storms were recorded in two years (during this period there was a peak of 11-year solar activity). It should be noted that the declustering program deforms the activity of 2007–2008, and it is better to draw conclusions from the original catalog. The observed increase in the average background activity since 2011 can be explained by the fact that since 2011 the seismic network became fully digital and the number of stations increased, which led to an increase in the number of minor events in the catalog. Overall, the graphs in Fig. 2 do not explicitly reveal the presence or absence of a relationship between earthquakes and magnetic storms.

Now for the samples for separate zones No. 1 (WSF segment) and No. 2 (Aprelovsky fault). We are particularly interested in the periods when the LURR parameter is in the abnormal range (> 3). To draw LURR graphs, the samples within the zones outlined by rectangles are insufficient, and the calculation was carried out in circular areas with a radius of one degree (Fig. 1a). The circle in the WSF area is off-set to the west of the WSF to avoid the influence of the CSF, whereas there are no off-setting options for the second circle, so the influence of the WSF is likely to be observed anyway. The graphs are shown in Fig. 3.

Now we calculate coincidences of times of earthquakes with the moments of the strongest magnetic storms (the moment of the storm and the day after). The results are presented for five sam-

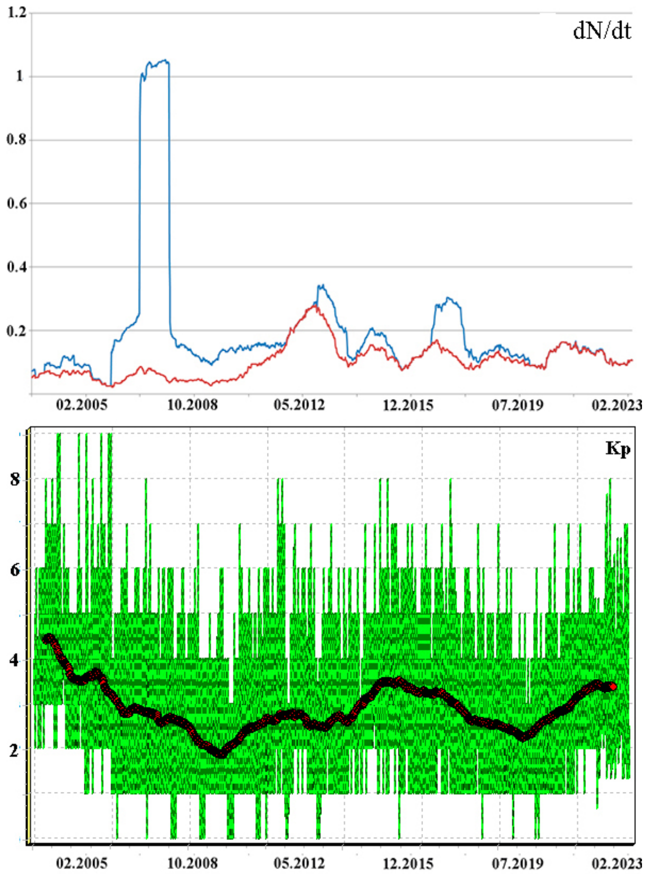

Fig. 2. Time distribution (mm.yyyy) of the accumulation rate of the number of earthquakes N (seismic activity, dN/dt) (blue line denotes original catalogue, red line denotes declustered catalogue) and geomagnetic index Kp in the period from 2003 to 2023.

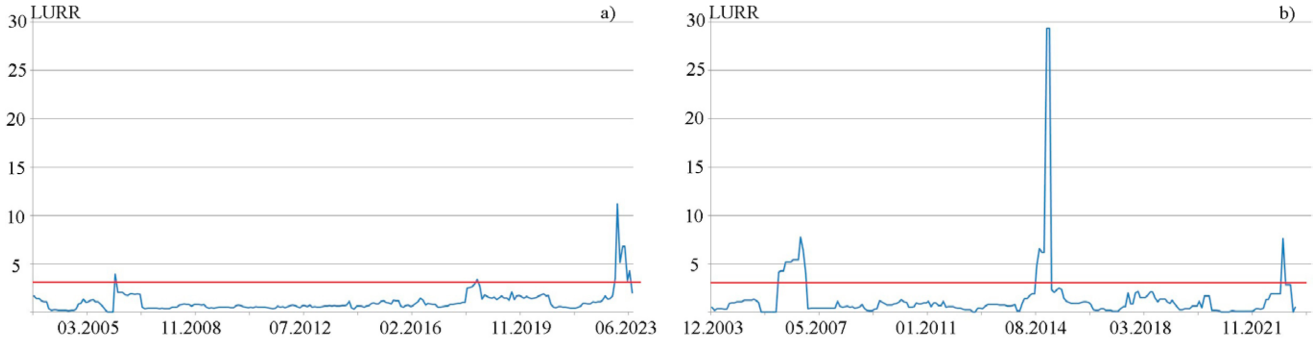

Fig. 3. Graphs of LURR parameter changes in circular calculation areas with a radius of one degree and coordinates: (a) 47E, 142.5N (for zone No. 2); (b) 46.7E, 141N (for zone No. 1). The red line indicates the anomaly cutoff threshold equal to 3.

ples of earthquakes (see the table). There were no earthquakes in 2003 in both samples.

The most important events over the entire study period should be highlighted. Thus, the geomagnetic activity maxima in terms of the number of extreme storms are observed in 2004–2006, 2015–2017, and will probably be expected in 2026–2028, which reflects the 11-year cycle of solar activity (see the table). Anomalies of the LURR parameter in the Aprelovsky fault region were observed in June 2023 (Fig. 4a), while in the WSF region in May 2007, July 2015, and June 2023 (Fig. 4b). We shall note the coincidence of the anomalies for the two lineaments in 2023 and will return to this later. For the WSF, the LURR anomalies in 2007 and in 2015 are forerunners of important seismic events: the Nevelsk earthquake, August 2, 2007, M = 6.2; the Onor earthquake, August 16, 2016, M = 5.8; and the Krilyon earthquake, April 23, 2017, M = 5. While the former occurred directly in the selected area, the Onor and Krilyon earthquakes were north and south within this lineament, and the 2015–2016 anomalies were observed throughout the entire area of the WSF across Sakhalin [19]. Despite the large number of earthquakes in 2007 (see the table), all of them occurred after August 2 and did not coincide with the anomaly in May. The coincidences of 2006 and 2007 in zone No. 1 occurred in the active phase of the aftershock activity after the Gornozavodsk (August 17, 2006, M = 5.6) and Nevelsk earthquakes. The other coincidences from the table occurred in 2013–2015, as well as once in 2020. The coincidences were observed mainly for earthquakes of small magnitude, and while for M > 2.7 there were nine of them in 20 years, for M > 3.1 their number is almost four times less. Therefore, in 2006–2007, a small number of coincidences with high seismic activity (including aftershocks) still occurred during the LURR anoma-

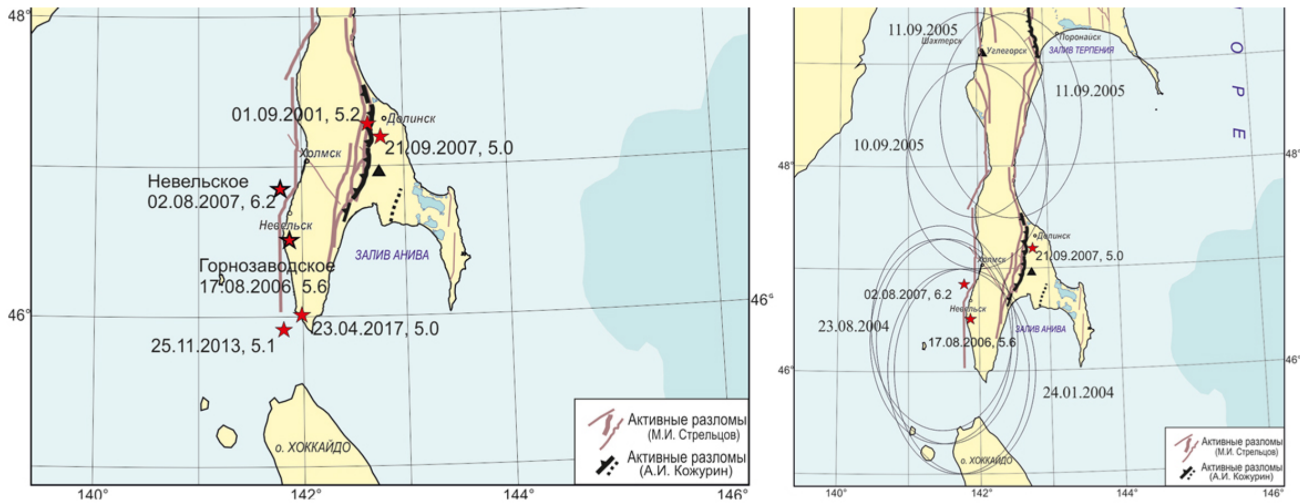

Fig. 4. a) Map of the strongest earthquakes in the south of Sakhalin from 1997 to 2019; b) map with anomalous LURR areas in the south of Sakhalin from 2004 to 2005.

Table. The ratio of the number of earthquakes (numerator) coinciding in time with the moments of magnetic storms (denominator)

Year	G1 storms and higher	$M > 2.7$	$M > 2.8$	$M > 2.9$	$M > 3$	$M > 3.1$
Zone 1						
2004	63	3 / 0	2 / 0	2 / 0	1 / 0	1 / 0
2005	75	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0
2006	43	5 / 1	4 / 0	1 / 0	1 / 0	1 / 0
2007	35	337 / 3	282 / 3	247 / 3	198 / 2	173 / 0
2008	23	25 / 0	20 / 0	18 / 0	14 / 0	12 / 0
2009	4	10 / 0	7 / 0	6 / 0	4 / 0	3 / 0
2010	20	15 / 0	13 / 0	11 / 0	6 / 0	6 / 0
2011	31	2 / 0	1 / 0	1 / 0	0 / 0	0 / 0
2012	36	7 / 0	5 / 0	3 / 0	2 / 0	1 / 0
2013	24	11 / 2	6 / 2	3 / 1	2 / 1	2 / 1
2014	27	3 / 1	2 / 0	1 / 0	1 / 0	1 / 0
2015	81	4 / 1	4 / 1	3 / 1	3 / 1	1 / 0
2016	67	1 / 0	1 / 0	1 / 0	0 / 0	0 / 0
2017	66	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0
2018	26	11 / 0	10 / 0	6 / 0	4 / 0	3 / 0
2019	18	3 / 0	2 / 0	2 / 0	2 / 0	0 / 0
2020	12	3 / 1	2 / 1	2 / 1	2 / 1	2 / 1
2021	30	5 / 0	4 / 0	2 / 0	1 / 0	1 / 0
2022	61	3 / 0	2 / 0	2 / 0	2 / 0	1 / 0
2023	45	1 / 0	0 / 0	0 / 0	0 / 0	0 / 0
Total		449 / 9	367 / 7	311 / 6	243 / 5	208 / 2
Zone 2						
2004	63	5 / 2	4 / 2	3 / 2	3 / 2	3 / 2
2005	75	2 / 1	2 / 1	1 / 1	1 / 1	1 / 1
2006	43	23 / 0	21 / 0	17 / 0	16 / 0	13 / 0
2007	35	13 / 3	11 / 3	9 / 1	4 / 0	2 / 0
2008	23	10 / 4	10 / 4	10 / 4	8 / 2	7 / 2
2009	4	2 / 0	2 / 0	2 / 0	1 / 0	1 / 0
2010	20	4 / 0	3 / 0	1 / 0	1 / 0	1 / 0
2011	31	4 / 0	4 / 0	3 / 0	2 / 0	2 / 0
2012	36	4 / 0	4 / 0	3 / 0	2 / 0	1 / 0
2013	24	23 / 5	18 / 4	14 / 4	13 / 4	12 / 4
2014	27	5 / 0	5 / 0	4 / 0	4 / 0	1 / 0
2015	81	4 / 0	4 / 0	3 / 0	2 / 0	2 / 0
2016	67	3 / 0	3 / 0	2 / 0	1 / 0	1 / 0
2017	66	5 / 0	5 / 0	4 / 0	3 / 0	3 / 0
2018	26	4 / 0	4 / 0	2 / 0	2 / 0	2 / 0
2019	18	5 / 0	5 / 0	4 / 0	3 / 0	3 / 0
2020	12	5 / 0	4 / 0	4 / 0	3 / 0	2 / 0
2021	30	4 / 0	3 / 0	2 / 0	2 / 0	1 / 0
2022	61	3 / 1	1 / 0	0 / 0	0 / 0	0 / 0
2023	45	5 / 3	5 / 3	3 / 2	2 / 2	1 / 1
Total		137 / 21	121 / 19	93 / 16	74 / 12	60 / 11

Note. Years when earthquakes coincided in time with the moments of magnetic storms are highlighted.

lous period for the selected fragment of the WSF (Fig. 4). The largest percentage of coincidences for zone No. 1 is observed in 2013–2015, and this coincides not only with the maximum of solar activity but also with the strongest LURR anomaly (Fig. 4).

The seismic activity of the selected area No. 2 is three times less than in the WSF area. There is a high percentage of coincidences in 2003–2005, and in most cases these are events with magnitude $M > 3.1$. There is also a high percentage of coincidences in 2022 and 2023, but the magnitude of the coinciding earthquakes is lower. In 2007 and 2008, the percentage of coincidences is much lower due to the increased seismicity after the Nevelsk earthquake and probably due to the redistribution of the load in the CSF structures, which includes the Aprelovsky fault. Coincidences in 2013 are mainly caused by high seismic activity, and we should primarily note the swarm of earthquakes from May 15 to 25 (this period included the storm of May 18), during which there were nine earthquakes with M = 2.8–3.9 alone. This is almost half of the number given in the table. As a matter of fact, the declustering programs, if they do not remove earthquakes in swarms completely, corrupt the catalogs with them very strongly, which is why we used the original catalog to search for coincidences instead of the seismic activity graphs, where both variants were present (Fig. 2). From 2013 to 2022, there were no coincidences at all, while for 2022–2023, there were 4 out of 8, or 50 %. The only anomaly of the LURR parameter in zone No. 2 was observed in 2023, which is interesting from the point of view of the considered problem of selective sensitivity of the medium to external influences. The question arises as to the absence of anomalies in 2003–2005 on the LURR graph (Fig. 3), since the percentage of coincidences in these years is the same (see the table). The probable answer is given in Fig. 4, which shows the maps from the study [19]. Anomalies in circular areas in 2004–2005 seem to bypass the Aprelovsky fault. However, the zone apparently had a certain energy reserve. This explains the fact that after the unloading of the West Sakhalin Fault segment near Nevelsk in 2006 and 2007, the Aprelovsky fault generated a strong earthquake with $M = 5$ almost immediately after the load redistribution in September 2007. The WSF and CSF are located at a short distance, and many processes occur in the same way, although sometimes in a different order. For example, the Takoye swarm in 2001 in the Aprelovsky fault region occurred a year after the Uglegorsk earthquake in 2000 (CSF), whereas after the Nevelsk earthquake (CSF), an earthquake with $M = 5$ occured a month later in the same region (Aprelovsky fault). The opposite was observed in 2013: the swarm in May 2013 in the Aprelovsky fault region preceded the earthquake in the WSF in November 2013 (Fig. 4a).

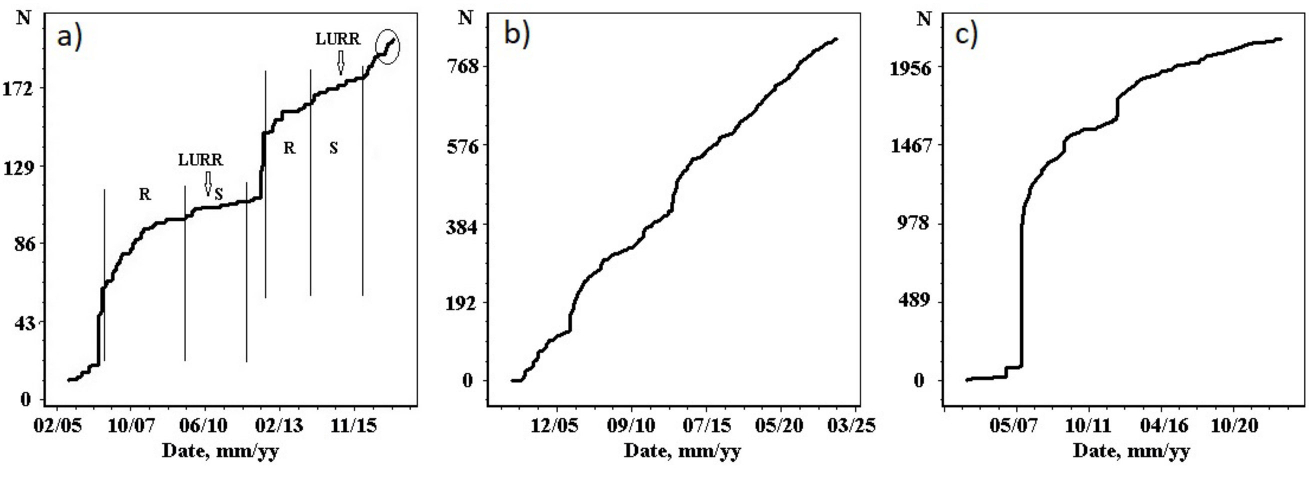

Fig. 5. Period accumulation curves (N, number of seismic events) for the epicentral area of the Krilyon earthquake from 2005 to 2017 (a), for segments of the CSF (Aprelovsky fault) (b) and WSF (c) from 2003 to 2023. R, attenuation process of seismic activity (relaxation); S, process of stationary activity; arrow indicates anomaly of the LURR parameter.

The coincidence of LURR anomalies for the two lineaments in the middle of 2023 is quite unusual and first such case during the study period. This raises the question of the likely consequences for the seismic process in southern Sakhalin as a result of such manifestations.

Important events in the seismic process are also well represented in the period accumulation curves (activity analog). The most typical example is the graph for Cape Krilyon, where the WSF and CSF not only are maximally close but also share a common intersecting lateral fault (Fig. 5a). In this area, strong earthquakes occurred in 2006 and 2013 (Fig. 4a), and the graph accurately reflects the stages of focal development: stationary mode of earthquake accumulation, main event, and relaxation.

It can also be seen here that the curve goes from accumulation to growth before the Krillyon earthquake in 2017. But this is an illustrative example to which everything fits well, including the moments of LURR anomalies. The graph for the selected Aprelovsky fault zone (see Fig. 1) is shown in Figure 5b, and the stages are less pronounced here due to the absence of strong earthquakes. However, they are present in September 2006 and May 2013, which indicates the coordinated involvement of both lineaments in a single process. Moreover, in the first case there was a reaction to the Gornozavodsk earthquake, and in the second case in 2013, the swarm occurred six months before the earthquake of 2013 in the La Perouse Strait in the WSF (Fig. 4a). Since 2014, the accumulation is present here, which is unusual because the Aprelovsky fault "operates" predominantly in swarms (September 2001, Takoye swarm; September 2006; May 2013) with moderate magnitudes on a relatively regular basis. The only relatively large magnitude event ($M = 5$) that was not part of a swarm occurred in September 2007, just one month after the Nevelsk earthquake. It should be noted that the Nevelsk earthquake in southern Sakhalin is the strongest earthquake in the last fifty years. And this is by the most conservative measures, because the Moneron earthquake (September 6, 1971, $M = 7.5$), which is geographically not far from Sakhalin, does not belong to the WSF structures. Thus, it is not surprising that the earthquake of 2007 had an effect on the structures adjacent to the West Sakhalin fault. The selected segment of the WSF is currently in the accumulation stage (Fig. 5c). The main events in the WSF in 2007 and 2013 are also identified here. According to the graphs (Fig. 5), the earthquake in April 2017 (Krilyon earthquake, $M = 5$), the epicenter of which was located on the sub-latitudinal intersecting fault between the WSF and the CSF, did not impact the considered segments and its effect was highly localized. This allows us to assume that the release of seismogenerating zones on both faults in 2024–2025 is highly probable.

Conclusion

The present study is valid for a relatively small seismically active area. In randomly selected segments of the West Sakhalin and Central Sakhalin faults in 2003–2023, the coincidences of the moments of separate seismic events (with $M > 2.7$) and magnetic storms with high index (G1 and higher) are observed.

Most of the coincidences occur during periods of increased anomalous activity of the LURR parameter and precede strong earthquakes. Thus, the coincidences of events in certain time periods, which are significant for both processes (geomagnetic and seismic), are observed. Even in the most favorable condition for the coincidence, when the number of days with storms reaches a quarter of the days in the year, the probability of each earthquake to coincide with them is very low. This probability is even closer to zero for the Aprelovsky fault region (zone No. 2) in 2023, when a storm occurred every 10th day and there were only five earthquakes in the sample. However, in 2023, we obtained the most striking result that excludes the behavior of both parameters as independent, and, apparently, we should return to this issue in a year or two.

One of the results of the study is also considered to be obtaining an unfavorable prediction of an earthquake with a magnitude greater than 5 for the CSF–WSF pair in the southern part of Sakhalin Island for 2024–2025 (the magnitude can be significantly higher for the WSF).

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About the Authors

Institute of Marine Geology and Geophysics, FEB RAS, Yuzhno-Sakhalinsk, Russia, Seismology laboratory:

Zakupin, Alexander S. (https://orcid.org/0000-0003-0593-6417), Cand. Sci. (Physics and Mathematics), Leading Researcher, a.zakupin@imgg.ru

Andreeva, Marina Yu. (https://orcid.org/0000-0002-7851-3311), Cand. Sci. (Physics and Mathematics), Senior Researcher, andreeva-mu@mail.ru

Zherdeva, Olga A. (https://orcid.org/0000-0003-4814-0865), Senior Engineer, o.zherdeva@imgg.ru

Institute of Marine Geology and Geophysics, FEB RAS, Yuzhno-Sakhalinsk, Russia, Department for research of geophysical fields and physical properties of geomaterials at the Center for collective use:

Kazakov, Artem I. (https://orcid.org/0000-0002-1378-185X), Leading Engineer, legn@inbox.ru

Stovbun, Nikolai S. (https://orcid.org/0009-0004-1927-798X), Junior Researcher, nikolay19972016@gmail.com

Gulyakov, Sergei A. (https://orcid.org/0009-0001-7924-6972), Junior Researcher, gulyakov_97@mail.ru

Об авторах

Институт морской геологии и геофизики ДВО РАН, Южно-Сахалинск, Россия, лаборатория сейсмологии:

Закупин Александр Сергеевич (https://orcid.org/0000-0003-0593-6417), кандидат физико-математических наук, ведущий научный сотрудник, a.zakupin@imgg.ru

Андреева Марина Юрьевна (https://orcid.org/0000-0002-7851-3311), кандидат физико-математических наук, старший научный сотрудник, andreeva-mu@mail.ru

Жердева Ольга Андреевна (https://orcid.org/0000-0003-4814-0865), старший инженер, o.zherdeva@imgg.ru

Институт морской геологии и геофизики ДВО РАН, Южно-Сахалинск, Россия, отдел исследования геофизических полей и физических свойств геоматериалов Центра коллективного пользования:

Казаков Артем Иванович (https://orcid.org/0000-0002-1378-185X), ведущий инженер, legn@inbox.ru

Стовбун Николай Сергеевич (https://orcid.org/0009-0004-1927-798X), младший научный сотрудник, nikolay19972016@gmail.com

Гуляков Сергей Александрович (https://orcid.org/0009-0001-7924-6972), младший научный сотрудник, gulyakov_97@mail.ru

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