JOURNAL OF VOLCANOLOGY AND SEISMOLOGY, 2025, No. 1, pp. 78–91

ON SEISMIC FORECASTING, THE RELATIONSHIP BETWEEN SEISMIC AND GEODYNAMIC PROCESSES AND THE CONCEPT OF INFORMATION CERTAINTY

© 2025 A. V. Solomatin

Institute of Volcanology and Seismology FEB RAS, Petropavlovsk-Kamchatsky, Russia
e-mail: alf55@mail.ru

Received April 24, 2024
Revised August 08, 2024
Accepted October 28, 2024

Abstract. The article considers a number of problems solved to one degree or another when forecasting the most dangerous — strongest earthquakes. The most important of them are: the problem of the effectiveness of seismic forecasting based on the idea of scenarios — basic patterns of development of foci of the strongest earthquakes; the problem of monitoring the development of such scenarios based on seismological data; the problem of modeling the relationship between seismic and geodynamic processes that determines these scenarios. To solve the last two problems, the article proposes to use the concepts of the energy and dynamic spectra of seismic activity of the geoenvironment, and the peculiarity of the proposed solution is the introduction of the mathematical concept of information certainty. As an example of using the proposed methods, the article presents a justification for a hypothetical multi-year oscillatory motion during the submersion of the oceanic plate in the Kamchatka subduction zone with a period of about 8.57 years. It is assumed that such oscillations largely determine the most probable periods of occurrence of regional strongest earthquakes.

Keywords: *seismic forecast, seismic monitoring, seismic process spectrum, geodynamic model, subduction zone, fuzzy estimates, information certainty*

DOI: 10.31857/S02030306250105e8

INTRODUCTION

Seismicity in the widest range of scales is one of the observed manifestations of dynamic processes of development of a complex, close to critical state seismically active geo-environment. At the same time, the seismic process reflects, on the one hand, its own activity of its various components and, on the other hand, its active responses to external influences of various nature. All this determines the essential complexity of studying the regularities of geosphere development on the basis of seismological data, including in the most important practical direction – forecasting the most dangerous – the strongest earthquakes.

At the same time, geodynamic processes at all levels of their hierarchy are to some extent inertial and, as a consequence, despite the variety of development scenarios, they, as well as their reflection in seismic and other processes, are largely predictable.

Based on the above, the problem of seismic forecasting should be considered not according to the general principle of attributing earthquakes to critical manifestations in the development of the geosphere, but on the basis of dividing the period of preparation of its source into a long predictable scenario interval of development and a relatively short interval of the critical state of some effective for the generation of the main event area. It is to the uncertainty of the outcome of the latter stage that, ideally, the entire uncertainty of the forecast should be propagated. Note that on the basis of such a representation it is rational to predict not so much the earthquake itself as the critical increase in its probability.

The method of long-term seismic prediction (LTSP), presented in the works of Academician of the Russian Academy of Sciences S.A. Fedotov [Fedotov, 1965, 1968, 2005; and others], is based on the scenario principle. Seismic prediction based on the LTSP method assumes as an optimal strategy the combination of the long-term scenario – the seismic cycle of development of the strongest earthquake sources – that has been tested for almost six decades, with the development of other scenarios to clarify the seismic hazard [Fedotov et al., 2008, 2011; and others].

To estimate the interval of critical increase in the probability of the strongest earthquake, the LTSP method uses a two-day scenario of strong ($M \geqslant 6$) foreshocks, which in a quarter of cases precede the strongest ($M \geqslant 7.7$) Pacific earthquakes [Fedotov et al., 1993, 2005, 2012].

The problem of the long absence of a medium-term scenario in the LTSP method was solved in [Solomatin, 2021b], but at the same time, to create a complete system for studying the properties of the seismic process and predicting the development of the strongest earthquakes, it is now required to build a seismic monitoring technique more adequate to the available ideas than the known ones.

Potentially, the task of seismic monitoring could be solved on the basis of developed methods of Epidemic Type Aftershock Sequences (ETAS) [Ogata, 1988, 1998; Baranov et al., 2019; and others]. However, they are based on an ambiguous characteristic of the seismic process – the level of seismic activity.

A different approach to determining the level of seismic activity, based on a fairly complete set of parameters A_{10}, A_{11} and D, is used in the LTSP method. These parameters reflect, respectively, the seismic activity of the investigated area of the seismogenic zone in the range of relatively weak (K = 10–11), medium (conditionally: K = 11–12) and the strongest earthquakes.

The main parameter of the Gutenberg-Richter law (GRL), the slope of the earthquake recurrence plot, is an important characteristic of the seismic process that links the parameters A_{10}, A_{11}, and D *in* the very first approximation. At the same time, the relative independence of these parameters [Fedotov et al., 2008] leads to the idea of more general ideas about the distribution of seismic event magnitudes.

Such an idea in the form of the concept of the energy balance of a seismic process was proposed in [Solomatin, 2011], and in an even more general form, based on the concept of the energy spectrum of a seismic process, was successfully applied in [Solomatin, 2021b]. Nevertheless, even such a maximally general spectral representation is ineffective in its unchanged form for the construction of detailed seismic monitoring. The solution of this problem as a mathematical concept is one of the main directions of the present study.

It should be noted that the LTSP method was developed on the basis of ideas about the most general scenarios of seismotectonic process development as the most adequate basis for joint use with forecast data of other methods, in particular, *M8* [Matvienko, 1998]. At the same time, in the case of building detailed and complex scenarios, including jointly with data from other geophysical methods of observing the state of the geosphere [Gavrilov et al., 2022; and others], it is reasonable to search for the harmonization of the results on the basis of general concepts, which determines the importance of developing the concept of reflection in the seismic process of changes in dynamic processes in the geosphere.

It should be noted that this direction is already represented by authoritative researchers. As the most typical in the domestic literature, we can present the studies of Y.L. Rebetsky [Rebetsky et al., 2017]. Despite the theoretical development of the ideas used in such studies about the relationship between geodynamics and the mechanism of seismic sources, the source material for the construction of such a relationship also cannot be the basis for detailed monitoring.

On the importance of developing a conceptual approach to the solution of seismological problems

Given that the proposed work addresses a number of long-standing research problems in seismology, for a better understanding of its essence, it is necessary to point out its exploratory, concept-level focus.

The natural ways of proving the usefulness of conceptual studies – bringing the hypotheses used in them either to a level adequate to modern theoretical concepts, or – obtaining on their basis an adequate practical result, including as a hypothetical basis for new theories. The first way is traditional, but with the existing gap between the accumulated material of observations and modern theoretical concepts it seems to the author rather controversial. The second way represents a more natural, "evolutionary" (rather than "evidentiary") direction of development of theoretical concepts. The author is an adherent of the second approach, and as a practical result he usually, not excluding this article, uses the construction of seismic forecasts verified both retrospectively and in real time.

SCENARIO APPROACH TO EARTHQUAKE FORECASTING

Scenario representations, as direct generalizations of known regularities, are an important link between seismic forecasting and observations of the seismic process development in the active geosphere and, as a result, the dynamic processes occurring in it. In the LTSP method scenario representations are based, on the one hand, on the regularities determining in the most general form the cycle of development of the strongest ($M \geqslant 7.7$) earthquakes foci, and on the other hand – on detailing the regularities of their development at the III, final stage. For earthquake sources of the Kuril-Kamchatka arc the duration of seismic cycle is $T = 140 \pm 60$ years, and the final stage – 15–20 years [Fedotov, 1968, 2005; Fedotov et al., 2008].

The scenarios used in the works of S.A. Fedotov and also in [Solomatin, 2021b] are intended, first of all, for the construction of long-term as well as medium-term forecasts with their subsequent possible short-term scenario refinement. At the same time, the practical application of the LTSP method also implies the factor of short-term critical uncertainty in the hearth development, which is effectively modeled for practical tasks by the foreshock scenario [Fedotov et al., 1993].

An important direction in the development of the scenario approach to earthquake forecasting is the concept of periodicity (quasi-periodicity in the general case) of seismic process development, conditioned both by factors of external nature [Shirokov, 1977; Shirokov and Serafimova, 2006; Gusev, 2008] and by properties of the geosphere itself [Khain and Khalilov, 2008; Fedotov et al., 2011; Solomatin, 2014, 2021b]. It is important that this concept potentially implies the hypothesis of quasi-periodicity of occurrence of time intervals of critical development of the strongest earthquake sources. Such intervals are manifested by seismic activations significantly (by years) removed from the main event – unrealized in the past strongest events and are an important factor for improving the efficiency of seismic forecasts.

It should be noted here that the concept of quasi-periodicity of geodynamic processes used by the author based on the results of [Fedotov et al., 2011; Solomatin, 2014, 2021b] assumes a very high (with a deviation of the first percent), given the complexity of the geosphere properties, accuracy of period determination.

In general, the following features characterize the concept of scenario approach to earthquake forecasting developed on the basis of the LTSP method:

– maximum attention in the LTSP method is paid to the most dangerous – the strongest earthquakes, determination of probable places and patterns of development of foci of which is the primary task, and such patterns essentially determine the whole regional seismic process;

– The LTSP method implies consistent coordination of long-term, medium-term and short-term, on the basis of immediate foreshocks, scenarios of development of the strongest earthquake sources;

– In the general case of specifying the seismic hazard of potential sources of the strongest earthquakes on the basis of short-term scenarios, an important task is to determine the critical time intervals corresponding to these scenarios.

METHODOLOGY OF DETAILED SEISMIC PROCESS MONITORING

The wide variety of geodynamic processes, as well as the assumed accelerated nature of their occurrence when approaching the critical stage of earthquake source development require the development of seismic monitoring techniques more advanced than the existing ones. In the present article, as a basis for such a technique, we chose the idea of energy and dynamic spectra of the seismic process, which, as it is supposed, reflect the dynamics of the geosphere development to the maximum extent in relation to the usual ideas about the seismic flow.

Taking into account the hierarchy of the processes under study, the proposed monitoring methodology should be applicable to a wide range of time representations: from overview – long-term, to the most detailed – event-by-event. This condition is satisfied by cumulative time series, which optimally highlight significant trends of the parameters used in any time scale.

All this, as well as the idea that the probabilistic-informational representation of seismological data is preferable, formed the basis for the methodology proposed below.

Let us consider a time series of values of energy classes of earthquakes [Fedotov, 1972] – $K(t)$, whose hypocenters belong to some rather homogeneous seismogenic region. Let us represent the values of these earthquakes in the scale of Fedotov's generalized energy class – K^F [Solomatin, 2021b, 2022b]. Then, in the limiting, undisturbed and energetically equilibrium [Solomatin, 2011] state of the seismogenic medium, the total sample of values of the parameter $K^F(t)$ obeys to the maximum extent the GRL with the slope of the recurrence graph $\gamma_0 = 1/2$.

According to the GRL, for the specified sample represented as ordered values of K^F with the minimum value of K^F_{min}, the relation is satisfied:

$$\lg\left(1 - P\left(K^F{}_i\right)\right) = -\gamma_0 \cdot \left(K_i^F - K^F_{\min}\right) \quad (1)$$

Or:

$$P\left(K_i\right) = 1 - 1\Big/\left(E_i/E_{\min}\right)^{\gamma_0}, \quad (2)$$

where $E = 10^K$ is the seismic energy [Fedotov, 1972].

In practice, the distribution function $P(K)$ can be constructed on the basis of ordered normalized ranks of the values of the parameter K^F, whereby the values of $P(K)$, and hence the values $1/(E/E_{\min})$^γ_0 = $1/(E/E_{\min})^{1/2}$, are uniformly distributed in the range [0; 1][1]. Thus, the earthquake magnitudes in the case of a hypothesized unperturbed seismic process are represented in the P-scale by a flat spectrum. Note that the expression $S = E^{1/2}$ defines the conditional Benioff deformations, so the inverse of these deformations, $S_{\min}/S$ [Solomatin, 2022b], can be considered uniformly distributed.

For what follows, it is important that the parameter P in its most general form, conventionally $P(X)$, has the additional sense of evaluating the possibility of assigning an event X to a fuzzy class of large values of it[2].

To represent the features of the P-scale in the case of seismological data, we use an expression already for an arbitrary value of γ [Aki, 1965]:

$$\gamma = -\lg(e)\Big/\left(K^F_{\mathrm{med}} - K^F_{\min}\right). \quad (3)$$

Taking expressions (1) and (3) as a basis, taking the individual values of the sequence – K^F_{med} as the limit of mean estimates K^F, and introducing the parameter $g = 1/\gamma$ and passing from decimal to natural logarithm, we construct point estimates:

[1] In (1) and (2), and in the following, the open interval]0; 1[is approximated instead of the closed interval [0; 1].

[2] The transition from concrete values to their fuzzy estimates is quite productive, in particular in possibility theory or in logistic regression analysis.

$$g\left(K^F\right)/g_0 = -\text{In}\left(P\left(K^F\right)\right), \quad (4)$$

$$g'\left(K^F\right)/g_0 = -\text{In}\left(1 - P\left(K^F\right)\right), \quad (5)$$

where $g_0 = 1/\gamma_0 = 2$.

Note that in expressions (4) and (5), in determining the variations of the coefficient g/g_0, the weakest events have more weight, and the coefficient g'/g_0 – the strongest events. Such an idea of two parameters describing variations in the spectrum of event magnitudes of a seismic process is in full agreement with the idea of the nature of the energy balance of the latter [Solomatin, 2011].

Given the identity substitutions $f(K^F) \equiv f(KF)(t)) \equiv \equiv f(t)$, we use the estimates based on expressions (4) and (5) to construct the following time series:

$$C(t) = \Sigma g(t)/g_0 = -\Sigma \ln(P(t))$$
$$\text{and } C'(t) = \Sigma g'(t)/g_0 = -\Sigma \text{Ln}(1 - P(t)). \quad (6)$$

These series, based on an extension of the GRL representations, reflect in cumulative form the deviations of the spectrum of seismic process event magnitudes from the baseline.

The mathematical meaning of the logarithmic representation of such deviations will be explained further; now, considering the transformations $\ln(P)$ and $\ln(1 - P)$ as nonlinear filters for asymmetric extraction of P-spectrum variations in two different parts of its range, series can be introduced as a symmetric alternative:

$$C^0(t) = \sum(P(t) - 0.5) \text{ and } C'^0(t) =$$
$$= \sum(0.5 - P(t)) = -C^0(t), \quad (7)$$

where $\overline{P(t)} = 0.5$.

Rows (7) reflect in integral form the current bipolar certainty of prevalence of events of the upper or lower parts of the P-spectrum. Since the parameter P can be measured in odds, the parameters $C(t)$ are also measured conditionally in the same units, but cumulatively and relative to the average level.

A characteristic feature of geodynamic processes is discrete transitions between relatively stable states of the geosphere at different levels of its hierarchical structure. These transitions, determined by both internal and external processes, are in practice usually displayed as stepwise cumulative plots of the energy degrees of a sequence of events, viz: $\Sigma E^0(t)$, $\Sigma E^{1/2}(t)$, $\Sigma E(t)$. Examples of meaningful interpretation of $\Sigma E(t)$ series are presented in [Fedotov et al., 1987, 2011].

Considering the above, the list of cumulative series commonly used in seismology can be supplemented with the series $\Sigma E^{-1/2}(t)$, equivalent to the series $\Sigma P(t)$. Moreover, all these degree series can also be complemented by the series (6) on the basis of logarithmization. Thus, the general meaning of constructing all these series is to select certain features of the seismic process as filters. As a result, the idea arises of constructing such filters to the greatest extent reflecting the relationship between variations in the characteristics of the seismic process and variations in the corresponding geodynamic conditions.

INFORMATION APPROACH TO SEISMIC PROCESS MONITORING. INFORMATION CERTAINTY

Despite the simplicity of the idea of selecting the filter needed to represent a particular aspect of geodynamic conditions based on representations of "natural" seismological parameters, this approach can hardly be considered sufficiently general compared to the information approach.

First, let us consider the information aspect of using the P-parameter, introduced above on the basis of the energy class K, in the general form $P(X)$. Let the considered sample of the observed parameter X has volume N. Let us construct the following distribution density function:

$$U(X) = 2\cdot P(X)/N = 2\cdot P(X)\cdot Q(P). \quad (8)$$

Here it is taken into account that $\overline{P(X)} = 0.5$ and $Q(P)$ is a deterministic, with zero information component, distribution: $Q(P) \equiv Q(P(X)) \equiv \equiv Q(X) = 1/N$.

For each of the values of X, expression (8) determines the normalized probability that it belongs to the class of large ($P(X) \to 1$ given the definition of $P(X)$).

We construct the Kullback-Leibler divergence (KLD) for the following distributions: estimated – $U(X)$ and reference – $Q(X)$:

$$D_0 = \sum Q(X) \cdot \ln[Q(X)/(2 \cdot P(X) \cdot Q(X)] \quad (9)$$

or given

$1/N \cdot \sum \ln(P(X)) = \overline{\ln(P(X))} = -1$:

$$D_0 = -\ln(2) + 1. \quad (10)$$

We turn to the time aspect of the problem by constructing a non-normalized – cumulative over time minus mean KLD estimate:

$$D(t) = \sum(\ln(Q(t)/(2 \cdot P(t) \cdot Q(t)) - D_0), \quad (11)$$

then:

$$D(t) = -\sum(\ln(P(t)) + 1). \quad (12)$$

Thus, the information contribution made by the parameter P is reflected by the Hartley measure, which is quite expected.

Conjugate for (12) row:

$$D'(t) = -\sum(\ln(1 - P(t)) + 1). \quad (13)$$

The system of expressions (12) and (13) is equivalent to the system (6). Thus, the above presented point monitoring based on extended representations of the GRL is equivalent to the information model for monitoring the variations of the energy spectrum.

It is important that in the case of a seismotectonic process, the information contributions of individual events in expressions (12) and (13) are generally not completely random, but reflect in a cumulative form the current, quite regular transitions between its states. As an important characteristic of such transitions, we propose to introduce the concept of their informational certainty on the basis of expressions (12) and (13). The above conditionally applies to expressions (7), which are an additional hypothetical representation of the linear in P-scale contribution of seismic events to a similar information certainty, but on the basis of the additive rather than multiplicative principle[3].

The advantages of the mathematical concept introduced in this way are, first, in the essential generalization of observations by statistically stable rank relations, and second, in the convenience of constructing information-probabilistic models on the basis of such observations.

It should also be noted that a substantially generalized estimate of the information certainty of seismic process variations is not the only possible result of monitoring on its basis. In particular, specific estimates for the characteristic time intervals preliminarily allocated on its basis can be calculated additionally.

SEISMIC ACTIVITY ESTIMATION BASED ON P-PARAMETERS

Let us consider some homogeneous seismic active region. Taking into account the parameter $P^K(t)$, reflecting a fuzzy estimate of the magnitude of the next event $K(t)$ in this region, and the parameter $P^T(t)$, reflecting the same estimate of confidence in the smallness of the interval between the observed and previous events in the same region, we construct a time series:

$$P^A(t) = 1 - ((1 - P^K(t)) \cdot (1 - P^T(t)))^{0.3}, \quad (14)$$

where the degree 0.3 is chosen rather arbitrarily and serves for satisfactory approximation of the distribution function of the product of P-parameters to a linear form.

Cumulative dependence:

$$C^A(t) = \sum(P^A(t) - P^A_{med}) \quad (15)$$

[3] Conventionally, we can speak of a spectrum of expressions for constructing the P-scale on the basis of the interval between the representations of additive and multiplicative principles, similarly to the way the original representation of entropy is nowadays complicated by a number of other representations, in particular, by the spectrum of Rényi or Tsallis entropies. But this greatly complicates the problem, either by transferring it to an essentially mathematical plane, or by requiring the construction of the concept under consideration at a much higher level of ideas about the properties of the analyzed data.

by the type of series (7) determines variations of information certainty of high seismic activity equally on the basis of both $P^K(t)$ and $P^T(t)$.

Similarly, we can define these variations in the information certainty scale along the lines of expression (12), but using decimal logarithms:

$$D^A(t) = -\Sigma\left(\lg\left(P^A(t)\right) - \overline{\lg\left(P^A(t)\right)}\right). \qquad (16)$$

CONSTRUCTION AND USE OF THE METHODOLOGY DETAILED MONITORING OF THE SEISMIC PROCESS TO STUDY THE DYNAMIC STATE OF THE GEO-ENVIRONMENT

The results of [Solomatin, 2014] indicated a connection at the level of quasi-periodicities of volcanic and seismic activity not only in the Kamchatka segment of the Kuril-Kamchatka arc, but also in the entire region. This fact suggests the progressively fluctuating nature of the dipping plate on a regional scale as one of the most probable causes of such a connection.

To verify the consistency of this geodynamic concept with seismological data, we further proposed a certain concept of the relationship between the characteristics of the seismic process and geodynamic conditions in the subduction zone. Although the conclusions obtained as a result of this analysis do not claim to be complete, the very success of such a justification can serve as a strong argument in favor of the prospects of the proposed direction of monitoring the variations in the geodynamics of the seismically active environment on the basis of seismic data.

Let us emphasize the following two factors of the geodynamic process in the subduction zone as the most important ones: release and redistribution of stresses. Note that strong seismic events correspond to the first of them to a greater extent, and background, weak ones to the second[4].

[4] It is possible to note extreme simplicity of statement in terms of fuzzy estimations of difficult problems in traditional for seismology parametric representation.

On the basis of this representation, we can propose the following model of the relationship between the properties of the seismic process in some region of the subduction zone, given as a contact between two fault faces, and the geodynamic conditions in it: an anomalously large number of strong events in this region carries information about the relative predominance of tangential stresses in it, and high activity in the range of background events – normal stresses.

As a working material in the article the regional catalog of earthquakes of Kamchatka Branch, FRC UGS RAS of Kamchatka section of the seismogenic zone in the range of geographical coordinates was used: 49–55°N and 153–163°E. To construct a sample of seismic events, the value $K_S = 8.5$ was used as the minimum value of energy classes of this catalog, which provides its sufficient completeness.

Taking into account the impact on the geodynamics of the region of the strongest deep Okhotsk Sea earthquake on May 24, 2013, the data were limited to the period 2015–2023. The 3-day interval of seismic activation associated with the strong ($M = 7.5$) earthquake that occurred in the back-arc region on March 25, 2020, and reflecting the processes in the subduction zone itself rather indirectly, was also excluded from consideration.

Data on seismic events of the sample obtained in this way were divided by hypocenter depth into two ranges with a boundary at a depth of $H = 100$ km.

In order to determine the character of influence of variations of normal (N) stress on the seismic process in accordance with the introduced hypothesis, the dependence (16) was chosen, which highlights the minimum seismic activity:

$$D_N(t) = -\Sigma\left(\lg(P^A(t)) - \left(\overline{\lg\left(P^A(t)\right)}\right)\right). \qquad (17)$$

Similarly, a series based on expressions (12) and (13) was investigated to show the predominant effect of tangential (T) stress variations:

$$D_T(t) = -\Sigma\left(\lg\left(1 - P^K(t)\right) - \lg\left(P^K(t)\right)\right), \qquad (18)$$

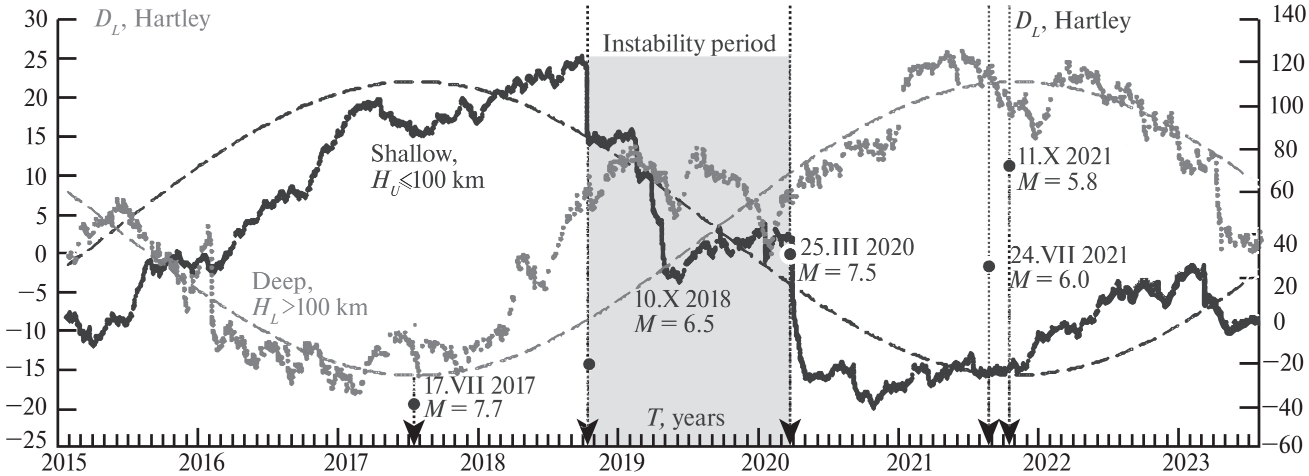

Fig. 1. Variations of information certainty based on expression (17) for shallow – $D_U(t)$ (black points) and deep – $D_L(t)$ (gray points) earthquakes of the Kamchatka section of the seismogenic zone.
Dotted lines are approximations of dependences D by the harmonic part of dependence (19) – function $F_G(t)$ with period $T = 8.57$ years and extremum at the point 17.VII 2017. Characteristic regional events for the period from 2015 are also given.

emphasizing the contribution to the energy spectrum of the strongest events relative to the contribution of the weakest.

The plots in Fig. 1, plotted on the basis of expression (17), indicate differences in the signs of variations of the parameter $D_N(t)$ for deep (L) and shallow (U) events, which is quite consistent with the introduced model of oscillatory motions of a sinking oceanic plate around a sufficiently deep axis. At the same time, during the investigated period, the cumulative variations of normal stresses for each of the selected ranges of hypocenter depths are quite satisfactorily described by the dependence based on the general harmonic function $F_G(t) = \pm\cos(2\cdot\pi\cdot(t-t_0)/T)$ with period T close to 9 years.

The full form of the dependence $N(t) \sim D_N(t)$ can be written in multiplicative form based on the introduction of some modulating function $A_M(t)$:

$$N(t) = A_M(t) \cdot F_G(t) = \\ = A_M(t) \cdot \cos(2 \cdot \pi \cdot (t-t_0)/T). \quad (19)$$

It is logical to try to explain the periodicities in the range $T = 8.40$–9.12 years revealed in the geodynamic development of the region on the basis of the proposed model [Solomatin, 2014]. The period $T = 8.57$[5] years is good enough for this purpose. The date of the strongest Middle Aleutian earthquake on July 17, 2017 can be conditionally accepted as the zero point t_0. This is the last of the earthquakes of the "strongest" class registered to date, which is significantly related to the regional seismic process [Fedotov and Solomatin, 2019].

As shown in Fig. 1, such an expression (19) using the above-mentioned values of the period and zero point quite satisfactorily represents the harmonic oscillations described ideally by the function $F_G(t)$. In this case, taking into account the integral form of curves (17), the extreme points of this function correspond to the hypothetical minimum effective normal stresses.

Fig. 1 shows only one period of variation of the $N(t)$ series, which is insufficient to substantiate the regularity of oscillatory motions in the form (19), and a similar analysis of all data is greatly complicated by the influence, in particular, of the Okhotsk Sea earthquake. However, since the

[5] The exact setting of the tested period T with the value 8.57 is explained by the fact that it is a multiple of the period of 2.86 years or 1044 ± 15 days. It is in such an interval that remote in time increased activity is observed before the largest ($M = 8.0$ and higher) earthquakes in the region [Solomatin, 2022a].

evaluated concept assumes only quasi-periodicity of $N(t)$ and monotonicity of the relation $N(t) \sim D_N(t)$, a relatively complete analysis may well be limited to comparison of extremums of the dependence $F_G(t)$ and moments of the strongest regional earthquakes.

For such analysis we selected 14 strongest earthquakes since 1841 within the boundaries of the extended area of seismogenic zone including the junction of Kurilo-Kamchatka and Aleutian arcs: from the origin of the Near Aleutian earthquake on 17.VII 2017 with $M = 7.7$ in the region of Bering and Medny islands to the origin of the earthquake on 1.V 1915 with $M = 7.8$ in the region of Onekotan - Shiashkotan group of islands (Table 1).

Row 13 in the table corresponds to the forecast of 2021 based on the scenario approach of high (at the level of 30% for a 3-year period) hazard of the strongest earthquake in the region of Paramushir Island – south of Kamchatka [Solomatin, 2021a, 2022a] and hypothetically filling the gap in the region of the past extremum $F_G(t)$.

The results of comparison of times of extremum t_e of $F_G(t)$ dependence and moments of earthquakes t_E in the form of deviations $\Delta t_E = t_E - t_e$ are presented in the table. To analyze these deviations, the rows are ordered and grouped by the absolute value of Δt_E, which is reflected in the last columns. The data for the deepest ($H \sim 500$ km) events are highlighted in gray background, and the data for the strongest ($M \geqslant 8.3$) events are highlighted in bold.

To demonstrate the relative proximity of hypothetical values of normal stresses at the time of earthquakes with the same hypothetical extreme values, the values of $F_G(t_E)$ are also given (see Table 1).

Given the notion of the strong influence of lunar tides on the specific timing of the strongest earthquakes (in particular, the intervals between close pairs of the strongest Kuril earthquakes: 7.IX 1918 – 8.XI 1918 and 15.XI 2006 – 13.I 2007, equal to 62 and 59 days, respectively, are close to double periods of the lunar month – 29.53 days). Table 1 presents the second, refined by the average duration of the lunar month variant of the definition of the zero point for the construction of the function $F_G(t)$, namely: $t'_0 = t_0 + 0.081$ (in years), or the specific date t'_0: 15.VIII 2017.

The analysis of Δt_E deviations (see Table 1) indicates quite certain regularities. First of all, 11 of the 15 presented events, taking into account the correction to t_0 of 0.081 years, have Δt_E deviations in the range of about half a year. Moreover, the spread of Δt_E in each direction for the group of 7 events is defined by extremely narrow limits: 0.50–0.55 years. For the group of 4 other events, the full spread is half as large: 0.26–0.06 years. It is important that the last two groups include all the strongest events. The attribution of the deepest events to them also justifies the generality of the proposed geodynamic model for all depths along the subduction direction.

Only 4 events out of 15 are close to the points of zero values of $F_G(t)$. This circumstance quite corresponds to the period of instability of seismic process highlighted in Fig. 1, when hypothetically enough unusual and not the most significant for the region strongest events similar to the Kronotsky earthquake 5.XII 1997, $M = 7.8$, or Zhupanovo earthquake 4.V 1959, $M = 7.9$ can occur[6].

Taking into account the properties of the deep geosphere, it is natural to assume the kinematic nature of normal stress variations determined by the motion of the oceanic plate sections along the normal to its conditional plane. In this case, the extrema of the curves in Fig. 1 correspond to the extreme positions of hypothetical oscillatory motions. Accordingly, during the period of time after the strongest Middle Aleutian earthquake and up to the end of 2021, the phase of uplift of the submerged part of the plate took place, and then the phase of its sinking took place.

---

[6] Considering the construction of the LTSP method in the works of S.A. Fedotov also for the seismogenic zone of Northeast Japan, it can be noted that the strongest event in this area – the catastrophic Tohoku earthquake 11.III 2011 with $M = 9.1$ occurred with a deviation of only 2 days from the point of zero value of $F_G(t)$. It is unlikely that such a coincidence is accidental, so this fact can become the starting point for extending the proposed model to the entire Kuril-Kamchatka region and adjacent areas.

Table 1. Correspondence of the strongest earthquakes of Kamchatka section of Kuril-Kamchatka seismogenic zone to extremums of harmonic component $F_G(t)$ of dependence (19) in the period 1841–2023

№	Date of event, t_E	M	$F_G(t_E)$	Deviations Δt_E (years)	Deviation intervals Δt_E (years)
0	17.VII 2017.	7.7	–	–	–
1	30.I 1917.	8.0	–0.173 / –0.115	–1.91 / –1.99	± (1.65–1.91) / ± (1.71–1.99) – close to the maximum (±2.14 years) deviations Δt_E
2	5.XII 1997.	7.8	–0.241 / –0.298	1.81 / 1.73	
3	25.VI 1904.	7.7	0.354 / 0.298	–1.65 / –1.73	
4	4.V 1959.	7.9	0.258 / 0.315	1.79 / 1.71	
5	15.XII 1971.	7.9	–0.894 / –0.919	0.63 / 0.55	± (0.42–0.63) /± (0.50–0.55) – semi-annual deviations Δt_E
6	1.V 1915.	7.8	0.896 / 0.921	0.63 / 0.55	
7	5.VII 2008.	7.7	0.943 / 0.922	–0.46 / –0.54	
8	**17.V 1841.**	**8.4**	**–0.948 / –0.927**	**–0.44 / –0.52**	
9	11.VI 1902.	8.0	–0.906 / –0.930	0.60 / 0.52	
10	15.IX 1905.	7.8	0.952 / 0.932	0.43 / –0.51	
11	**04.XI 1952.**	**9.0**	**–0.952 / –0.933**	**–0.42 / –0.50**	
12	**03.II 1923.**	**8.4**	**0.991 / 0.982**	**–0.18 / –0.26**	–0.18–0.14) / –0.26–0.06) – quarter-year deviations Δt_E
13	25.VIII 2021.	⩾7.8	–0.991 / –0.982	–0.18 / –0.26	
14	**24.V 2013.**	**8.3**	**–0.995 / –0.999**	0.14 / 0.06	

Note. Columns present sequentially: dates of the strongest ($M \geqslant 7.7$) earthquakes of the investigated region, including pre-instrumental period of observations, t_E; their magnitudes on the basis of data from NEIC world catalog and data from works of S.A. Fedotov; values of function $F_G(t_E) = \cos(2 \cdot \pi \cdot (t_E - t_0)/T)$ in two variants t_0: dates of the Middle Aleutian earthquake 17.VII, 2017 without correction and with correction equal to the mean lunar month duration; deviations of the time t_E of the corresponding earthquake from the time t_e, the nearest extremum of the F_G function in the same two variants of t_0; intervals of deviations Δt_E in the same two variants of t_0. The data on the time of the Middle Aleutian earthquake (line 0), including the specified correction, serve as an estimate of the value of t_0.

If the motions of the plate oscillations in different depth ranges of immersion are different, then its motions, determined for the same ranges by the influence of variations of tangential stresses $T(t) \sim D_T(t)$, should be common (Fig. 2). These plots, plotted for two depth ranges, are described on the basis of the same function $F_G(t)$, but with a shift by a quarter period:

$$T(t) = A'_M(t) \cdot F'_G(t) = -A'_M(t) \cdot \sin(2 \cdot \pi \cdot (t - t_0)/T), \quad (20)$$

where $A'_M(t)$ is some modulating function formally analogous to $A_M(t)$ in (19).

It is logical to assume that, in the proposed model, the plate approaching the upper position is accompanied by a weakening of the normal stress in the region of the upper (above the assumed oscillation axis), the most rigid contact zone, which probably contributes to the occurrence of significant events at all depths (see Fig. 2, positive slope of the curves). Conversely, the plate approaching the lower position leads to a relative deficit of sufficiently strong events also at all depths (see Fig. 2, negative slope of the curves).

In general, the mechanism of realization of the strongest earthquakes on the basis of the above proposed idealized scheme of periodic oscillations of the dipping plate can be functionally similar to the anchor clock mechanism.

PREDICTIVE CAPABILITIES OF THE PROPOSED GEODYNAMIC MODEL AND FLUID DYNAMICS

The above analysis (see Fig. 1, 2, Table 1) indicates a certain prognostic potential of the proposed geodynamic model. According to the graph in Fig. 1, the previous extremum was observed 27.XI 2021. The next possibility of realization of the strongest earthquake in the region, apparently, will arise in the annual interval near the next extremum 11.III 2026.

The mentioned data should be categorized as a medium-term scenario, clarifying the forecast data on the basis of the LTSP method [Fedotov, Solomatin, 2019] and the two-cycle model of the final stage of focal development of the strongest Pacific earthquakes [Solomatin, 2021b], within which the same period of 8.57 years is part of a more complex temporal structure, as well as on the basis of the extended model of the foreshock scenario, in which periodically (with high temporal accuracy, but with a significant share of uncertainty in manifestation) the activations occurring at the III – final stage of the seismic cycle are considered as potential, but unrealized opportunities for the strongest earthquakes [Solomatin, 2022a].

Both of the latter models seem to be closely related to the fluid dynamics of seismogenic zones. Highly mobile fluids are able to ensure high accuracy of following of essentially inert seismotectonic processes to certain periodicities [Fedotov et al., 2011; Solomatin, 2014], as well as to enhance the dynamic interaction of seismotectonic processes in significantly remote parts of the seismogenic zone [Fedotov and Solomatin, 2015, 2017, 2019].

CONCLUSION

The most important practical task of seismological research is still the forecast of the most dangerous

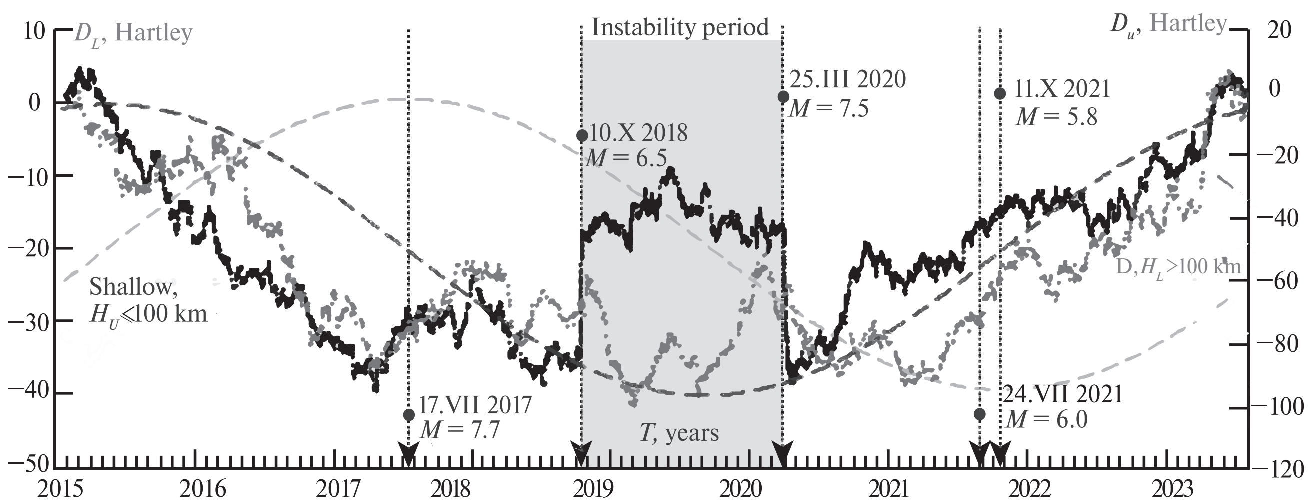

Fig. 2. Variations of information certainty based on expression (18) for shallow – $D_U(t)$ (black points) and deep – $D_L(t)$ (gray points) earthquakes of the Kamchatka section of the seismogenic zone.
The dark dashed line is a general approximation of the dependences D by a function of the form $F'_G(t)$, similar to $F_G(t)$, but with a shift by a quarter of its period. The light dashed line shows the approximation of the function $F_G(t)$ for shallow events (see Fig. 1).

earthquakes. The article considers a number of questions concerning the solution of this problem based on the basic ideas of the proven method of long-term seismic prediction (LTSP) of S.A. Fedotov. The greatest attention is paid to the problem of building a detailed monitoring of seismic process in the application to the study of geodynamic conditions determining it.

As a general provision determining the principal possibility of building effective methods of seismic forecasting, the paper develops the principle adopted in the LTSP method, which determines the predictability of the development of the sources of the most dangerous – strongest earthquakes on the basis of scenarios of this development: from long-term – in the order of hundreds of years, to short-term – in a few days. At the same time, it is possible to assume a short time interval during which the development of the source passes the critical stage. The result of passing this stage is determined to a much lesser extent, and it is on it that the current possibility of realization of the strongest event directly depends. As a consequence, in the hypothetical case of successful realization of the whole set of forecast scenarios, the full assessment of the probability of the forecasted event as the degree of seismic hazard growth should refer only to the specified small period. This is the approach used in determining the critical increase in the hazard of the strongest earthquake based on the foreshock scenario of the LTSP method [Fedotov et al., 1993].

In the article, a mathematical concept of information certainty based on fuzzy estimates was proposed, which provides the most informative and the most detailed representation of time-process monitoring data at the level of individual events. As a basic concept for seismic process monitoring, the concepts of energy and dynamic spectra of the seismic process were used, which significantly expand the traditional seismological concepts of quiescence and activation.

As the most important result, the paper proposes a conceptual model of reflection by the results of detailed seismic monitoring of geodynamic processes. Practical use of this model on the seismological material of the Kamchatka region (regional earthquake catalog of the Kamchatka Branch, FRC UGS RAS) allowed us to introduce as a hypothesis an assumption about the perennial oscillatory motion of the oceanic plate in the subduction zone with the period $T = 8.57$ years. It is supposed that such motion to a significant extent determines the time of occurrence of the strongest earthquakes in the region.

At the same time, deviations of the moments of the strongest earthquakes in the region from the found regularity make us assume a more complex character of these oscillations, quite probably including a component with a close period $T \approx 9.1$ years [Solomatin, 2014].

The proposed geodynamic model is not sufficiently defined to refine forecasts of the strongest earthquakes, but as a long-term-medium-term scenario can complement other forecasting methods, in particular – scenarios of the LTSP method.

To justify short-term scenarios of seismic process development, especially in the near-critical state of the seismically active geosphere, it is probably necessary to introduce fluid dynamic concepts.

CONFLICT OF INTEREST

The author of this paper declares that he has no conflict of interest.

FUNDING

This work was funded from the budget of the Institute of Volcanology and Seismology of the Far Eastern Branch of the Russian Academy of Sciences. No additional grants were received to conduct or supervise this particular study.

REFERENCES

1. *Gusev A.A. About* the reality of the 56-year cycle and the increased probability of strong earthquakes in Petropavlovsk-Kamchatsky in 2008–2011 according to the lunar cyclicity // Volcanology and Seismology. 2008. No. 6. Pp. 55–65.
2. *Matvienko Yu.D.* Application of the *M8* method in Kamchatka: successful advance forecast of the earthquake on December 5, 1997 // Volcanology and Seismology. 1998. No. 6. Pp. 27–36.

3. *Rebetskiy Yu.L., Sim L.A., Marinin A.V. From* slip mirrors to tectonic stresses. Methods and algorithms / Editor-in-Chief Y.G. Leonov. M.: GEOS, 2017. 234 c.
4. *Solomatin A.V.* Law of earthquake recurrence and energy balance of seismic process // Voprosy Engineering Seismology. 2011. Vol. 38. No. 4. Pp. 39-48.
5. *Solomatin A.V.* Study of the relationship between volcanic activity and the strongest earthquakes of the Kuril-Kamchatka region // Volcanology and Seismology. 2014. No. 1. Pp. 61–76.
6. *Solomatin A.V.* Long-term seismic forecast for the Kuril-Kamchatka arc for XII 2020 – XI 2025, mid-term assessment of seismic hazard in the area of southern Kamchatka – northern Kuril Islands // Proceedings of the XXIV Annual Scientific Conference dedicated to the Day of Volcanologist "Volcanism and Related Processes" Petropavlovsk-Kamchatsky: IV&S FEB RAS, 2021a. Pp. 105–108.
7. *Solomatin A.V.* Energy spectrum of seismic process in application to long-term seismic forecast and mid-term short-term refinement of seismic hazard // Volcanology and Seismology. 2021б. No. 2. Pp. 67–79.
8. *Solomatin A.V.* Long-term seismic forecast for the Kuril-Kamchatka arc for III.2022 – II.2027; analysis of the results of the mid-term short-term forecast for the area of Paramushir Island, given for the fall of 2021 // Proceedings of the XXV Annual Scientific Conference devoted to the Day of Volcanologist "Volcanism and Related Processes" Petropavlovsk-Kamchatsky: IV&S FEB RAS, 2022a. Pp. 107–110.
9. *Solomatin A.V.* Energy properties of the seismic process and the possibility of introducing a generalized energy class of earthquakes // Volcanology and Seismology. 2022б. No. 4. Pp. 80–92.
10. *Fedotov S.A. About* regularities of distribution of strong earthquakes of Kamchatka, Kuril Islands and North-Eastern Japan // Proceedings of the Institute of Physiological Physics of the USSR Academy of Sciences. 1965. No. 36. Pp. 66–93.
11. *Fedotov S.A. About* the seismic cycle, the possibility of quantitative seismic zoning and long-term seismic forecast // Seismic zoning of the USSR. M.: Nauka, 1968. Pp. 121–150.
12. *Fedotov S.A.* Energy classification of Kuril-Kamchatka earthquakes and the problem of magnitudes. Moscow: Nauka, 1972. 116 c.
13. *Fedotov S.A.* Long-term seismic forecast for the Kuril-Kamchatka arc. Moscow: Nauka, 2005. 302 c.
14. *Fedotov S.A., Solomatin A.V.* Long-term seismic forecast for the Kuril-Kamchatka arc for IX 2013 – VIII 2018; peculiarities of the arc seismicity during the preceding deep Okhotsk Sea earthquakes of 2008, 2012 and 2013 with $M = 7.7$, 7.7 and 8.3 // Volcanology and Seismology. 2015. No. 2. Pp. 3–19.
15. *Fedotov S.A., Solomatin A.V.* Long-term seismic forecast for the Kurilo-Kamchatka arc for IV 2016 – III 2021, its development and application; peculiarities of seismicity of the Kurilo-Kamchatka arc before and after the deep Okhotsk Sea earthquake 24.V.2013, $M = 8.3$ // Volcanology and Seismology. 2017. No. 3. Pp. 3–17.
16. *Fedotov S.A., Solomatin A.V.* Long-term seismic forecast for the Kuril-Kamchatka arc for VI 2019 – V 2024; properties of the previous seismicity in I 2017 – V 2019. Development and practical application of the LTSP method // Volcanology and Seismology. 2019. No. 6. Pp. 6–22.
17. *Fedotov S.A., Solomatin A.V., Chernyshev S.D.* Aftershocks and focal area of the Sredne-Kurilskoe earthquake 15.XI 2006, Ìs = 8.2; long-term seismic forecast for the Kuril-Kamchatka arc for IV 2008 – III 2013 // Volcanology and Seismology. 2008. No. 6. Pp. 3i23.
18. *Fedotov S.A., Solomatin A.V., Chernyshev S.D.* Long-term seismic forecast for the Kuril-Kamchatka arc for IX 2010 – VIII 2015, reliability of previous forecasts and their application // Volcanology and Seismology. 2011. No. 2. Pp. 3–27.
19. *Fedotov S.A., Solomatin A.V., Chernyshev S.D.* Long-term seismic forecast for the Kurilo-Kamchatka arc for IX 2011 – VIII 2016; probable place, time and development of the next strongest earthquake of Kamchatka with $M \geqslant 7.7$ // Volcanology and Seismology. 2012. No. 2. pp. 3-26.
20. *Fedotov S.A., Chernyshev S.D.* 20 years of long-term seismic forecast for the Kuril-Kamchatka arc: reliability in 1981-1985, in general for 1965–1985

and forecast for 1986-1990 // Volcanology and Seismology. 1987. No. 6. Pp. 93–109.

21. *Fedotov S.A., Chernysheva G.V., Shumilina L.S.* Assessment of seismic hazard of earthquakes with $M \geqslant 6$ accompanying the strongest ($M = 8$) Pacific earthquakes // Volcanology and Seismology. 1993. No. 6. Pp. 3–12.

22. *Khain V.E., Khalilov E.N.* Spatial and temporal regularities of seismic and volcanic activity. Burgas: SWB, 2008. 304 c. ISBN 978-9952-451-00-9

23. *Shirokov V.A.* Influence of space factors on the geodynamic situation and its long-term forecast for the northwestern part of the Pacific tectonic zone // Volcanism and Geodynamics. Moscow: Nauka, 1977. Pp. 103–115.

24. *Shirokov V.A., Serafimova Yu.K. About* connection of 19-year lunar and 22-year solar cycles with strong earthquakes and long-term seismic forecast for the north-western part of the Pacific tectonic belt // Vestnik KRAUNTS. Earth Sciences. 2006. No. 2. Issue. 8. Pp. 120–133.

25. *Aki K.* Maximum likelihood estimate of b in the formula lg N = a – bM and its confidence limits // Bull. Earthq. Res. Ins. 1965. Vol. 43. Pp. 237–239

26. *Baranov S.V., Gvishiani A.D., Narteau C., Shebalin P.N.* Epidemic type aftershock sequence exponential productivity // Russian Journal of Earth Sciences. 2019. Vol. 19. ES6003.
DOI: 10.2205/2019ES000695

27. *Gavrilov V.A., Deshcherevskii A.V., Vlasov Yu.A. et al.* Network of multidisciplinary borehole measurements at the Petropavlovsk-Kamchatsky geodynamic testing area // Seismic Instruments. 2022. Vol. 58(2). Pp. 121–138

28. *Ogata Y.* Statistical models for earthquake occurrences and residual analysis for point processes // J. Am. Am. Stat. Assoc. 1988. Vol. 83. No. 401. Pp. 9–27.

29. *Ogata Y.* Space-Time Point-Process Models for Earthquake Occurrences // Ann. Inst. Stat. Math. 1998. No. 50. Pp. 379–402.