Chapter

Investigation of the Dynamics of the Seismic Regime in the Kamchatka Region Based on the Combination of Methods of Nonequilibrium Thermodynamics and the Axiomatic Method of Kolmogorov A.N.

Vadim Bogdanov and Aleksey Pavlov

Abstract

In the presented chapter, the preparation of an earthquake on the example of the Kronotsky event that occurred on 1997-12-05 with a magnitude Mc = 7.7 is considered from the standpoint of nonequilibrium thermodynamics, in which the evolution of systems is due to self-organization processes. With this approach, the lithosphere is an open nonlinear system in which, due to internal dissipation and the coordinated interaction of its elements, a self-organization process can occur, leading the system to a critical state. In this case, the scales of the connection between different parts of the nonlinear structure change, that is, the scales of temporal and spatial correlation change. However, the methods of seismological monitoring of the stress-strain geoenvironment can be expanded if, for its study, the method of calculating the probability distribution of earthquakes for various random events is used, based on the axiomatic approach of Kolmogorov A.N., applied to the catalog of Kamchatka earthquakes. This makes it possible to follow the dynamics of correlated spatial and temporal changes in the probability distribution of random variables for weak earthquakes preceding a strong event using probabilistic methods.

Keywords: nonequilibrium thermodynamics, open systems, unstable dissipative nonlinear systems, self-organization processes, Kolmogorov's axiomatic method, probability space, random variables and events, earthquake

1. Introduction

The study of the processes that determine the evolution of open physical systems has led scientists to understand the fact that their development is due to unstable dissipative nonlinear systems [1]. Moreover, the instability of open systems is understood as such that, at characteristic observation times, as a result of the influence of minor external perturbations, it comes to a deviation in its state by an amount comparable to the characteristic values of the quantities that determine this state. In turn, an open nonequilibrium system that is in a stationary state far from thermodynamic equilibrium, which is provided by a balance between energy dissipation within the system itself and the influx of energy coming from outside, is called a dissipative system or a dissipative structure [1]. In addition, in an open system, due to the coordinated interaction of many of its elements through intensive (flow) exchange of matter and energy with the environment in nonequilibrium conditions, an ordering process (spatial, temporal, or spatio-temporal), called self-organization, can occur. In other words, in such systems, the coordinated behavior of subsystems is observed, as a result of which the degree of its ordering increases, i.e. entropy decreases. The conducted research in the field of "dissipative structures" led to the conclusion that the process of "self-organization" occurs much faster in the presence of external and internal disturbances (noise) in the system. Thus, noise phenomena lead to an acceleration of the self-organization process.

It is clear that any real open physical system is continuously under the action of small external and internal perturbations. Based on the most general considerations, it can be assumed that an earthquake is the result of a manifestation of a certain set of processes in the lithosphere, which is a nonlinear unstable system and which is under the action of the background field of external disturbances. A regular process, determined by compression or extension of the lithospheric plate, or other physical and chemical phenomena in a seismically active region on a global scale, is affected by a certain set of external disturbances in a consistent system of geospheres, determined by the system of solar-terrestrial relations. These perturbations excite the development of various instabilities, ultimately leading to local (in the volume of the focus) destruction of the structure, which is in a special limiting (critical) state. This state is characterized by a certain but rather complex balance between fluctuations in the system and its average characteristics, which determine the macroscopic state.

Thus, from the most general considerations, we can consider the preparatory stage of an earthquake as the development of instability that forms in local areas of the lithosphere against the background of external disturbances that arise in the chain "Sun—heliosphere—magnetosphere—ionosphere—neutral atmosphere—lithosphere."

The proposed work uses the catalog of earthquakes recorded by the Kamchatka regional network of seismic stations of the Kamchatka branch of the Geophysical Service of the Russian Academy of Sciences (KB GS RAS). This catalog can be divided into two parts [2]. The first part includes events from 1962 to 2009. By 2010, the approaches and methods for calculating the main parameters have changed, and the conditions for the formation of the catalog in close to real time have developed. This second part of the catalog contains data on earthquakes from 2010 to the present and is formed with a delay of 1–7 days. The Kronotskoe earthquake (1997-12-05) falls into the first part.

It should be noted that the greatest difficulties in processing the parameters of the catalog arise when determining the depth of an event. Each real value of the depth h_{real} is within the corresponding error interval $\pm \Delta h_{mist}$ relative to the depth h_{met} calculated by a certain method. Strictly speaking, the relation $h_{real} \in h_{met} \pm \Delta h_{mist}$ holds. That is, the real depth h_{real} can take any value from the set of values covered by the interval $h_{met} \pm \Delta h_{mist}$. Therefore, in this fuzzy situation, we will be interested not in some undefined value of the depth h_{real}, which falls somewhere in the corresponding error interval, but in the depth value h_{met} itself, calculated according to a certain method, for which the error interval $\pm\Delta h_{mist}$ is calculated. In this case, the depth value h_{met} is a fixed value and will depend only on the method of its calculation. For a homogeneous catalog, this technique is the same for all calculated depths. In the analysis carried out in this chapter, we will follow the dynamics of the trend, which would indicate a tendency in the distribution of the depths of various "background" earthquakes that form on large spatial scales, to group at the depth of the source of the impending major event. In other words, we will be interested in the question: at what depths h_{met} do "background" events fall on the eve of a strong earthquake. At the same time, we believe that the trend h_{met} reflects the general tendency of the real depth h_{real} of "background" earthquakes to cluster at the source depth of a major event. We will study this trend by probabilistic methods using wavelet decomposition methods [3, 4].

If the error is taken into account and some of its numerical values Δh_{mist} are specified, then in this case, events for which this error is greater than the specified one will be filtered out of all earthquakes in the catalog for the period under consideration. Naturally, in this case, the statistics will be reduced. Moreover, the smaller the given error, the closer the value of the real depth h_{real} to the value h_{met}, the smaller the statistics. In what follows, unless otherwise specified, the event depth will be understood as h_{met}.

2. Probabilistic methods for describing the seismic regime

As noted above, in a seismically active region against the background of external disturbances, conditions are formed for the development of local nonlinear processes, which are described by methods of nonlinear dynamics. The final stage of such instability is its destruction, which is registered on the Earth's surface in the form of an earthquake. Therefore, in order to consistently fulfill an earthquake forecast and answer the questions "where and when" a structure will form in a special state, and "what energy will be released" when it is destroyed, you need to know the trajectory of the unstable system, which describes the evolution of the active structure of the source zone in the phase space with dimension equal to the number of variables describing the behavior of the source zone.

For such a description of earthquakes, it is necessary to create a model that includes the whole complex of phenomena of various nature, and it is also necessary to know the parameters of the macroscopic state of the structure, as well as the boundary conditions. But there is no such model. However, assuming that the structure of the source zone is an unstable nonlinear system, which is under the influence of external perturbations, then, according to the general principles of nonlinear dynamics, it can go into a special limiting state. In this case (purely theoretically), we must calculate various averaged characteristics on the actual trajectories of unstable systems, the dynamics of which has the nature of chaos [5].

The averaging functional is chosen as a certain probability. Consequently, initially nonlinear systems with chaos dynamics are described by probabilistic methods. Therefore, the transition of the system to one or another special state and its destruction itself is of a probabilistic nature. However, it is the destruction of unstable structures in the lithosphere in a seismically active region that is perceived as an earthquake, and this fact, therefore, also has a probabilistic character. Thus, by studying the result of the destruction of the nonlinear structure of the source zone as a random event, we ultimately study the seismic regime by probabilistic methods and, ultimately, by indirect methods, study the dynamics of the structure of seismically active zones of the lithosphere.

The methods of seismological monitoring of a stress-strain geoenvironment related to the study of changes in the seismic regime can be extended if the method for calculating the probability distribution of earthquakes for various random events proposed in [6] and further developed in [7] is used to study it. This method is based on the axiomatic approach proposed by A.N. Kolmogorov in 1933 [8]. The application of this method to the catalog of Kamchatka earthquakes makes it possible to study the dynamics of the seismic regime using probabilistic methods for various regions both over the entire time period of instrumental observations and over various intervals lasting several years. With this approach, the catalog of seismic phenomena is represented as a probabilistic space of three objects. This allows us to consider each earthquake as a single outcome ω_i in the space of elementary events Ω, the power of which is determined by the number of events n (catalog). In turn, each elementary event ω_i in Ω is characterized by a system of random variables: energy class K_i, latitude φ_i, longitude λ_i, depth h_i, and time t_i. The time of a specific event in this model, as a random variable and having no mathematical expectation, is excluded from this system. In the future, we will consider a certain time interval ΔT, in which random events fall according to the catalog. The seismicity of the entire region or its selected part is considered as a complete group of events and is described in the form of distributions of conditional and unconditional probabilities P having a frequency representation. Random events are defined as combinations of a system of random variables φ, λ, h, and K in the set $\tilde{F}$. This allows us to represent the catalog of seismic events over the observation period as a probability space of three objects $\{\Omega, \tilde{F}, P\}$ and makes it possible to calculate probability distributions for various random events. If the distribution law of a system of random variables is given in analytical form by means of the distribution function $F(\varphi,\lambda,h,K)$ or its density $f(\varphi,\lambda,h,K)$, then the distribution laws of individual variables can be found using standard formulas. In our formulation, the most logical is the reverse representation of the problem: using the laws of distribution of random variables, obtain the distribution law of the system. For continuous values of the probability of hitting random events for some interval, the time interval ΔT within the given intervals in latitude $\Delta\varphi_i$, longitude $\Delta\lambda_j$, depth Δh_m, and class ΔK_n are calculated by the formula:

$$\begin{aligned} P(\Delta\varphi_i, \Delta\lambda_j, \Delta h_m, \Delta K_n) &= F(\varphi_i, \lambda_j, h_m, K_n) - F(\varphi_{i-1}, \lambda_{j-1}, h_{m-1}, K_{n-1}) = \\ &= P(\Delta\varphi_i) \cdot P(\Delta\lambda_j|\Delta\varphi_i) \cdot P(\Delta h_m|\Delta\varphi_i, \Delta\lambda_j) \cdot \\ &\quad P(\Delta k_n|\Delta\varphi_i, \Delta\lambda_j, \Delta h_m), \end{aligned} \tag{1}$$

where i, j, m, and n are the indices of the corresponding intervals of random variables. This expression uses the notation: $P(\Delta\varphi_i)$ is the unconditional probability of events falling into the interval $\Delta\varphi_i$; $P(\Delta\lambda_j/\Delta\varphi_i)$ is the probability of occurrence of events in $\Delta\lambda_j$ provided that the latitude of events is $\Delta\varphi_i$; $P(\Delta h_m/\Delta\lambda_j,\Delta\varphi_i)$ is the probability of hitting Δh_m, provided that the latitude and longitude are, respectively, $\Delta\varphi_i$ and $\Delta\lambda_j$; $P(\Delta k_n/\Delta h_m,\Delta\lambda_j,\Delta\varphi_i)$ is the probability of falling into the interval of the energy class ΔK_n, provided that the longitude, latitude, and depth are $\Delta\lambda_j$, $\Delta\varphi_i$, and Δh_m, respectively. Numerical values of $P(\Delta\varphi_i, \Delta\lambda_j, \Delta h_m, \Delta k_n)$ representations are easy to calculate. In a similar way, unconditional distribution laws are calculated for all random variables φ, λ, h, and K, as well as various combinations for conditional distribution laws from these variables. Processing the catalog according to the above formula makes it possible to calculate the frequencies of seismic events in a given interval of variation of random variables Δ and obtain the values of the distribution function $F(\Delta\varphi_i, \Delta\lambda_j, \Delta h_m, \Delta k_n)$. Let us consider the practical application of this approach to describe the seismic regime using examples of the study of the distribution of the depth of weak events $K_S \geq 8.5$ on the eve of Kronotsky (1997-12-05).

To this end, on the basis of the described approach with the subsequent use of wavelet decomposition methods, we study the dynamics of changes in the probability distributions over the depth of "background" earthquakes that occur several years before strong Kamchatka events with $M \geq 7.0$. This allows us to identify the depth range at which anomalous changes the parameters of this wavelet decomposition. At the same time, according to the findings of nonlinear dynamics, it is known that as the degree of instability of an arbitrary system increases and it approaches the critical state, both the intensity of parameter fluctuations and the time and length of correlations increase [1]. Therefore, the initial local ("microscopic") internal processes develop and acquire the character of coordinated ones, forming already on a global ("macroscopic") scale and capturing large seismically active areas. An increase in the length and amplitude of correlations in a nonequilibrium seismically active system indicates the connection of processes in some local selected area with its other parts. But logically, this should lead, over a certain time interval τ, to the formation of conditions conducive to an increase in the frequency of earthquakes in various parts of this region with less energy than in the main impending shock. Therefore, during the preparation of a strong (catastrophic) earthquake, large volumes of the lithosphere of a seismically active region are involved in the preparation area with a simultaneous increase in the frequency of occurrence of weak (background) events.

Based on the foregoing, it can be assumed that the preparation of an earthquake corresponds to the formation of an unstable nonlinear system, which is under the influence of external disturbance factors and develops according to the scenario of nonlinear dynamics. The interaction of the lithosphere with the environment (the chain "Sun—heliosphere—magnetosphere—ionosphere—neutral atmosphere"), with its nonequilibrium conditions, can be the starting point in the emergence of a new dynamic system, called the dissipative structure [9]. In this case, the scales of the connection between different parts of the nonlinear structure change. In other words, the scales of temporal and spatial correlation change. For example, during the formation of a dissipative structure, which are Benard cells or self-oscillating Belousov-Zhabotinsky reactions, the spatial scales change from intermolecular 10^{-8} cm, which describe the interaction between molecules, to several cm [10, 11]. In turn, the time scales vary from 10^{-15} s, corresponding, for example, to the periods of oscillations of individual molecules, to several seconds, minutes, or even hours [12]. With this in mind, we hypothesize:

During the preparation of the main major event with $M \sim 7.0$ in a certain volume of a seismically active region, which is in an unstable state far from equilibrium, a consistent, correlated increase in seismic activity occurs at the "background" level, which covers areas far from the epicenter of the future event. At the same time, strong foreshocks with subsequent development of aftershock activity are possible in these areas at the depths of an upcoming earthquake. The scales that determine the temporal τ and spatial L correlation during the formation of these earthquakes are several years for τ and hundreds of kilometers for L and depend on the magnitude M of the upcoming main shock.

To test this hypothesis, the Kronotsky earthquake was considered: 1997-12-05 11:26:51 (UT), φ = 54.64° N, λ = 162.55° E, depth h = 10 km, depth determination error

2 km, energy class in terms of the amplitude of the S wave, determined by the nomogram of S. A. Fedotov K_S = 15.5, local magnitude of the Kamchatka region (according to Ch. Richter) M_L = 7.0, magnitude by code waves Mc = 7.7.

Figure 1 shows the area along the eastern coast of the Kamchatka Peninsula, which is divided into 12 sectors, defined by intervals of latitude $\Delta\varphi$ = 1° and longitude $\Delta\lambda$ = 1.5°. For these areas, based on the catalog of seismic events provided by the KB GS RAS, on the basis of equation (1) the probability distributions $P(\Delta h)$ (histograms) characterizing the occurrence of seismic events with an energy class $K_S \geq 8.5$ ($M \geq 3.5$) in the given depth intervals with a step Δh = 1 km will be further calculated up to H = 100 km for two cases—without taking into account the determination of the depth error and taking into account the given error. At the next processing step, the obtained seismic event probability distribution series $P(\Delta h)$ over depth were presented in the form of a continuous wavelet decomposition [4], which makes it possible to smooth the histogram of the probabilistic representation of the earthquake depth distribution:

$$(W_\Psi P)(b, a) := |a|^{-1/2} \int_{-\infty}^{\infty} P(h) \overline{\Psi\left(\frac{h-b}{a}\right)} dt \qquad (2)$$

where Ψ is the basis wavelet, $P(h)$ is the numerical series of probabilities, and coefficients are $a, b \in R$, and $a \neq 0$.

In the process of transformation, orthonormal Daubechies wavelets of the third order were used [4]. The decomposition was carried out up to the 32nd scale level. As an example, **Figure 2a** shows the original probability distribution series calculated for 1996 for the entire area indicated in **Figure 1**. **Figure 2b** shows the results of the wavelet transform of this distribution. Since the wavelet transform coefficients are proportional to the squares of the probabilities and, therefore, give the distribution of the intensity ("energy") of the process over scales [3, 4], the sum of the wavelet coefficients was calculated over all scale levels that characterize the distribution of the

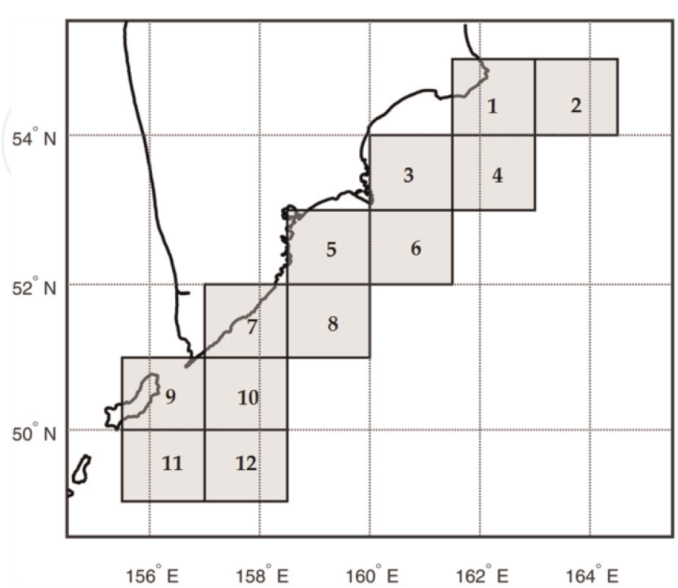

Figure 1.
Location of 12 regions along the eastern coast of Kamchatka with dimensions in latitude and longitude $S_i = \Delta\varphi \times \Delta\lambda = 1° \times 1.5°$.

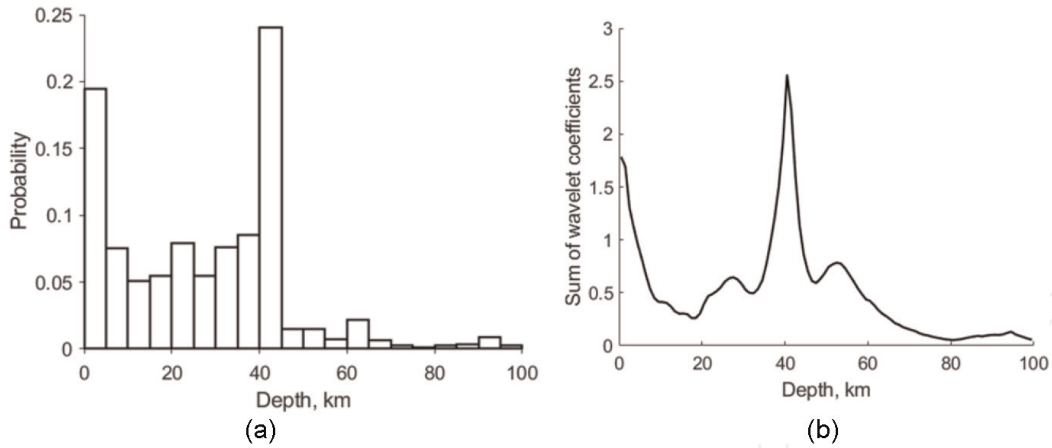

Figure 2.
(a) Probability distribution earthquakes by depth for 1996 and (b) sum of wavelet coefficients for probability distribution earthquakes by depth for 1996.

"energy" of the studied seismic process in depth in a given sector (y-axis in **Figure 2b**):

$$E = \sum_{i=1}^{n} W_{\Psi} P_i \tag{3}$$

where n is the number of scale decomposition levels and $W_{\Psi}P_i$ is the wavelet coefficient at the ith level of decomposition of the function $P(h)$.

3. Analysis of the Kronotsky earthquake without taking into account the determination of the error in the depth of the event

For the Kronotsky earthquake, four time periods were considered from 1 January to 31 December for 1994, 1995, and 1996 and from 1 January to 4 December, 1997 until the event itself (see **Figures 3** and **4**). The earthquake itself occurred on 1997-12-05 in sector № 1. The consideration was carried out without an error in taking into account the depth of the event.

Figure 3 shows the results of wavelet decompositions for 1994 and 1995 for all the studied sectors. In sector № 1 in 1994, 23 events occurred (N is marked in the legend for the corresponding year and in the corresponding sector) with their concentration at depths of 18 km and 40 km, while the sum of the wavelet coefficients for these depths was respectively $(\text{Coeff})_{18} = 1$ and $(\text{Coeff})_{40} = 1.5$. In 1995, the number of events in this sector increased to 44, and their intensity shifted to depths in the region of 30, 40, and 50 km and $(\text{Coeff})_{30} = 1.1$, $(\text{Coeff})_{40} = 1.6$, $(\text{Coeff})_{50} = 1.1$. In 1996, the number of events increased to 96 with a clear maximum at 40 km ($(\text{Coeff})_{40} = 2.2$) and additional maxima at 12 km ($(\text{Coeff})_{12} = 0.5$), 23 km ($(\text{Coeff})_{23} = 0.9$), and 50 km ($(\text{Coeff})_{50} = 1.1$). In 1997, the number of events decreased to 64 with two intensity maxima at depths of 36 km ($(\text{Coeff})_{36} = 0.6$) and 48 km $(\text{Coeff})_{48} = 0.8$) (see **Figure 4**). Moreover, at a depth of 40 km, there was a clear decrease in seismic activity $(\text{Coeff})_{40} = 0.2$.

Corresponding changes for the period 1994-01-01/1995-12-31 (**Figure 3**) also occurred in each of the studied sectors from 2 to 12, and an increase in the number of

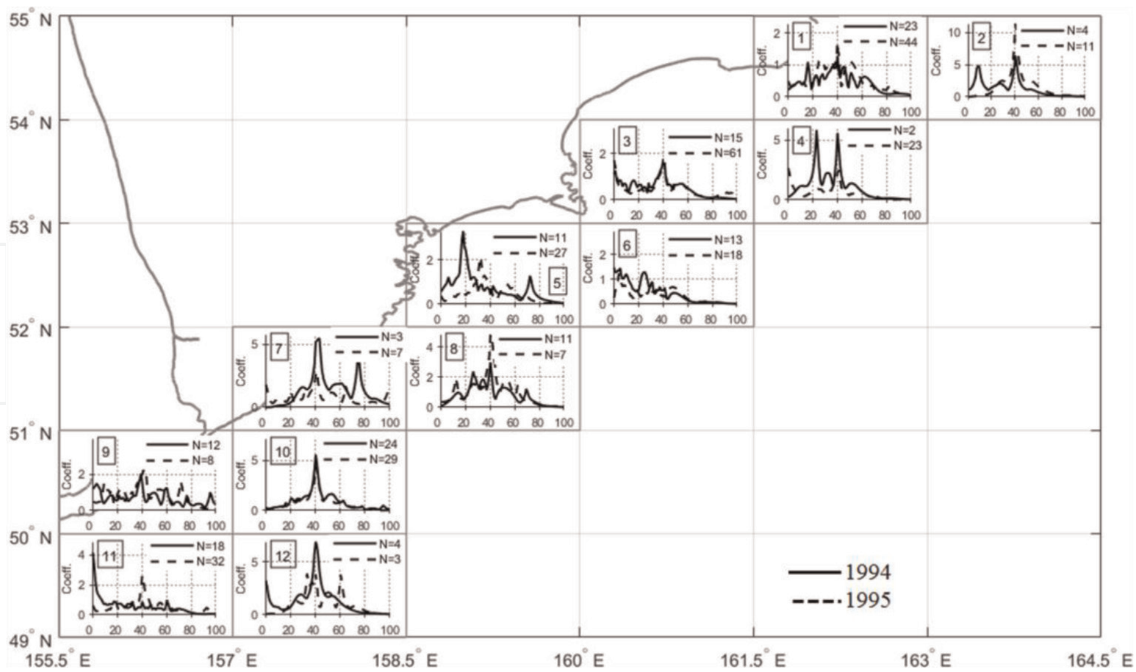

Figure 3.
The summed wavelet coefficients from scale level 1 to 32 for probability distributions P(Δh) *of earthquakes with energy class* $K_S \geq 8.5$ *over depth intervals Δh = 1 km for 1994 and 1995.*

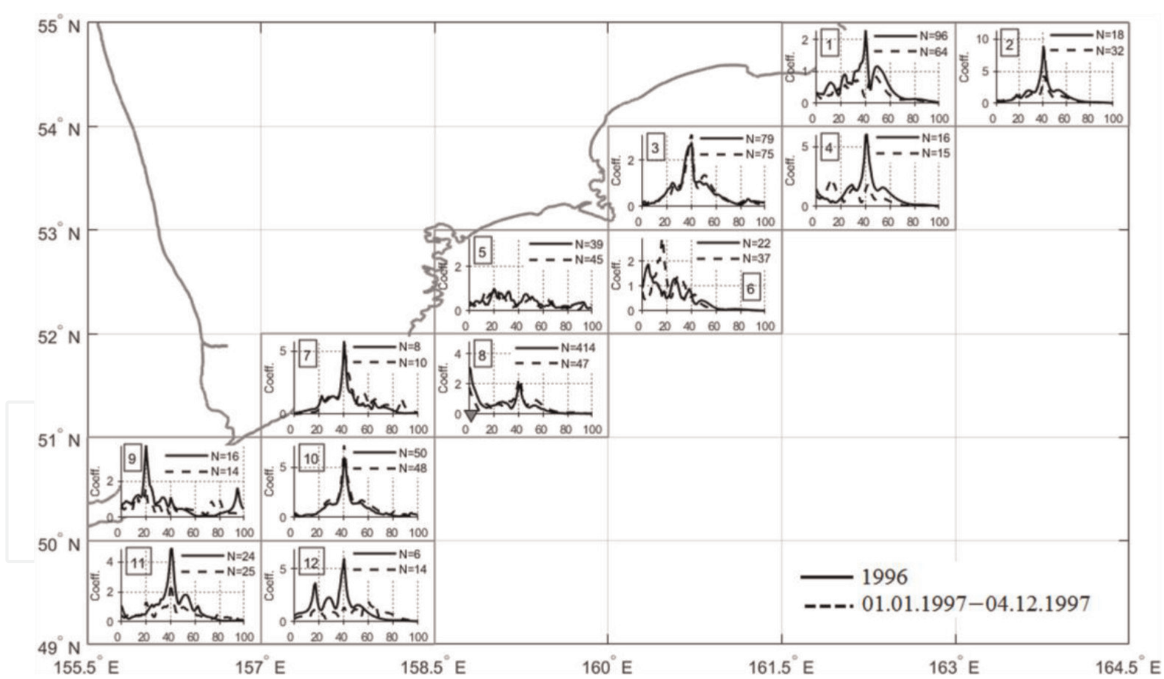

Figure 4.
The summed wavelet coefficients from scale level 1 to 32 for the probability distributions P(Δh) *of earthquakes with energy class* $K_S \geq 8.5$ *over depth intervals Δh = 1 km for 1996 and for the period from 01.01.1997 to 12.04.1997. The triangle in sector № 8 marks two earthquakes on June 21, 1996 and July 18, 1996 (see text).*

events is characteristic of all sectors. The exceptions are sectors № 8, № 9, and № 12, for which the number of events decreased from 11, 12, and 4 in 1994 to 7, 8, and 3 in 1995. At the same time, a shift to shallow depths with increasing earthquake intensity occurred in 1995 in sectors № 4 (at zero depths with $(\text{Coeff})_0 = 2.4$) and №. 7 (at zero depths with $(\text{Coeff})_0 = 1.8$). In sector № 6, the intensity of events at shallow depths up to 20 km in 1994 slightly decreased compared to 1995. In sector 11, the intensity of events in 1994 was located at shallow depths from 0 to 10 km with a maximum at zero depth ($(\text{Coeff})_0$ = 4). In 1995, the intensity of earthquakes dropped sharply with the formation of a maximum at a depth of 40 km with $(\text{Coeff})_0$ = 2.2. It should be noted that for the period 1994-01-01/1995-12-31 at a depth of 40 km, distinct maxima of events of different intensity formed at a depth of 40 km in sectors 2, 3, 4, 7, 8, 10, and 12.

In 1996 (see **Figure 4**), an increase in the intensity of earthquakes at shallow depths up to 20 km clearly manifested itself in sectors № 6 ($(\text{Coeff})_5$ = 1.9) and № 8 ($(\text{Coeff})_0$ = 3). During this period, two earthquakes occurred in sector № 8, followed by aftershock activity with a total number of events N = 414:

- 1996-06-21.; φ = 51.27, λ = 159.63; h = 2 km, K_S = 13.9; M = 6.2;
- 1996-07-18; φ = 51.22, λ = 159.82; h = 8 km, K_S = 13.5; M = 6.0.

From 1996-01-01 to 1996-06-20 (before the earthquake of 1996-06-21), five seismic events with $K_S \geq 8.5$ occurred in sector № 8. From 1996-06-21 to 1996-07-17 (before the earthquake of 1996-07-18), there were 348 earthquakes with $K_S \geq 8.5$ (aftershock activity). After the earthquake of 1996-07-18, the aftershock activity in this sector sharply decreased, and until 1996-12-31, only 61 seismic events with $K_S \geq$ 8.5 occurred. Seismic activity at a depth of 40 km decreased in 1997 in sectors № 1, 2, 4, 9, 11, 12.

Graphs of the summed wavelet coefficients calculated from the probability distributions $P(\Delta h)$, calculated for the entire area S_Σ, which includes 12 regions, are shown in **Figure 4**. This figure shows the dynamics of changes in the intensity distributions of seismic events over the years, starting from 1994-01-01 and ending on 1997-12-04 (one day before the Kronotsky event). For comparison, **Figure 4** shows the distribution of seismic events averaged over the period of instrumental observations from 1962-01-01 to 2021-12-31 without taking into account the error in determining the depth of earthquakes. In this figure, for the average intensity plot 1962-01-01/2021-12-31 at a depth of 40 km, the peak of seismic activity for the entire eastern coast is clearly distinguished, which is also distinguished for shorter periods of time (1994-01-01/1997-12-31). In addition, **Figure 4** also shows less intense "petals" of averaged activity at depths of approximately 12, 18, 30, and 55 km, which, to one degree or another, repeat the "petals of activity" for 1994, 1995, 1996, and 1997 with large values of the wavelet expansion coefficients Coeff. This similarity indicates that in the lithosphere, at least along the studied area of the eastern coast of Kamchatka, there is a certain "fine" structure of zones of increased activity [13].

It follows from **Figures 3–5** that for 1994, starting from zero depths, the intensity of seismic events (numerical values of Coeff) decreases with increasing depth and merges with the averaged intensity of 1962-01-01/2021-12-31 obtained over the entire instrumental period of observation. Starting from 30 km, the intensity for 1994 exceeds the average. Over 1995, the intensity at shallow depths (from 0 to 10 km) becomes less than the intensity over 1994. In 1996, due to the earthquakes of 1996-06-21 and 1996-07-18, and aftershock activity, the intensity of seismic events at shallow depths (from 0 to 15 km) exceeds the intensity for 1994 and 1995, remaining similar to the average intensity for the period of instrumental observations from 1962 to 2021-12-31. In 1997, the intensity at shallow depths decreases and practically merges with the intensity from 1994 to 1996 at depths greater than 35 km.

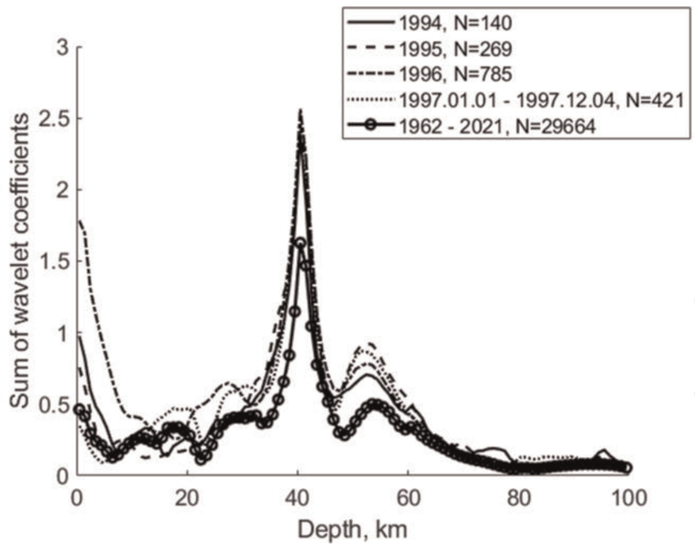

Figure 5.
The summed wavelet coefficients from scale level 1 to 32 for the probability distributions P(Δh) *of earthquakes with energy class* $K_S \geq 8.5$ *over depth intervals* Δh = 1 *km for the* S_Σ *region for the entire period of 1994, 1995, and 1996 and from 01.01.1997 to 04.12.1997. For comparison, the intensity distribution of seismic events for the period of instrumental observations from 01.01.1962 to 31.12.2021 is presented, against which events develop for the considered period of time 1994–1997.*

4. Analysis of the Kronotsky earthquake, taking into account the determination of the error in the depth of the event

Let us consider the case when the error in determining the depth of the earthquake hypocenter $\Delta h_{mist} \leq 5$ km is taken into account. **Figures 6** and **7** show the results of wavelet decompositions for 1994, 1995, and 1996 and from 1995-01-01 to 1997-12-04 for all the studied sectors. As can be seen from the figures, taking into account the error in determining the depth of the hypocenter leads to a sharp reduction in statistics. In some sectors, there are no events at all, which, of course, complicates the analysis. **Figures 8** and **9** for the region S_Σ present the summed wavelet coefficients from scale level 1 to 32 for the probability distributions $P(\Delta h)$ of earthquakes with $K_S \geq 8.5$ over depth intervals Δh = 1 km and the error in determining the depth of hypocenters for. For comparison, **Figures 8** and **9** show the intensity distribution of seismic events over the period of instrumental observations from 1962-01-01 to 2021-12-31, taking into account $\Delta h_{mist} \leq 5$ km, against which events develop over the considered time period 1994–1997. As can be seen from **Figures 8** and **9**, taking into account the error leads to a significant change in the depth distribution of earthquake intensity. So in **Figure 8**, the peak of the maximum seismic activity at 40 km for 1994, which is clearly distinguished in **Figure 5**, is completely absent. Instead of a maximum at this depth, we have a minimum.

In addition, **Figure 8** for 1994 shows several clear intensity peaks in the altitude range of 18–40 km (Coeff ≈ 1.4, Coeff ≈ 1, and Coeff ≈ 1.2), 40–65 km (Coeff ≈ 0.7), and 65–90 km (Coeff ≈ 0.4). In turn, the intensity at shallow depths from 0 to 10 km for 1994-01-01/1995-12-31 slightly exceeds the intensity for the period 1962-01-01/ 2021-12-31. The absence of a maximum at a depth of 40 km in **Figure 8** indicates that the error in determining the depth for 1994 is mostly greater than the selected Δh_{mist} ≤ 5 km, so these earthquakes were not included in the statistics and were sifted out. In turn, in 1996, the accuracy in determining the depth of hypocenters equal to 40 km

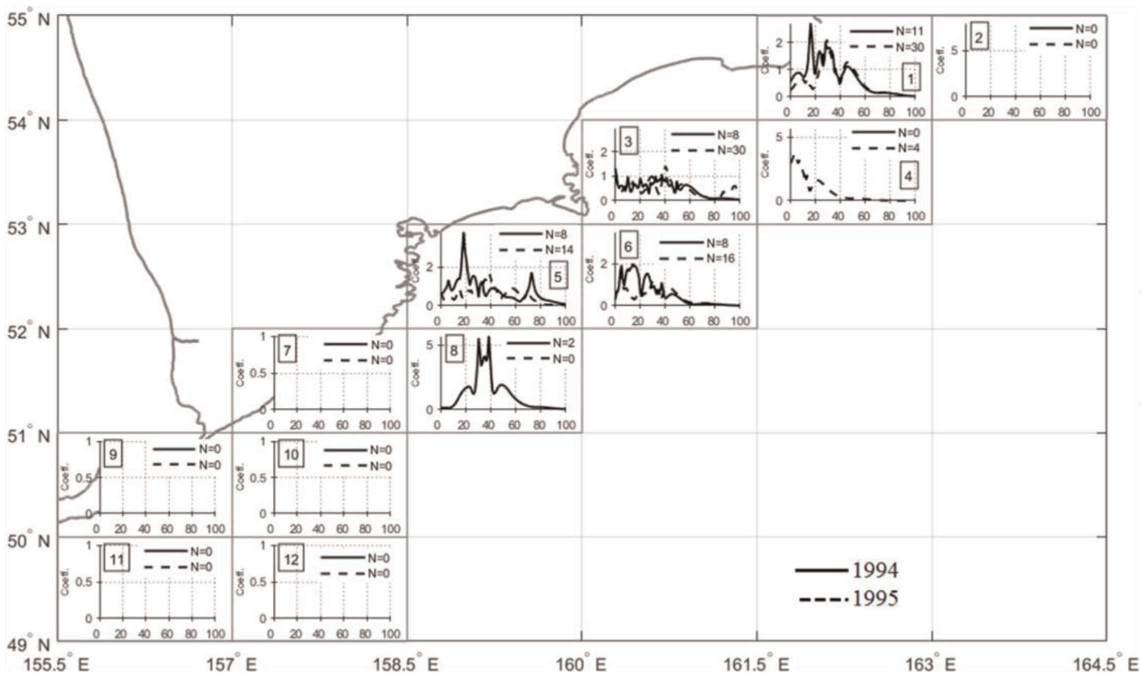

Figure 6.
The summed wavelet coefficients from scale level 1 to 32 for the probability distributions P(Δh) *of earthquakes with energy class* $K_S \geq 8.5$ *over depth intervals* Δh = 1 *km for 1994 and 1995, taking into account the error in determining the depth* $\Delta h_{mist} \leq 5$ *km.*

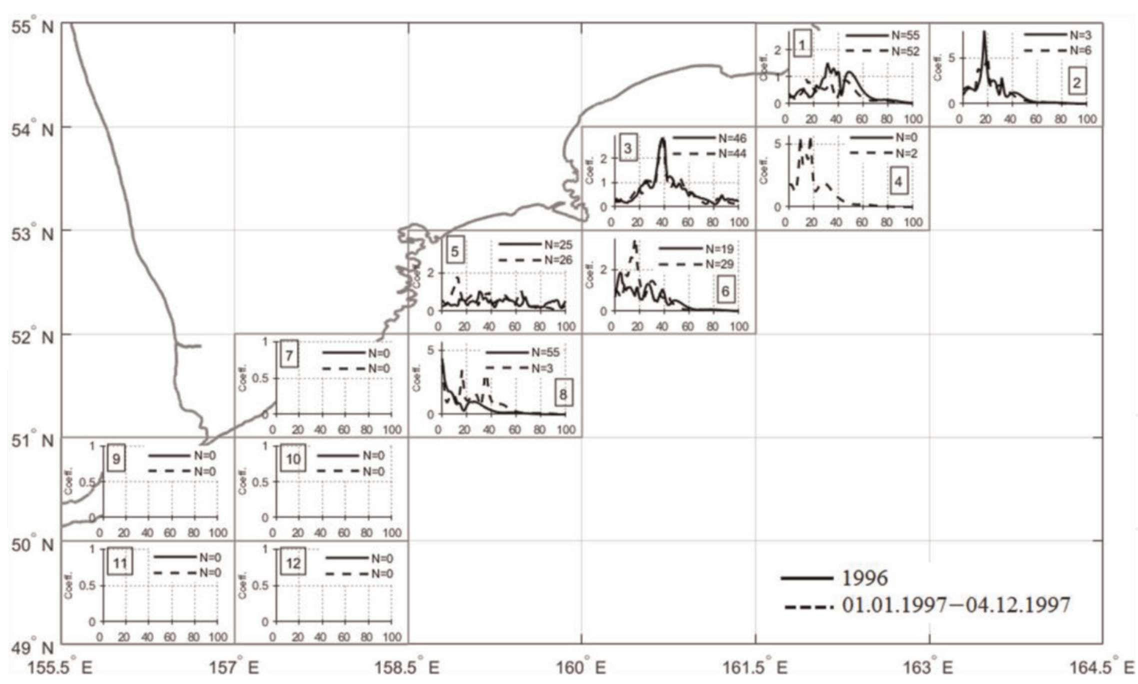

Figure 7.
The summed wavelet coefficients from scale level 1 to 32 for the probability distributions P(Δh) *of earthquakes with energy class* $K_S \geq 8.5$ *over depth intervals* Δh = 1 *km for 1996 and for the period from 01.01.1997 to 04.12.1997, taking into account the error in determining the depth* $\Delta h_{mist} \leq 5$ *km.*

mostly satisfied the accuracy of $\Delta h_{mist} \leq 5$ km, and as a result, the intensity peak was identified (see **Figure 9**).

It follows from the analysis of **Figure 8** that the intensity of the wavelet coefficients at depths from 0 to 10 km in 1996 increased sharply compared to 1994 and

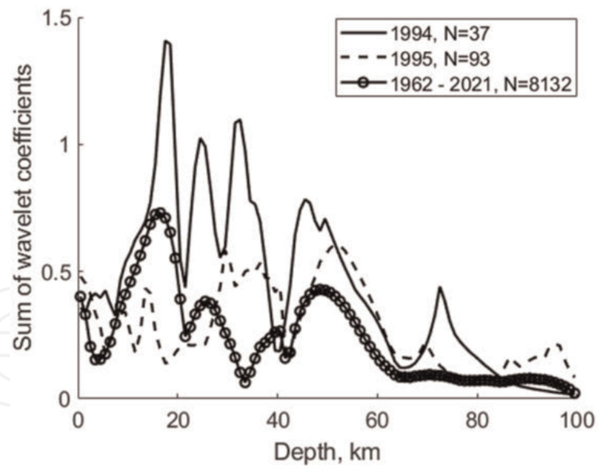

Figure 8.
The summed wavelet coefficients from 1 to 32 scale decomposition level for the probability distributions P(Δh) *of earthquakes with* $K_S \geq 8.5$ *over depth intervals* Δh = 1 km *and an error in determining the depth of hypocenters* $\Delta h_{mist} \leq 5$ *km. The periods under consideration are 1994, 1995, and 1962–2021.*

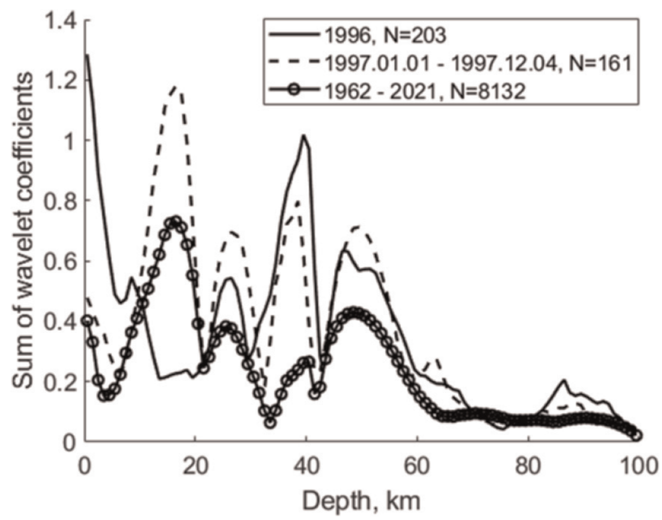

Figure 9.
The summed wavelet coefficients from scale level 1 to 32 for the probability distributions P(Δh) *of earthquakes with* $K_S \geq 8.5$ *over depth intervals* Δh = 1 km *and an error in determining the depth of hypocenters* $\Delta h_{mist} \leq 5$ *km. The periods under consideration are 1996, 1997.01.01–1997.12.04, and 1062–2021.*

1995. This happened, as we know, as a result of aftershock activity after the earthquake of June 21, 1996.

If we compare **Figure 5** with **Figures 8** and **9**, then the latter show some chaotization in the distribution of wavelet coefficient intensity peaks over depths with similar Coeff values. A similar picture is also observed in the averaged distributions of wavelet coefficients for 1962-01-01/2021-12-31, taking into account the determination of the error in the depth of hypocenters and without taking into account. This suggests that with such a choice of the numerical value of Δh_{mist}, we simply lose information about the intensity of the distribution of events over h.

5. Conclusions

Taking into account the hypothesis stated earlier, we will summarize this section. In sector № 8 in 1996, two earthquakes with magnitudes M ≥ 6 took place at depths ranging from 0 to 10 km. The first event (1996-06-21) was accompanied by increased aftershock activity (348 earthquakes with $K_S \geq 8.5$ occurred from 1996-06-21 to the second shock on 1996-07-18). After the second shock, the activity decreased sharply, and until 1996-12-31, only 61 seismic events occurred. Considering the dynamics of general seismicity over the years (see **Figures 3** and **4**), we see that in areas far from the main shock, at the depths of the upcoming earthquake, strong events with aftershock activity arose, after which a seismic lull followed and continued until the main event on 1997-12-05 with $M_L = 7.0$, which occurred at a depth of $h = 10$ km. The distance from the main shock, which took place in sector 1, to the seismic events preceding it in sector 8 with subsequent intensification of aftershock activity, was more than 400 km. In turn, from 1994 to the main shock on 1997-12-05, seismic activity increased at shallow depths (from 0 to 20 km) in sectors that are mosaically scattered along the eastern coast of Kamchatka, as well as in different time intervals (not simultaneously).

To support this hypothesis, we can note:

- for several years, sectors of the background enhancement of seismic activity at the depths of an impending major event, mosaically scattered along the eastern coast;
- the occurrence of foreshock events far and at the depths of an impending major earthquake.

It is absolutely clear that the consideration of one event as a confirmation of the stated hypothesis is not enough and requires further research on the example of other large earthquakes. In addition, the impossibility of a more accurate determination of the hypocenter depth and its replacement by h_{met}, when the error Δh_{mist} is commensurate with the depth itself, seems to be somewhat arbitrary. However, the ideology of this approach to the analysis of the depth distributions of earthquake epicenters on the eve of major events based on the application of the general conclusions of nonequilibrium thermodynamics, in our opinion, is promising.

Author details

Vadim Bogdanov* and Aleksey Pavlov
Institute of Cosmophysical Research and Radio Wave Propagation FEB RAS, Paratunka, Russia

*Address all correspondence to: vbogd@ikir.ru

References

[1] Nikolis G, Prigozhin I. Poznanie slozhnogo. Editorial URSS; 2003. p. 344

[2] Chebrova A, Matveenko E. Sostojanie okonchatel'nogo kataloga zemletryaseniy Kamchatki i Komodorskikh ostrovov v 2013 godu. In: Problemy kompleksnogo monitoringa Dal'nego Vostoka Rossii; 29 sentjabrja-5 oktjabrja 2013; Petropavlovsk-Kamchatskij. Obninsk: GS RAN; 2013. pp. 122-126

[3] Dobeshi I. Desjat' lekcij o vejvletah. Izhevsk: NIC "Reguljarnaja i haoticheskaja dinamika"; 2001. p. 464

[4] Chui K. Vvedenie v vejvlety. Per. s anglijskogo, M.: Mir2001. p. 412

[5] Zhigulev V. Dinamika neustojchivochtej (Dinanstika): Fizicheskie osnovy nelinejnoj dinamiki. MFTI; 1996. p. 344

[6] Bogdanov V. Verojatnostnaja interpritacija zakona povtorjaemosti zemletrjasenij na primere Kamchatskiz zemletrjasenij. Dokl. AN. 2006;**408**: 393-397

[7] Bogdanom V, Pavlov A, Poljuhova A. A Probabilistic model of seismicity: Kamchatka earthquakes. Journal of Volcanology and Seismology. 2010;**4**: 412-422

[8] Kolmogorov A. Osnovnye ponjatija teorii verojatnostej. Nauka; 1974. p. 120

[9] Prigozhin I, Stengers I. Vremja. Haos. Kvant. M. Editorial URSS; 2001. p. 240

[10] Chandrasekhar S. Hydrodynamic and Hydromagnetic Stability. Oxford, England: Clarendon Press; 1961. p. 652

[11] Merischal M, Malek MM, Puhl A, Kestemont E. Molecular hydrodynamic versus hydrodynamic in two-dimensional Rayleigt-Benard Systems. Physical Review Letter. 1988;**61**:2550

[12] Prigozhin I, Stengers I. Porjadok iz haosa: Novyj dialog cheloveka s prirodoj. Editorial URSS; 2001. p. 312

[13] Boldyrev SA. Otrazhenie struktury i svojstv litosfery v sejsmicheskom pole Kamchatskogo regiona. Fizika zemli. 2002;**6**:5-28