Chapter

Analysis of Seismic Responses of Rock Massif to Explosive Impacts with Using Nonlinear Methods

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Abstract

When conducting mining operations in high-stress rock massive, technogenic seismicity is manifested, with forecasting and prevention issues being given much attention in all countries with a developed mining industry. An important role here belongs to the short-term forecast; the methodology for identifying criteria for it is still a problem, both in mining and in seismology. From the point of view of the paradigm of physical mesomechanics, which includes a synergetic approach for changing the state of rock massive of material with different compositions, this problem can be solved with the help of monitoring methods tuned to the study of hierarchical structural media. Changes in the environment, leading to short-term precursors of dynamic phenomena, are explained within the framework of the concept of self-organized criticality, for which the central moments are heterogeneity and nonlinearity. Introduction of the proposed integrated passive and active geophysical monitoring, aimed at studying the transient processes of redistribution of the stress–strain and phase states, can contribute to the prevention of catastrophic dynamic manifestations during the development of deep-lying deposits. Methods of active geophysical monitoring should be tuned to a model of a hierarchical heterogeneous medium and provided with new results of propagation of wave fields in layered block media with inclusions of a hierarchical structure.

Keywords: electromagnetic, seismic, monitoring, impact-threatening rock massive, new analysis, new monitoring methodology, nonlinear, hierarchical model of the environment

1. Introduction

Synergetics is an interdisciplinary science that allows one to imagine the phenomenon of self-organization in the tasks of physics, chemistry, biology, earth sciences, sociology, and other open systems. The term synergetics was proposed in the 1970s by the German physicist Haken [1]. His works had been devoted to the theory of self-organization in various natural systems. At present, important theoretical and experimental results have been obtained, confirming the relevance of synergetic approach for studying the universal properties of open nonequilibrium dynamical systems, cooperative effects in self-organization processes [2]. In recent decades, interest is aimed to study of nonlinear dissipative systems in which a decrease in the number of degrees of freedom that effectively describes them has been observed. Sometimes it is possible to distinguish several degrees of freedom, to which all the others are adjusted. They determine the dynamics of processes and are therefore called order parameters. When studying dissipative systems, their existence allows for a simplified description or construction of an entire hierarchy of simplified models. A decrease in the number of degrees of freedom means that self-organization occurs in the system, i.e., the system has properties that none of the subsystems possesses. To emphasize this circumstance, the theory of self-organization is also called synergetics. The term "dissipative structure" was introduced by I. Prigozin. He and his school helped to establish the connection between the origin of structures, phenomenological models, and representations of nonequilibrium thermodynamics, which played a big role in the theoretical and experimental study of ordering in open systems [3–5]. Removability from equilibrium and nonlinearity can serve ordering in the system. Between order, stability, and dissipation, a nontrivial relationship arises. Ordered configurations that appear outside the stability region of a thermodynamic branch will be called dissipative structures, which can exist only due to a sufficiently large energy or matter flow. The appearance of order in open nonlinear systems is a paradoxical fact.

In equilibrium systems, dissipative processes destroy any order, and thermodynamic equilibrium is established. In nonlinear open systems, together with other processes, dissipative processes affect the type, form, and size of the dissipative structures. It is known that the geological environment is an open dynamic system that undergoes natural and artificial influences at various scale levels, changing its state, resulting in a complex multi-face hierarchical evolution, which is also one of the subjects of the study of geosynergetics [6–10]. The large number of geological systems is open and nonequilibrium, which can exist for a long time only in the mode of pumping energy through them. The termination of the energy flow leads the system to transition to the conservation stage, when the duration of existence is determined by its energy potential due to the accumulated energy at the previous stage. A distinctive feature of open geological systems is their irreversibility and multifunctionality. Using the synergetic approach, it is necessary to clearly distinguish the scale of natural phenomena. Thus, the growth of individual crystals obeys the laws of thermodynamics, and already the morphology of crystals clusters' changes of their forms is determined by the state of the growth medium linked with external influences [11].

Geological environments can be divided into concentrated and dispersed states. Concentrated systems are characterized by their continuity; they represent as a whole on the considered time interval and state by parameters, determining at the first approximation their stationary state. It can be a magmatic chamber, a single fluid system, a block of rocks of a similar composition, a water basin, an oil deposit, or a massive ore body. In concentrated stationary systems, nonequilibrium processes occur aimed for equalizing the thermodynamic parameters characterizing their state. The distributed systems represent a set of autonomous subsystems that are interconnected by heat and mass transfer channels within the framework of irreversible processes, which can be broken down into several stationary states characterized by a constancy of the main control parameters of the process in the chosen time interval. For heterogeneous and complex in composition real geological systems, it is advisable to talk about the equality of not all parameters but only those that determine the macroscopic state of a particular system—its control parameters. In a predominant number of cases, geological systems are non-stationary, since their parameters do not remain unchanged during their existence. The entire development path of such systems is divided into a number of stationary subsystems, characterized by small changes in their parameters at the chosen time interval. Accordingly for each stationary subsystem, a set of stationary processes are fixed in certain structurally real complexes.

At a certain stage of development, an open dynamic system, exchanging matter and energy with the environment, breaks up into a number of subsystems, which in turn can further split into even smaller systems. How to draw boundaries between them if the processes in these systems could take place tens and hundreds of millions of years ago and sometimes billions? The criterion for determining the boundaries of such systems is one of the tasks of synergetics: macroscopic processes in systems where self-organization processes occur in the nonlinear area are carried out cooperatively, in concert and coherently. In the case of geological systems, the boundary will pass along the line of replacement of some structural-material complexes by others, usually mineral aggregates. The basis of the processes of self-organization in open nonequilibrium geological systems is the energy source. If the energy potential does not reach the threshold value, then the processes of self-organization do not occur, but if it is sufficient to compensate for its loss to the external environment, then self-organization processes will appear and spatial–temporal or temporal structures will be formed. The transition of the chaos structure is carried out abruptly. If the energy input into the system is too much, the structuring of the medium stops, and we have a transition to chaos. In any open, dissipative, and nonlinear systems, self-oscillating processes arise, supported by external sources of energy, as a result of which self-organization proceeds [12].

The paradigm of physical mesomechanics introduced by academician Panin V. Y. and his school [13], which includes a synergetic approach, is a constructive tool for studying and changing the state of heterogeneous materials. This result was obtained by this school on samples of various materials. In our studies of the non-stationary geological environment, in the framework of full-scale experiments in real mountain massifs under strong technogenic influence, it was shown that the dynamics of the state can be detected using synergetics in hierarchical environments [14, 15]. An important role in the study of dynamic geological systems is played by a combination of active and passive geophysical monitoring, which can be carried out using electromagnetic and seismic fields. The change in the state of the system on the investigated spatial bases and times is manifested in parameters related to the structural features of the medium of the second and higher rank. Thus, the study of the dynamics of the state and its structure and the phenomenon of self-organization of the array should be led by geophysical methods tuned to the multi-rank hierarchical non-stationary model of the environment [16]. The results obtained from laboratory experiments allowed physicists to propose a model of periodic structural transformations based on a system of nonlinear differential equations that determine the joint evolution of the densities of decaying boundaries, chaotic dislocations, and the boundaries of the emerging structures and also to show that the synergetic scheme allows to describe in a unified way the structurally caused plastic deformation in condensed media [17]. For the fields of plastic deformation and stresses, a system of nonlinear equations is proposed that makes it possible to represent such a regime in agreement with the experimental data. The available results of terrestrial and especially borehole and underground geophysical observations indicate nonlinear manifestations in rock massive during their development.

2. Results of the using theoretical principles for the analysis of active monitoring of mountain massifs under technogenic impact

One of the fundamental problems of mining, which is traditionally attributed to the problems of geomechanics, is the development of theoretical and experimental methods for studying the structure and state of rock massive with a view to predicting and preventing catastrophic phenomena in the mining of deposits. This problem is complicated by the fact that the rock massif is influenced by direct or indirect technogenic impact, which leads to a significant non-stationary of both the structure and the state of it. The ideological inspirer of the search for integrated geophysical and geomechanical approaches to the solution of this problem in the Ural was N. P. Vlokh [18]. An analysis of the manifestations of mountain impacts in the mine workings of the Oktyabrsky deposit of the Norilsk ore site showed that more than 60% of them are confined to tectonic disturbances. Peeling and intensive incineration occur mainly in excavations located outside the zone of influence of clearing works at a distance of 10–12 m from the surface of the tectonic disturbance. In the ores and rocks of medium disturbance, the dynamic phenomena dominate in the areas of interface of the excavations and are accompanied by collapse of the massif. When intersections with excavations of areas of the massif with irregularities have two or more planes of displacement, with a zone of crumpled and fragmented rocks, collapse from the roof and collapses from the sides are observed, accompanied by a dynamic effect and reaching considerable volumes [19]. When conducting mining operations in high-stress rock massive, technogenic seismicity is manifested, with forecasting and prevention issues being given much attention in all countries with a developed mining industry. An important role here belongs to the short-term forecast; the methodology for identifying criteria for it is still a problem, both in mining and in seismology [20]. From the point of view of the paradigm of physical mesomechanics, which includes a synergetic approach to changing the state of rock massive of different material composition, this problem can be solved with the help of monitoring methods tuned to the study of hierarchical structural media [13, 21]. Changes in the environment, leading to short-term precursors of dynamic phenomena, are explained within the framework of the concept of self-organized criticality [17, 20], for which mainly significant moments are heterogeneity and nonlinearity [13].

Within the framework of the IGD SB RAS School, important results have been achieved in studying the state of the rock mass within the framework of nonlinear geomechanics [22] using geophysical methods that have the resolving power to detect the nucleation and decay of self-organizing structures [23].

For the first time, using the electromagnetic method developed in the IGF UB RAS, it was possible to realize the idea of identifying zones of disintegration in an array of rocks within the framework of field studies [24, 25] and to monitor their morphology [26]. The technique used relates to geophysical methods of nondestructive testing. It differs from the previously known methods of semitransparency or tomography by observation systems and the subsequent interpretation method based on the concept of three-stage interpretation [27]. In [28] the first full-scale results on the detection of the self-organization phenomenon in a rock massif with anthropogenic impact and the method of developing stability criteria based on the proposed classification methodology had been represented. These results were obtained on the basis of analysis of several cycles of electromagnetic monitoring of the massif of the shock-dangerous Tashtagol underground mine, conducted in 2000, 2001, 2002, 2003, 2004, and 2005 in a number of excavations located on four horizons at depths from 540 to 750 m in order to reveal the morphology of the zones of disintegration in the near-working space in a rock massif that is under intense man-caused impact and the influence of the natural stress field. In the work [23], studies were conducted aimed at developing criteria for spatial–temporal complex active and passive seismic and electromagnetic monitoring to prevent destructive dynamic phenomena based on 6-year seismic monitoring data conducted by the service of rock shocks in Tashtagol underground mine and the experience gained using the IGF UB RAS systems of induction electromagnetic space–time monitoring on arrays of various material composition before and after mass explosions.

We analyzed the morphology of the structural features of the disintegration zones before a strong dynamic phenomenon during the next cycle of electromagnetic observations at the Tashtagolsky mine during August 2007. On August 9, there was a rock explosion with the energy: lg E = 6.9 in the range of the ort 3 at a level of 16 m below the horizon −280 (**Figure 1**), N = 108 (**Figure 2(a)** and **(b)**). The analysis of the second curve (**Figure 1**) demonstrates the irregularity of the number of weak dynamic phenomena in the array of the entire mine field with energy lgE < 6 in time. So, after a mass explosion on the same day, 42 phenomena were registered, for the next day, already 17, and then this number in the next day is even more reduced. Before the rock impact, there is a significant rarefaction of the number of dynamic phenomena—a zone of calm. During the day, when there was a rock shock after it, 12 weak dynamic phenomena were observed, similar to how it happened on the third day after the mass explosion.

Three days before the rock shock in the ort 4 (**Figure 2(a)** and **(b)**) in the geoelectrical sections of the massif, subvertical discrete structures are found, into which disintegration zones have merged. These structures manifested themselves in a resonant mode at different frequencies and only at one frequency for each of the units. We discovered the same phenomenon earlier during one day at the mine Estyuninsky and SUBR (mine15) [21] (**Figure 3**).

Regarding **Figure 4** we see the comparative data from 2000 to 2007 the distribution of the parameter of the interval intensity Spint (in 2007 the results were given according to the electromagnetic measurements before and after the rock shock) in the bottom of the Ort 2 of the massif, horizon −210 at two frequencies: 5.08 and 20 kHz. According to the classification [29], the state of the array of the Ort 2 was defined as quasi-stable. The obtained results show that, despite the very close location to the site where the rock shock occurred, the massif remains practically in a state described by the gradation quasi-stable. For the period from August 2 to August 13, 2007, the maximum of the parameter *Spint* moved from the fourth interval (3–4 m) to the first (0–1 m) without increasing its amplitude. The emergence of these structures of subvertical morphology is a forecast of a strong dynamic phenomenon; however, in order to determine the place and magnitude of an event, it is necessary to have information on the state of the arrays and their belonging to the appropriate ranks of stability of the array, as was done in [29].

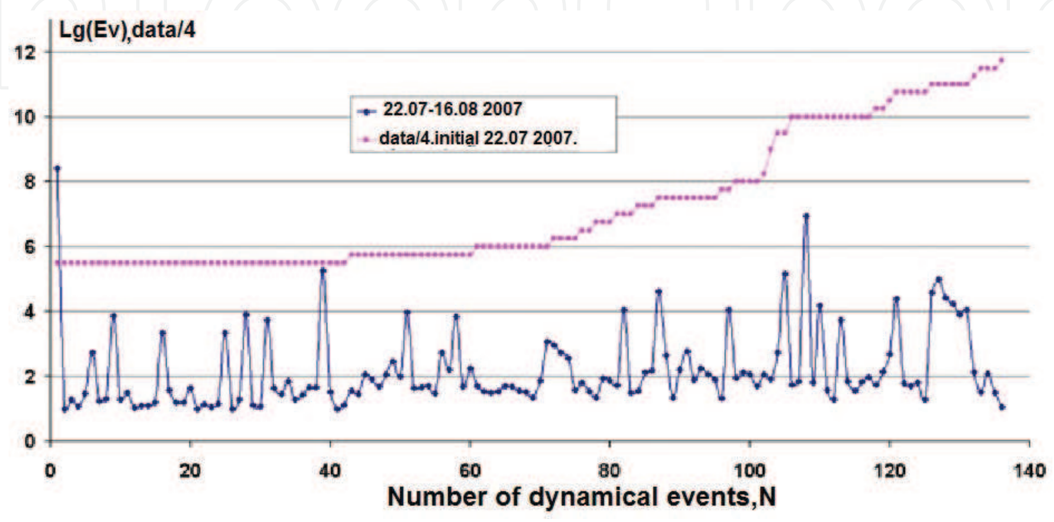


Figure 1.
The distribution of the dynamic phenomena in the Tashtagolsky mine after the mass explosion (N = 1). (Data from the seismological catalog of the Tashtagolsky mine (authors Klimko V. K., Shipeev O. V.)).

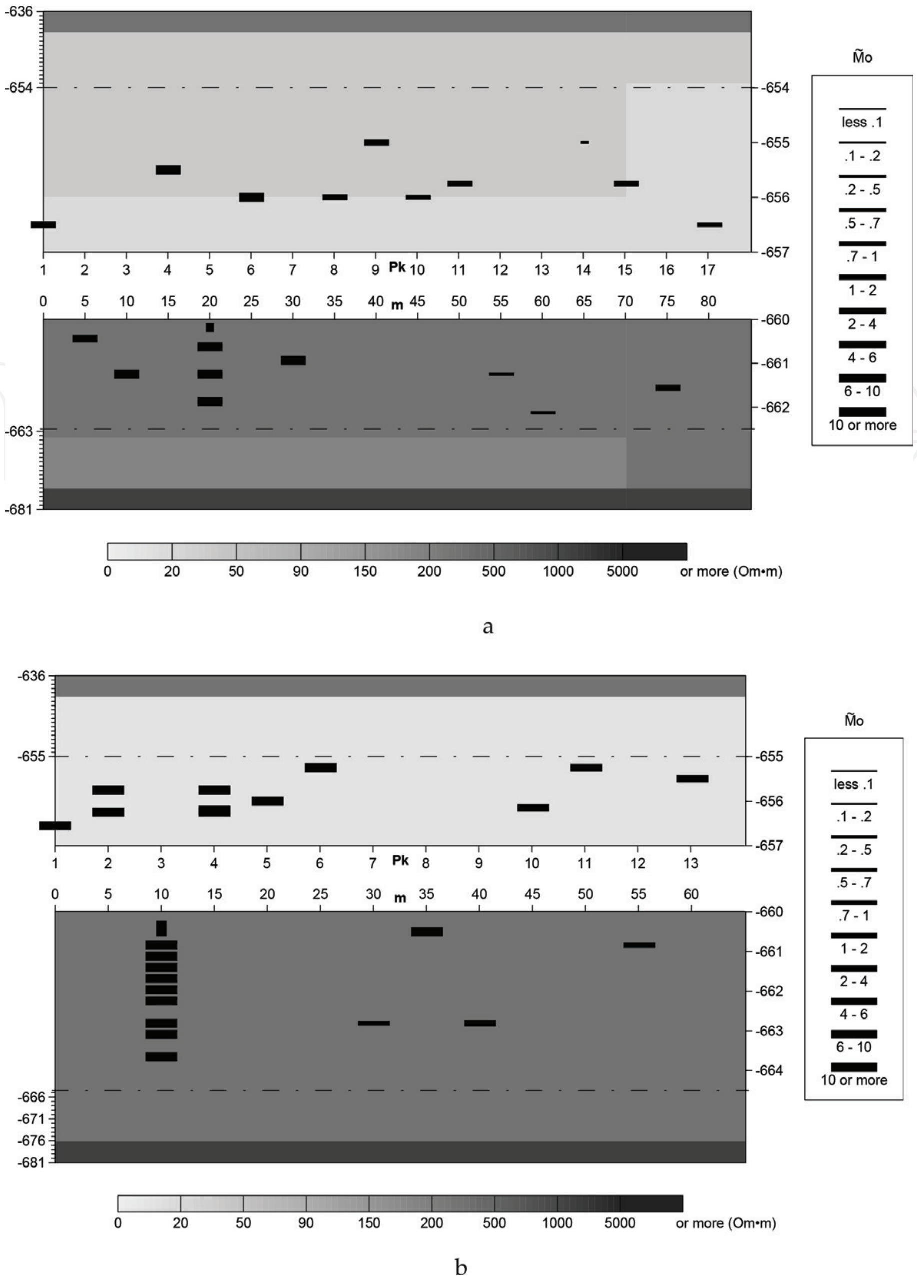


Figure 2.
Geoelectric sections along the profile ort 4, horizon −210, northwestern section. (a) August 6 and (b) August 8, 2007, frequency: 10.15 kHz. Legend: $\tilde{M}_0^i = M_o \times L_o \times 10^3$*, where* M_o *is the coefficient by which the moment of the electric current line is multiplied by the influence of the zone by the parameter of geoelectrical heterogeneity equivalent over the field and which is proportional to the ratio of the conductivity difference of the disintegration zone to the conductivity of the surrounded medium,* L_o *is the length of the current line, and the resistance of the section is given in ohms. Vertical values are given in m (absolute marks), horizontal axes and output length in pickets (pc) and meters.*

Thus, the introduction of the proposed integrated passive and active geophysical monitoring, aimed at studying the transient processes of redistribution of the stress–strain and phase states, can contribute to the prevention of catastrophic dynamic manifestations during the development of deep-located deposits. Methods of active geophysical monitoring should be tuned to a model of a hierarchical heterogeneous medium.

The technology of working out ore deep-lying deposits provides carrying out of preventive and safety control measures. For this purpose, a number of the largest Russian mining enterprises have installed multichannel-automated seismic monitoring systems within the mine fields influenced by underground mining [30].

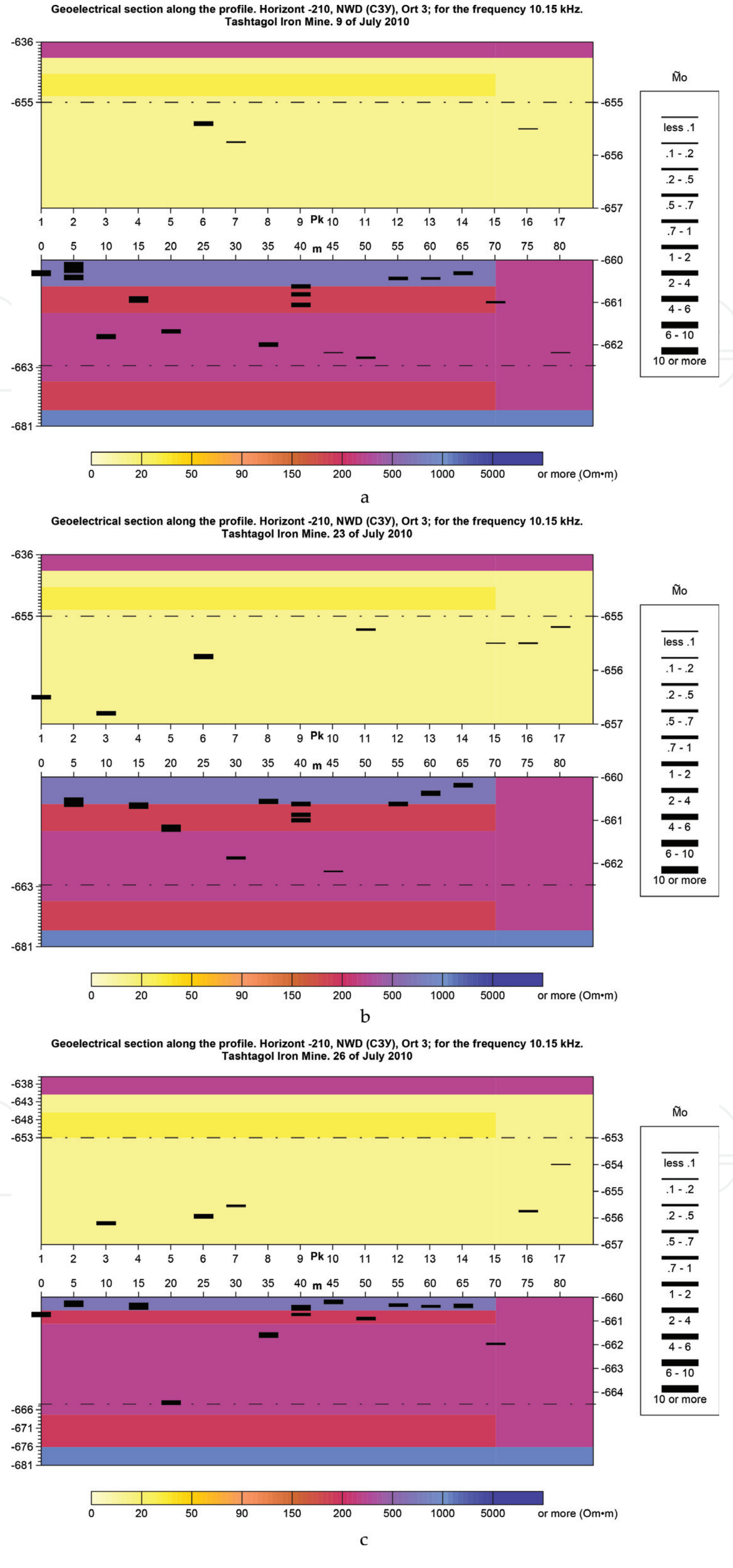
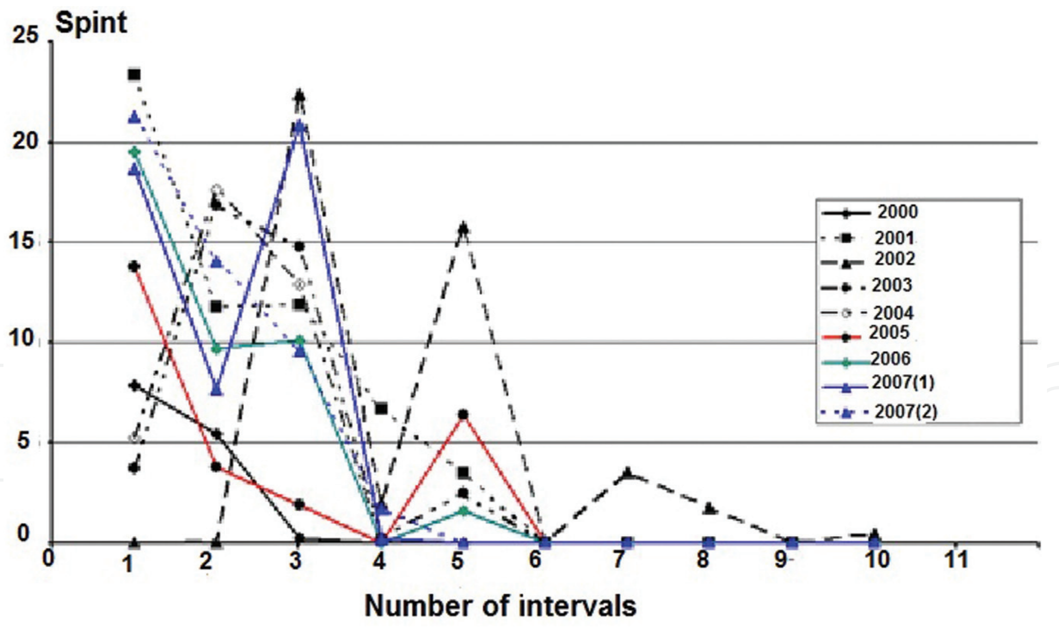


Figure 3.
(a–c) Geoelectrical section along profile ort 3, horizon −210, northwestern section. (a) July 9, (b) July 23, and (c) July 26, 2010, frequency: 10.15 kHz. The legend is the same as in the ***Figure 2(a)*** *and* ***(b)****.*



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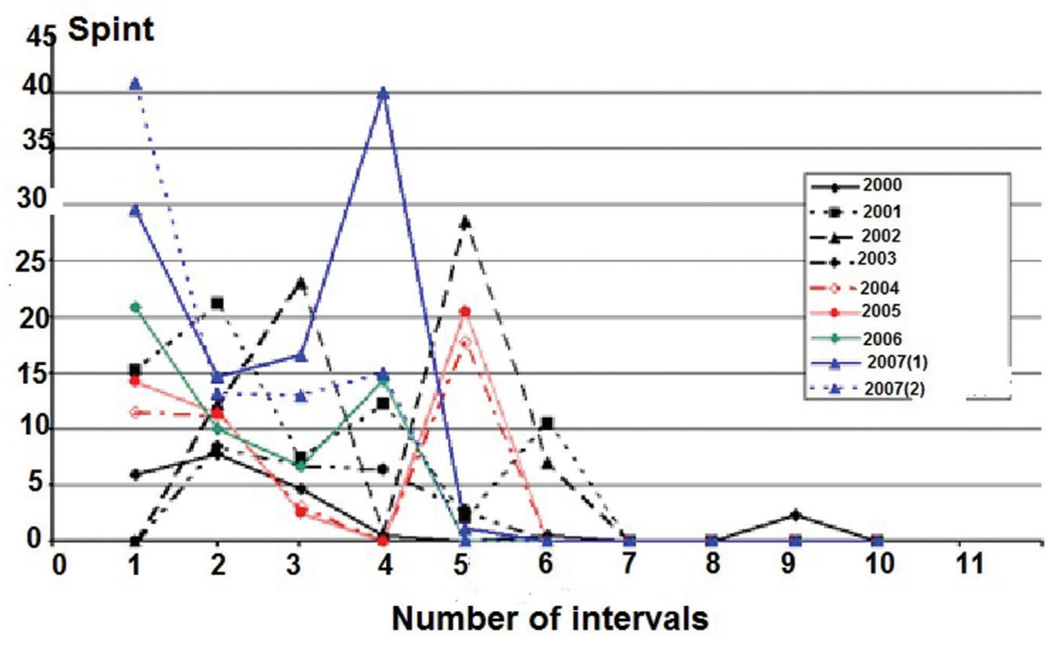

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Figure 4.
The distribution of the parameter of the interval intensity Spint *for eight observation cycles in the array of Ort 2, horizon −210, Tashtagolsky mine according to active electromagnetic induction monitoring. (a) Observations in 2000–2007 years, frequency 5 kHz. (b) Observations in 2000–2007 years, frequency 20 kHz; 2007 (1) in the legend corresponds to data before rock shock; 2007 (2) in the legend corresponds to data after rock shock. Axes Y-*$\text{Spint}(N,T) = \sum_{i(N)} \tilde{M}_0^i(T)$ *-parameter of the interval intensity of geoelectrical heterogeneities of the second rank, detected by electromagnetic induction monitoring, where N is the number of the interval into which the soil of near-working space is divided and where* $\tilde{M}_0^i$ *is the intensity of the disintegration zone and T is the year of observation [14].*

Analysis of a large database of seismic records of shocks and rock shocks recorded by the Norilsk seismic station at the Norilsk deposit mines using the previously proposed analysis method [31] detects the pulsating seismic energy release from stressed areas of ore and rock massive from the motion of fronts of induced seismicity by the type of oscillating pendulum [32]. In the development of this result, studies were carried out to study the transient process of redistribution of the stressed and phase states of the massif between strong man-made impacts at the

Tashtagol underground mine [33]. We studied the parameters of seismological monitoring as the values of the total energy *lg (Ev)*, extracted by the array of a specific development block in the form of dynamic phenomena after each mass explosion, the values of the absorbed array of the same energy block we define as *lg (Ep)*, and the maximum volume of the mine field where the dynamic phenomena occur from the given mass explosion *lg (Vmax)*.

The transient process of energy release by an array in the form of a response to anthropogenic impact is analyzed—a mass or technological explosion for the realization of a particular technological procedure (cutoff, segmenting, compensation, collapse) in the development block. The analysis of the seismic detailed mine catalog data allows us to draw the following conclusions: when working out a specific block of the array, the entire array of the mine field undergoes a change in the stress–strain and phase states from explosion to explosion; the amount of energy absorbed and delivered by the array is not equal to each other, and therefore energy accumulation takes place in the array; the process of energy release occurs with a delay and depends strongly on the gradient of the energy absorbed from mass explosions; in the array there are zones of dynamic calm; these zones should be monitored using seismic monitoring data using the parameters proposed by us; after it is out of the minimum of the lull, it is necessary to conduct a spatial–temporal active electromagnetic or seismic monitoring within a week or 2 weeks before the technological collapse, in order to identify zones of potential instability of the second rank; these zones may be after a mass explosion, timed to collapse by sources of strong dynamic phenomena; and introduction of the proposed integrated passive and active geophysical monitoring aimed at studying the transient processes of the redistribution of the stress–strain and phase states in the system of testing can help prevent catastrophic dynamic manifestations during the development of deep-seated deposits. These conclusions are based on the analysis of seismological data spatially related to the array of a specific processing unit. However, analysis of seismological data shows that strong dynamic phenomena (rock shocks) can occur in a wider area than the actual block of mining and can be initiated with time lags. Within 9 years from 2000 to 2008, in the mine of the Tashtagolsky mine on four horizons in a number of excavations, active electromagnetic induction monitoring was carried out within the framework of the frequency-geometric technique. On the basis of these detailed data and their subsequent interpretation, a method was developed for estimating and classifying an array of near-working space within the limits of developing its stability in three respects relative to strong technogenic impacts during the development of large and super-large deposits. As a result, a positive verification of the site forecast and evaluation of the magnitude of the destructive dynamic phenomenon in the mine of the Tashtagolsky mine were carried out [34]. As the experience of our studies has shown, the change in the state of the system at the investigated spatial bases and times is manifested in parameters related to the structural features of the medium of the second rank. Thus, the study of the dynamics of the state and its structure and the phenomena of self-organization of the array can be conducted by geophysical methods tuned to the multi-rank hierarchical model of the environment. This conclusion satisfies the principles of the paradigm of physical mesomechanics introduced by academician Panin V. E. and his school [13], which are also a constructive tool for studying the state of the non-stationary geological environment, which is an open dynamic system [14, 27, 35]. The use of an in-plane multi-level induction electromagnetic method with a controlled source and an appropriate processing and interpretation technique made it possible to identify disintegration zones that are an indicator of the stability of the array [26]. The introduction of the integral parameter—the intermittent distribution of the intensity of the disintegration zones—allows us to proceed to a detailed classification of the array in terms of the degree of stability, introduces quantitative criteria for this, and characterizes the stability of the array from the viewpoint of reaching the stationary cyclic position of the maximum of the parameter *Spint* as a function of the distance from the output *Zmax*. Analysis of the variance from the frequency of *Zmax* allows us to introduce additional gradations on the stability of the array in its detailed classification. Comparison with the data of seismological monitoring made it possible to carry out the geodynamic classification of the array using the integral parameter *Sp* [15].

In [35], the possibility of using the mathematical results of the developed physical and mathematical theory of the study of the state of open dynamic conservative and dissipative systems [17, 36] is shown. These include also rock massive during the process of mining. A dynamical system is understood as an object or process for which the concept of a state as a collection of values of certain quantities at a given moment of time is defined and an operator defining the evolution of the initial state in time is specified [36]. If to describe the behavior of a system, it is sufficient to know its state at a finite number of moments of time, and then such a system is called a system with discrete time. As a rule, the control of the state of a rock massif in mines is not continuous but within the framework of observation cycles or at discrete moments of time. To describe its development, differential analogs of differential evolution equations are used. Dynamic systems are divided into conservative and dissipative systems. For the former, the total energy of the system is preserved; for the second, energy losses are possible. In the appendix to our problem, when studying the state of an array that is in the process of working out, the model of the heterogeneous and non-stationary dissipative system is closest. Nevertheless, in the array can be such local parts of it, which will be described by a conservative dynamic model, i.e., model of energy balance. The analysis of the phase portrait of the dynamic system allows us to conclude that the system is characterized during its observation period. So, in conservative systems there are no attracting sets. An attractor is a subset of the phase space P_N, to which trajectories starting in some neighborhood of it incline with time. If a periodic motion exists in a conservative system, then such motions are infinitely large and are determined by the value of the energy under the initial conditions. Attractive sets can exist in dissipative systems. Stationary undamped oscillations for dissipative dynamical systems are not characteristic. However, in nonlinear systems it is possible to have a periodic asymptotically stable motion, in the mathematical image of which is the limit cycle, represented in phase space by a closed line, to which trajectories from some neighborhood of this line are contracted with time. In terms of the shape of the phase portrait, one can judge the characteristic behavior of the system, and the "smooth" deformations of the phase space do not lead to qualitative changes in the dynamics of the system. This property is called the topological equivalence of phase portraits. It allows you to analyze the behavior of various dynamic systems from a single point of view: on its basis, the set of dynamical systems under consideration can be divided into classes within which systems demonstrate qualitatively similar behavior. From the mathematical point of view, the "smooth deformation" of the phase portrait is a one-to-one and mutually continuous transformation of the phase coordinates, as a result of which new singular points cannot appear, and on the other hand, singular points cannot disappear. The earlier results of the study of the phase state of the rock mass [15] indicate that the classification of the massif with respect to its stability and its further control can be very effectively carried out using the parameter *Spint*-interval intensity of second-rank heterogeneities or, according to the terminology adopted in geomechanics, the disintegration zones.

In addition, when using the integrated intensity parameter Sp: ($S_p = \sum_i \tilde{M}_0(x, H)$, where H is the investigated thickness of the massif in the bottom of the hole, the x-coordinate of the center of the zone along the generation, and i is the number of the zone), there is good convergence with seismic monitoring data of the same research area and the active electromagnetic monitoring. Therefore, to construct the phase portrait of the state of the array at various horizons and in the excavations located at various distances from the clearing space, we use as parameters the parameters *Spint* and *d/dt (Spint)*, as well as *Sp* and *d/dt (Sp)* defined for seven cycles of active electromagnetic induction monitoring. By the symbols *d/dt (Spint)* and *d/dt (Sp)*, we mean the difference of consecutive (in time) values; the time interval is 1 year. By a phase trajectory, we mean a discrete set of points in the phase plane defined by phase coordinates in a given time sequence corresponding to the observation cycles. All phase trajectories can be divided into three groups according to the occupied area in the phase plane and the position on the phase plane of the center of gravity of the figure described by this trajectory. By the area occupied by the phase trajectory on the phase plane, we mean the exact lower bound of the set of areas of convex polygons containing a given phase trajectory. The center of gravity of the constructed figure may turn out to be a point of attraction; however, due to the lack of data, this point will be called the center of gravity of the figure described by the phase trajectory. The three groups identified by the new criteria completely coincide with the earlier classification by the parameter *Spint*: stable arrays (mountains −210, ort 4) the smallest area of the figure described by the phase trajectory, quasi-stable (mountains −210, ort 2), (mountains. −350, ort 18) is an intermediate in size area occupied by phase trajectories and unstable (mountain −350, ort 19) is the maximum area occupied by the phase trajectory. Thus, in [37] the thesis that the rock mass is an open dynamic system, the state of which is determined by synergetic properties, was demonstrated quantitatively by analyzing phase portraits using phase coordinates in the form of parameters of the integral and the interval intensity of the heterogeneity zones of the second rank and their difference analogs of time derivatives, determined from the data of active electromagnetic induction spatial–temporal discrete monitoring. To date, the question of the topological equivalence of the constructed phase trajectories, following the definition given above, remains open. Investigating this issue will be possible with an increase in the number of phase data.

3. Using the approaches of the theory of dynamic systems to determine the criteria for changing the regimes of dissipation of real mountain massifs under strong man-made impact

To realize this research, the seismic catalog of the Tashtagol underground mine was used for 2 years from June 2006 to June 2008. As the data, the space–time coordinates of all the dynamic phenomenal responses of the array that occurred during this period inside the mine field, as well as the explosions produced for working out the array, and the value of the energy fixed by the seismic station were used. In our analysis, the entire mine field was divided into two halves: the development of the northwestern section, the areas of the trunks of the western and Novo-Kapital and the outputs from 0 to 14 are designated by us, as the northern section, from 15 to 31 and the southern ventilation and field drifts. The trunk of the southern mine is designated as the southern section. All event responses from horizons −140, −210, −280, and −350 m were taken into account. Explosions were carried out in the southeastern section of mine development at the horizons +70 m, 0 m, −70, on the remaining sections—on the above horizons. As the data, the space–time coordinates of all the dynamic phenomena occurring within the minefield and fixed by the seismic station, as well as their energy characteristics were used.

The phase portraits of the state of the arrays of the northern and southern sections are plotted in the coordinates $Ev(t)$ and $d(Ev(t))/dt$, where t is the time expressed in fractions of the day and Ev is the seismic energy extracted in the array in joules. In this paper, we will first analyze the morphology of the phase trajectories of the seismic response at various successive intervals of time in the southern section of the mine for two reasons: (1) According to the data on the technological and mass explosions produced (**Figure 5**), most of the energy was pumped into the southern part of the mine. (2) At the end of 2007, the one of the strongest rock shocks occurred in the history of the mine happened in the southern sector. **Figure 6 (a)–(h)** shows the evolution of the morphology of the phase trajectories of the array response to technogenic impacts from the middle of 2006 to the middle of 2008. **Figure 6(c)** shows the characteristic morphology of phase trajectories of the response of an array located locally in time in a stable state: there is a local region in the form of a tangle of intertwined trajectories and small outliers from this coil, which do not exceed 10^5 joules in energy. This same feature is manifested in all the figures presented in **Figure 6(d)**, except that at some intervals this ejection exceeds 10^5 joules, reaching 10^6 joules (**Figure 6(d)** and **(e)**) and even 10^9 joules (**Figure 6(g)**). Since the volume of the array under study is the same and we are studying the process of its activation and decay, obviously, there are two mutually dependent processes: the accumulation of energy in the region attracting the phase trajectories and the resonance discharge of the stored energy (e.g., **Figure 6(g)**). It is interesting to note that after this reset, the system returns again to the same region attracting the phase trajectories.

Comparison of the phase portraits of the response of the state of the array before and after the mountain impacts of different intensity and at different time intervals indicate that the volume selected by us in the form of the southern section reacts to the effect exerted on it, similarly, by reflecting a coherent or joint mechanism for releasing the accumulated energy **Figure 8(a-b)**. The first results obtained from the analysis of a detailed seismological catalog from the point of view of the

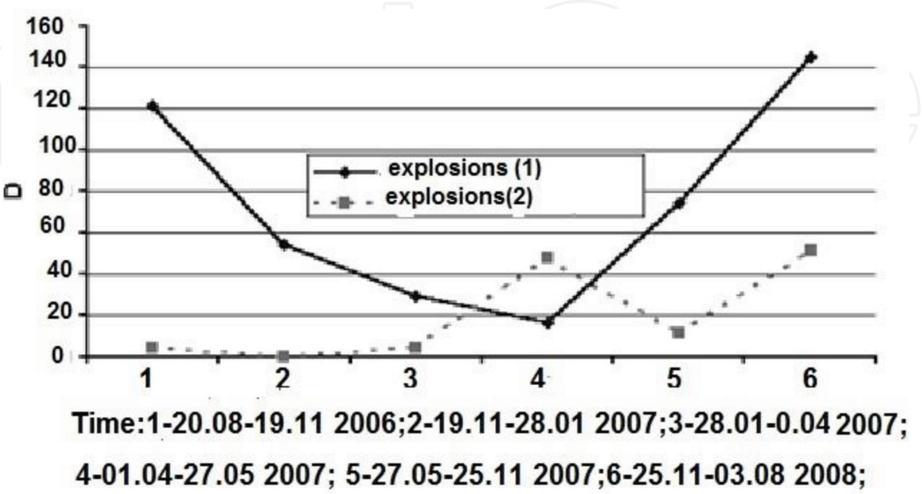
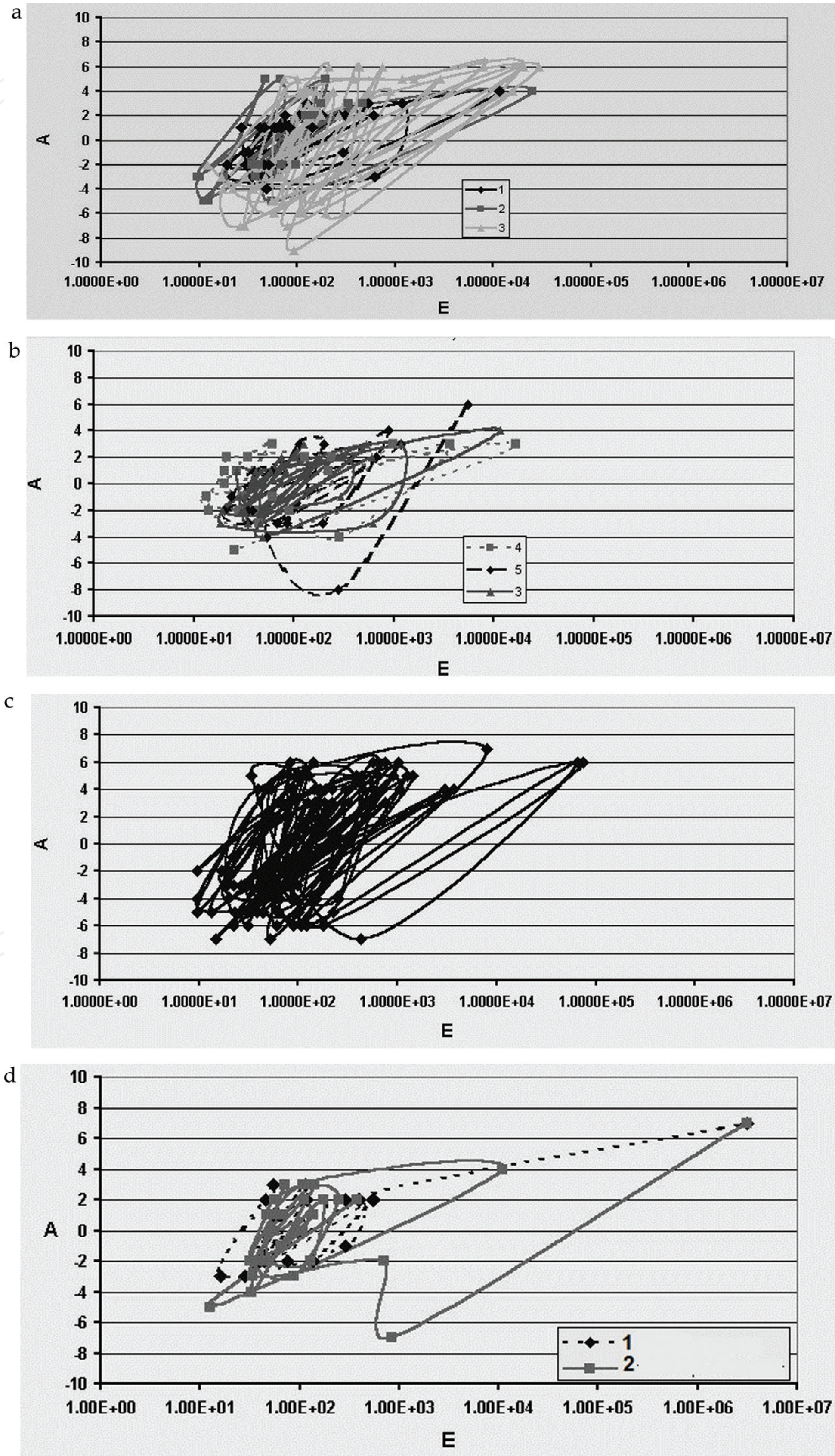


Figure 5.
Distribution in time of the absorbed seismic energy as a result of working out of an array by technological and mass explosions.Axis OY: D = Σlg (Ep (N)), where N is time intervals in days (OX axis) and Ep is absorbed energy from explosions. Explosions (1) provided in the southern part of the mine; explosions (2) provided in the northern part of the mine.

mathematical foundations of synergetics and open dynamical systems possessing the properties of nonlinearity and dissipativity [2, 17, 20, 38] lead us to the necessity of posing a new mathematical modeling problem different from the one previously performed. If in previous productions, the problem of the transition of a system from an ordered state to chaos was investigated; in our case, for our system, the



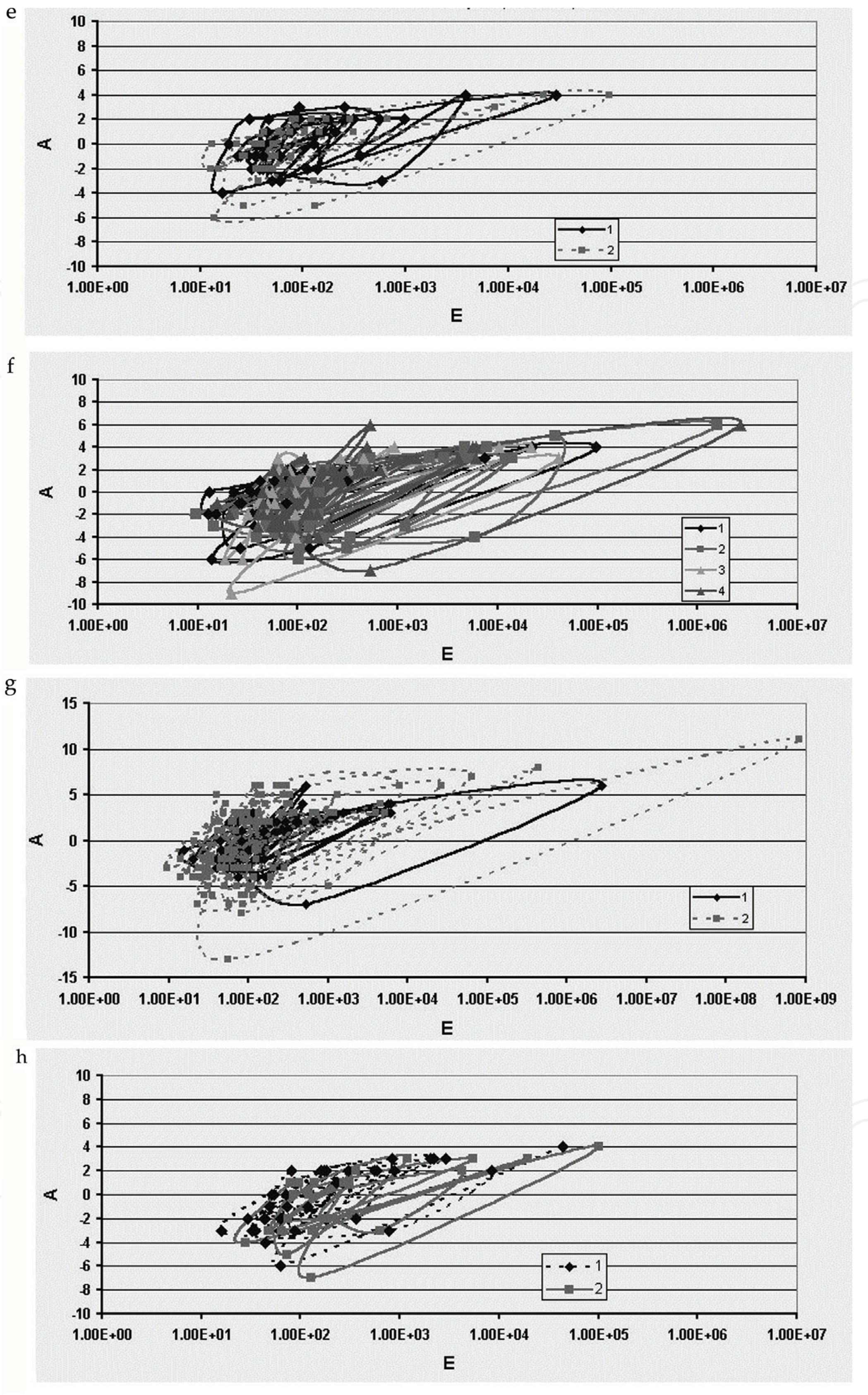
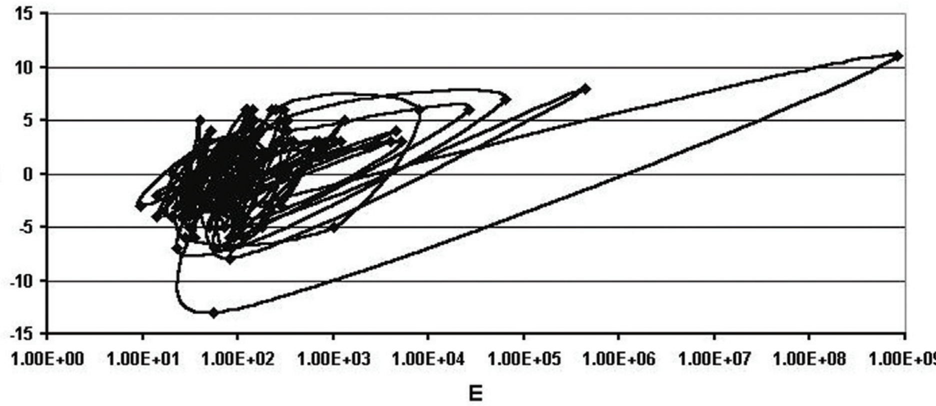
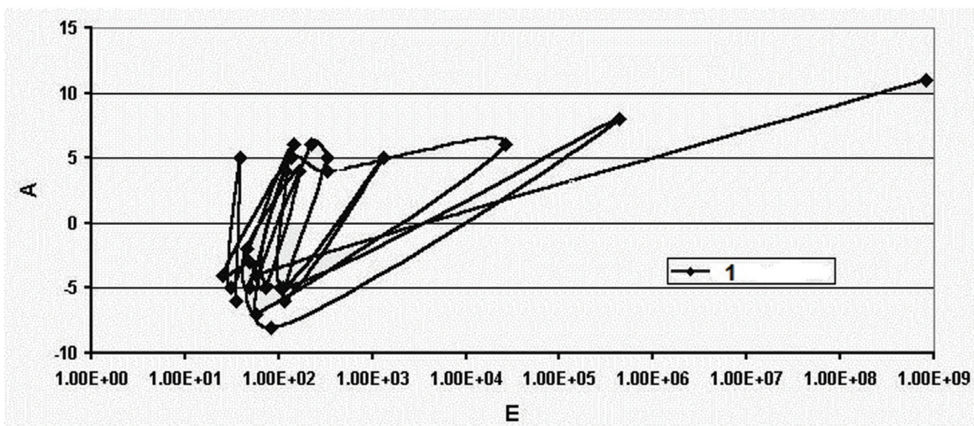


Figure 6

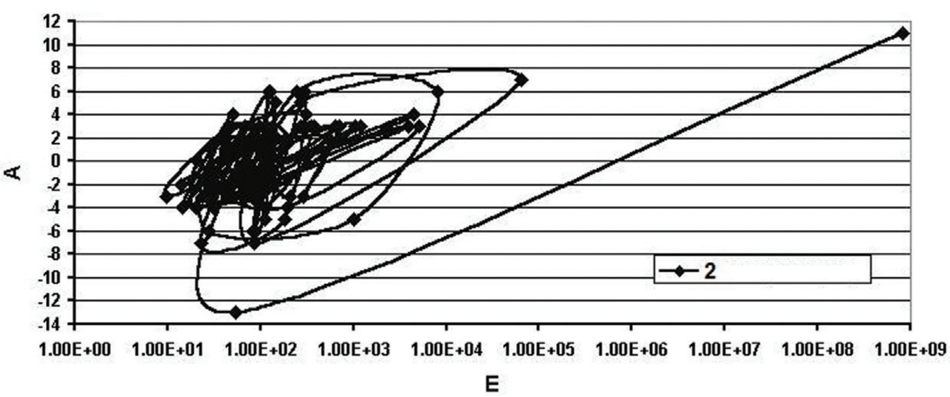
(a–h) Phase portraits of the array state response in consistent time intervals: (a) 5-24.09-29.09, 4-01.10-13.10, 3-14.10-12.11 2006; (b) 1-14.10-12.11, 2-12.11-18.11, 3-19.11-25.11 2006; (c) 24.12-29.12 2006; (d) 1-01.01-28.01 2007; (e) 1-29.01-31.03, 2-02.04-25.05 2007; (f) 1-02.04-25.05, 2-25.06-19.07, 3-22.07-27.09, 4-27.09-24.11 2007; (g) 1-30.09-24.11, 2-25.11-29.12 2007; (h) 1-29.12 2007-21.04 2008, 2-01.06-05.08 2008. The axis OX is the energy allocated by the array in joules at appropriate intervals. The axis OY: A = aLgf, $f = \left|\frac{\partial E}{\partial t}\right|$, a = sign ∂E, *where* t *is time in fractions of a day. It is of interest to analyze in more detail the phase trajectories of the seismic response of the array before and after the strongest impact (**Figure 7(a)–(c)**). The entire process is described by three attractive phase regions: a large number of phase-traversing low-energy region trajectories, which both precede strong energy resonance (**Figure 7(b)**) and follow after a strong energy resonance (**Figure 7(c)**).*



a



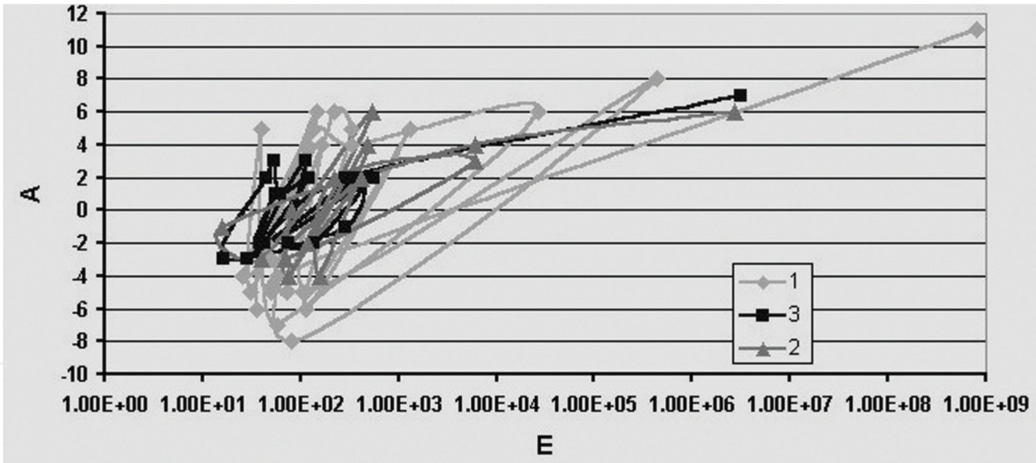
b



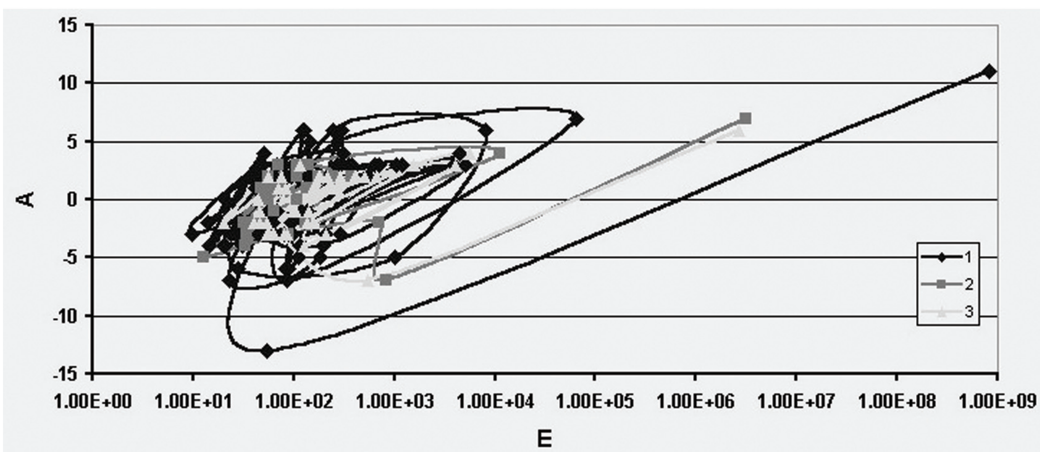
c

Figure 7.
Phase portrait of the response of the state of the array during one of the most powerful mountain impacts at the Tashtagolsky mine, (a) for a time interval of 25.11-29.12 2007, (b) for a period of time before a rock shock (1), and (c) for a period of time after a rock shock (2). The legend for the axes is the same as in ***Figure 6****.*

chaos of a given level is, on the one hand, a stable state for the system. On the other hand, this parameter is the control for the transition of the system to a state with another parameter, which is catastrophic for it. After the realization of this catastrophe, the system again creates a chaos region with a parameter close in value to the first. This process differs from the bifurcation process, because in the space of the distributions of phase trajectories studied by us, there is an attractive point, in the plane, the extracted energy, and the time derivative of the logarithm of the extracted energy. Thus, further study of the detailed seismic catalog will allow us to formulate the criteria for predicting the behavior of the rock mass from the point of view of the mathematical theory of synergetics [36]. This approach can also be used to analyze seismological data at seismological landfills (**Figure 8**).



a



b

Figure 8.
*Comparison of the phase portraits of the response of the state of the array before and after the mountain impacts of different intensity and at different time intervals in 2007. (a) 1-25.11, 2-01.01-13.01, 3-27.09-11.10. (b) 1-25.11-29.12, 2-13.01-28.01, 3-11.10-24.11. The legend for the axes is the same as in **Figures 6** and 7.*

4. Conclusion

At present, theoretical results on the modeling of the electromagnetic and seismic fields in a layered medium with inclusions of a hierarchical structure are in demand. Algorithms for modeling in the electromagnetic case for 3D heterogeneity are constructed, in the seismic case for 2D heterogeneities [39–41]. It is shown that with increasing degree of hierarchy of the medium, the degree of spatial nonlinearity in the distribution of the components of the seismic and electromagnetic fields increases, which corresponds to the detailed monitoring experiments conducted in the shock-hazard mines of the Tashtagolsky mine and the SUBR. The constructed theory demonstrated how the process of integrating methods that use the electromagnetic and seismic field to study the response of a medium with a hierarchical structure becomes more complicated. This problem is inextricably linked with the formulation and solution of the inverse problem for the propagation of electromagnetic and seismic fields in such complex media. The problem of constructing an algorithm for solving the inverse problem using the equation of the theoretical inverse problem for the 2D Helmholtz equation is considered in [41], [42]. The explicit equations of the theoretical inverse problem for the cases of scattering of an electromagnetic field (E and H polarization) and scattering of a linearly polarized elastic wave in a layered conducting and elastic medium with a hierarchical conducting or elastic inclusion, which are the basis for determining contours of nonaligned inclusions of the first rank of the hierarchical structure, are written out. Obviously, when solving the inverse problem, monitoring systems that are set up to study the hierarchical structure of the environment should be used as initial monitoring data. On the other hand, the more complex the medium, each wave field introduces its information about its internal structure, so the interpretation of the seismic and electromagnetic field must be kept separately, without mixing these databases.

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