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GEOPHYSICS

Diagnosis of Stressed States in the Lithosphere of the Baikal Rift System

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The results of investigation of the structure and dynamics of stresses at the modern (instrumental) stage of the evolution of the lithosphere in the Baikal Rift System (BRS) are presented. The application of the theoretical methods of nonlinear dynamic systems for diagnosis of the stressed states allowed us to formulate the concept of the complex stressed state of the BRS lithosphere. In this concept, the time distribution of large earthquakes is explained by bifurcations (catastrophes) of stresses. The analysis of the results obtained points to possibilities of a catastrophe of stresses in the BRS lithosphere in the next few years and the consequent realization of large earthquakes with magnitude $M \approx 7$. A model of triple equilibrium bifurcation is suggested for the evolution of stresses in the BRS lithosphere.

Rapid processes of stress rearrangement in the BRS lithosphere are consistent with the behavior of complex self-organizing unstable thermodynamic systems [1]. Since they are observed synchronously in three zones of the maxima of structural force inhomogeneities, we classify the BRS as a spatiotemporal open self-organized nonlinear dissipative system [2]. A complex system is considered self-organized if it maintains its instability at a level sufficient for effective resistance to the variations in the active medium, thus saving itself from collapse. We understand self-organization as an antientropic process of buildup, interaction, and maintenance of coherence between the elements of the system with increase of its complexity and formation of the attractor structure. Complex synergetic phenomena are exemplified in the literature as different processes of self-organization in physicochemical and biological systems. Their analysis allows us to establish the general features, which are characteristic of complex phenomena, and formulate the main principles irrespective of the specific nature of the system. Each of such processes has unique features. The role of nonlinearity, fluctuations, oscillations, bifurcations, and the attractor is manifested very clearly in these examples. Therefore, when modeling the behavior of geophysical systems, one should use the advantage of new perspectives discovered by science during the investigation of complex behavior of nonlinear dynamic systems. This is especially important in light of the modern tendencies of forecasting and controlling the seismic process, since forecast and control imply knowledge of the properties and peculiarities of the system under control. They begin with gathering of information about the state of the system, its links, and the logic of its functioning.

It is known [1, 3] that changing systems can be identified as dynamic ones. This is a model of matter motion in a force field from the physical point of view and an operator in the space of states (phase space) from the mathematical point of view. The states of the system form vector $\mathbf{x} = (x_1, x_2, \ldots, x_n)$ and represent the axes of this space. They are related to the observed quantitative characteristics of the system. In the theory of dynamic systems, a variation in the vector of state is determined by the vector velocity field $\mathbf{f}(\mathbf{x}, t)$, which is an operator of the system evolution. Such a model of dynamics corresponds to differential equation

$$\frac{d}{dt}\mathbf{x} = \mathbf{f}(\mathbf{x}(t), \lambda), \quad (1)$$

where λ is the governing parameter. If time changes discretely, the dynamics is described by mapping

$$x_{k+1} = F(x_k), \quad k = 0, 1, 2, \ldots, \quad (2)$$

which can be a result of approximation of Eq. (1), the Poincaré mapping, or the only possible model of dynamics if the state can be fixed only at isolated time moments $k = 0, 1, 2, \ldots$. Discrete portraits of the dynamic system can be presented as a law, which relates the previous point of the trajectory to the next one. Such portraits would be uniquely generated by the

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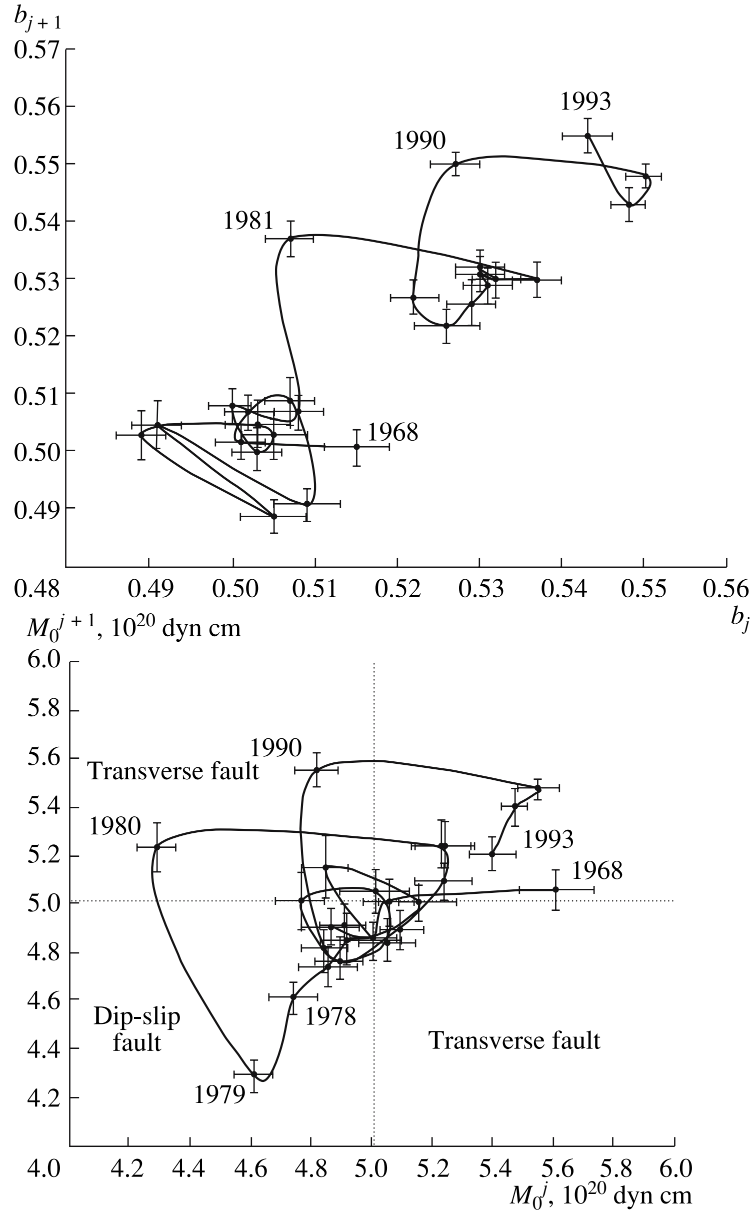

Fig. 1. Presentation of the structure and dynamics of stresses in the BRS lithosphere in phase spaces b_{j+1}, b_j and M_0^{j+1}, M_0^j. Dashed lines show the levels of the seismic moment of earthquakes with $K_P = 7$ corresponding to the transition from shock-faults to transverse faults.

flow and frequently serve as the only method for investigating natural systems.

Investigation of the structure and dynamics of stresses in the BRS lithosphere is usually based on phase spaces with the coordinates of state represented by parameters b_j and M_0^j, where index j identifies the year ranging from 1968 to 1994. Parameter b_j is a coefficient in the equation of the correlation between the logarithm of the seismic moment and energy class of all earthquakes with energy class $K_P \geq 7$ recorded during year j. This parameter characterizes indirectly the annual stressed state in the entire system of seismogenesis. Parameter M_0^j is the annual mean seismic moment of shocks with $K_P = 7$. This parameter indirectly characterizes the annual mean stressed state at the minimal energy level of the studied seismogenesis system. The values of b_j and M_0^j are unique functions of time. The mapping point moves along a broken line in the phase space (phase trajectory), and the corresponding phase velocity V_f would be equal to the trajectory length negotiated over a year.

Figure 1 presents the structure and dynamics of stresses in the BRS lithosphere in the phase space of

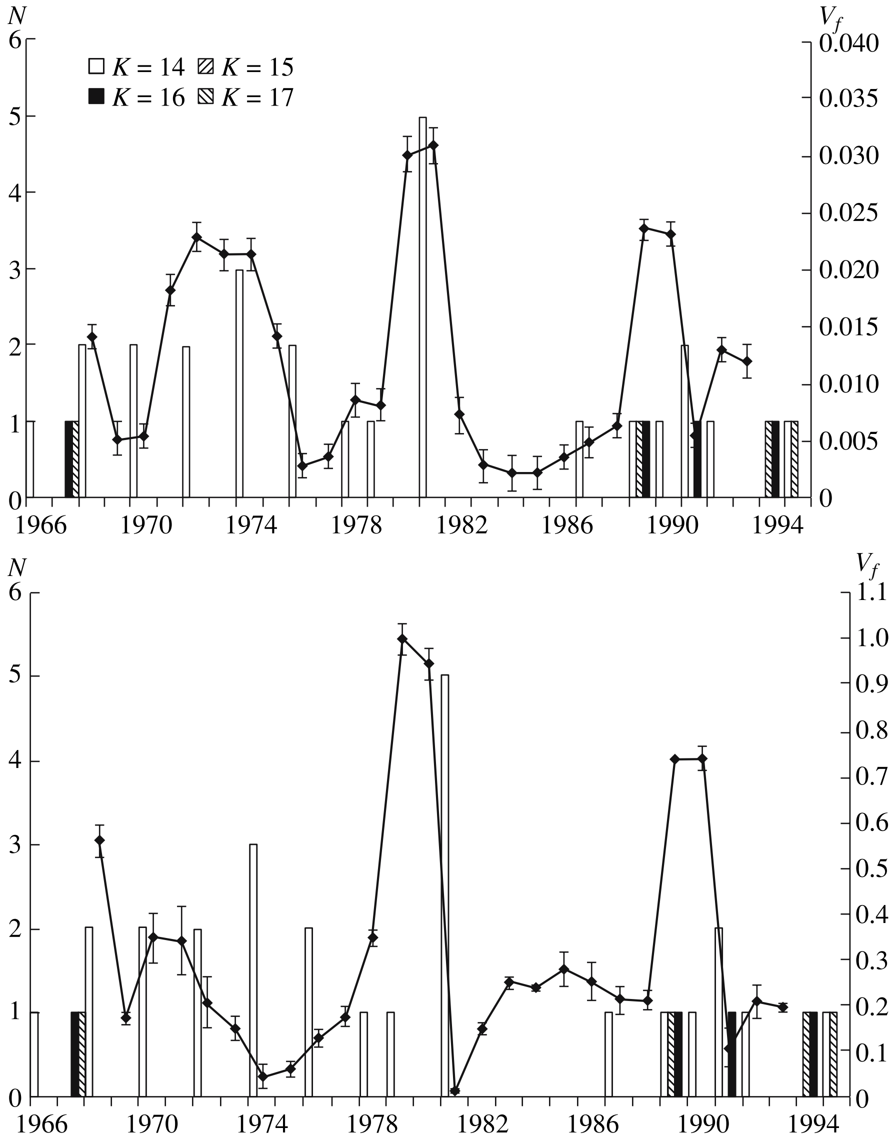

Fig. 2. Phase velocities V_f in spaces b_{j+1}, b_j (upper plot) and M_0^{j+1}, M_0^j (lower plot) and a bar chart of the distribution of annual numbers N of large earthquakes ($K_P \geq 14$) in the BRS.

parameters b_{j+1} and b_j. One can clearly see three attractors with a weak compression of phase portraits in the 1970s, 1980s, and 1990s. The free space between the attractors was rapidly overcome in 1981 and 1990. The figure also presents the structure and dynamics of stresses in the BRS lithosphere in the phase space of parameters M_0^{j+1} and M_0^j. It is seen that one attractor is formed at the shock-fault/transverse-fault transition boundary. The first deviation from the attractor starts in 1978. The maximum distance is recorded in 1980, and the system returns to the attractor in 1981. The second deviation from the attractor in 1990 is sharper, and the return of the system to the attractor possibly occurred in 1993.

To generalize the information presented in Fig. 1, we used phase velocities V_f, the time variations of which are shown in Fig. 2. The main peculiarities of the behavior of phase velocities retained in all graphs in different coordinate systems are as follows: the velocities increase sharply during the transition from one attractor to another and during deviation from the trajectory, whereas their fluctuations are insignificant in the rest period. The distributions of annual numbers of large earthquakes in the region with $K_P \geq 14$ and graphs of phase velocity V_f (Fig. 2) point to the correlation between bifurcations in the stress system with strong seismic events. Phase velocities in the BRS increase sharply before large earthquakes. In the M_0^j space, a jump is observed approximately one year earlier than in

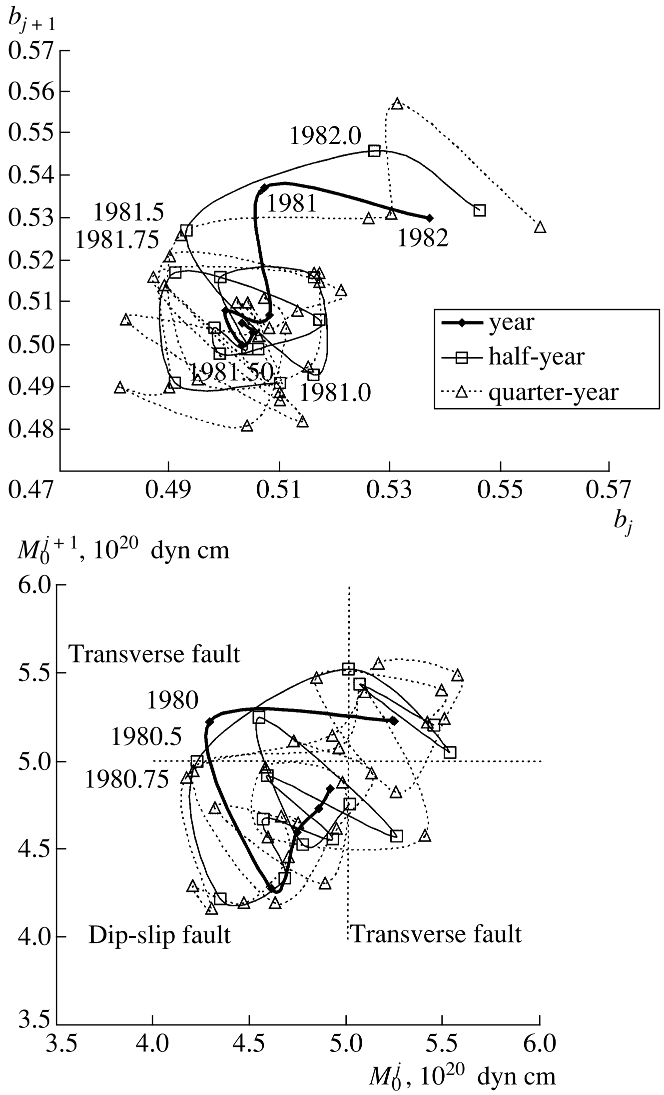

Fig. 3. Structure and dynamics of stresses in the BRS lithosphere in phase spaces b_{j+1}, b_j and M_0^{j+1}, M_0^j for annual mean, half-year, and quarter-year samplings from 1976 to 1983. The vertical and horizontal dashed lines show the levels of the seismic moment of earthquakes with $K_P = 7$ corresponding to the transition from shock-faults to transverse faults. One and two decimal points after the whole numbers of a year are assigned to half- and quarter-year data, respectively.

the b_j coordinate system. Such priority in the increment of stresses at a lower level is obviously caused by the fact that variations in the spatiotemporal and energetic gradients of stresses in the lithosphere, first of all, influence small earthquakes and can be used for medium-term forecasting of large seismic events.

It is seen in Fig. 2 that the maximum variations in the BRS lithosphere in the study period occurred during the deviation from the attractor at the end of the 1970s and beginning of the 1980s. We calculated the mean values of parameters b and M_0 over half- and quarter-year intervals to scrutinize the behavior of the stress system during this period. Figure 3 shows the structure and dynamics of stresses in the BRS lithosphere in the phase space of parameters b_{j+1}, b_j and M_0^{j+1}, M_0^j for mean annual, half-year, and quarter-year samplings of data from 1976 to 1983. Such detailed analysis makes it possible to determine more exactly the time of the transition from one attractor to another. The transition corresponds to the second and third quarters of 1981 in the coordinate system b_{j+1}, b_j and to the third quarter of 1980 in the coordinate system M_0^{j+1}, M_0^j. In general, the phase trajectories and points obtained from the data on smaller time intervals fall on the trajectories and oscillate around the points of the annual data samples.

The instantaneous (on the geological scale) and unique character of this phenomenon excludes the possibility of its nonmodal repetition and statistical description. Therefore, in order to verify the possibility of the existence of oscillatory processes during the deviation from the attractor, we performed additional experimental research into the behavior of the systems of biological populations of Turbellaria (*Phagocata sibirica* and *Baikalobia guttata*) of Lake Baikal. In particular, we carried out a series of experiments on phototaxis: 15 specimens of Turbellaria were placed in pans (40 × 20 cm) half-shadowed with dense black fabric. The response of phototaxis was determined at the following intensities of natural light (lx): 0, 5, 10, 50, 100, 500, 1000, 5000, 10 000, 15 000, 20 000, 30 000, and 50 000. Initially, all specimens studied in the experiment were located in the illuminated part. The motion of the specimens was observed for 5 min with recording of their position each min. Figure 4 presents bar charts of the rate of Turbellaria migration to the dark part of the pan at different intensities of illumination. During the first minute of the experiment, three sequential stages of increase in the migration of specimens to the dark zone are recorded at illuminations of 50–500, 1000–10 000, and 15 000–50 000 lx. This fact suggests the appearance of periodic oscillatory processes depending on the intensity of illumination. During the second minute, the weak correlation of migration disappears and migration reaches a maximum at an illumination of 10 000 lx, indicating the formation of one strong resonance migration. During the third minute, the system again demonstrates a weakly (but less prominent) correlated behavior. Only two increment stages are recorded at an illumination of 1000–5000 and 15 000–50 000 lx. During the fourth minute, one sufficiently strong correlation of the system is recorded at a smaller illumination of 5000 lx. During the fifth minute, weak correlated behavior can be observed only under high illumination of 20 000–50 000 lx. Hence, the system demonstrates during the transition a complex turbulence-type aperiodic behavior, which illustrates the tendency of many natural systems to chaotic evolution under special conditions [1]. Thus, the wave

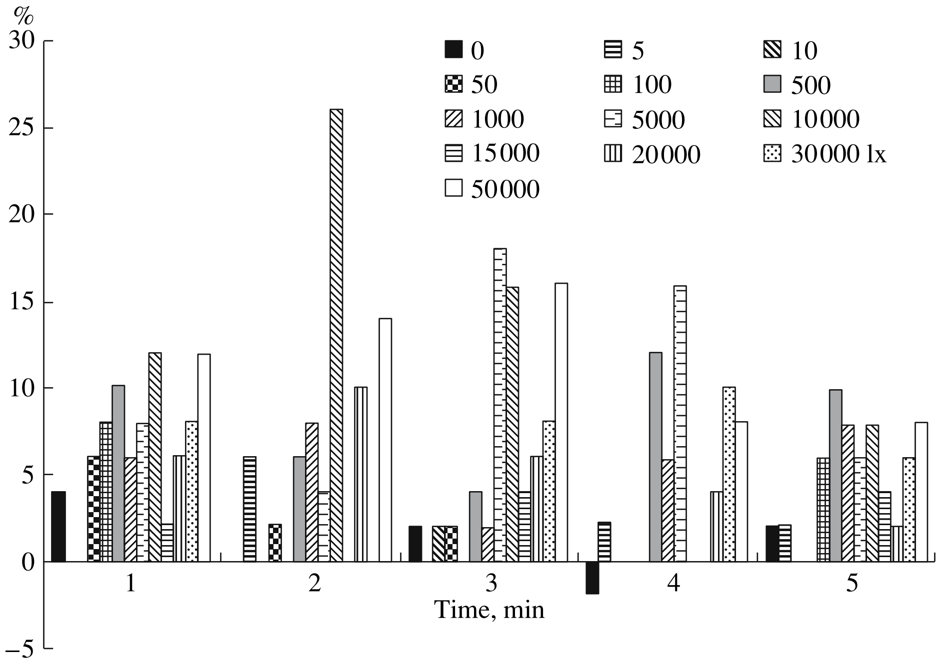

Fig. 4. Bar charts of percent distribution of the number of Turbellaria species transferred to the dark part of the pan during the first 5 min of phototaxis reaction.

phenomena observed in the stress system of the BRS lithosphere during the deviation from the attractor do not contradict the oscillatory processes observed in the behavior of the Turbellaria biological system in Lake Baikal when the state deviates from the attractor as a result of the phototaxis reaction.

Zoback [4] considers intraplate seismicity as a result of the global shear strain field and believes that intraplate distribution of stresses should be relatively uniform and quasi-stationary. Three types of stress regimes can be formed depending on the relative stresses. Extension regime $S_V > S_H > S_h$, where S_H and S_h are the maximal and minimal horizontal components, while S_V is the vertical component of the stress field. This regime is mainly favorable for earthquakes related to dip-slip faults. The two other regimes are related to compression. Compression regime $S_H > S_V > S_h$ is dominated by strike-slip faults. Another compression regime $S_H > S_h > S_V$ is dominated upthrust-type shocks. In some regions, the stress field can be a transition type between other regimes. For example, the stress field $S_V \approx S_H \gg S_h$ is characterized by earthquakes with the dip-slip and strike-slip motions, while the stress field $S_H \gg S_h \approx S_V$ will be characterized by a combination of strike-slip and upthrust faults. We shall use these relations to analyze time variations in the stress system of the BRS lithosphere. First of all, we note that the first three relations mentioned above characterize stable states of stresses, whereas the last two relations describe the system in states of the transitional instability. These states qualitatively agree and fit the behavior pattern of the stress system in the BRS lithosphere with the formation of three stable states (attractors) and two transitional states (bifurcations). Therefore, we suppose that model triple equilibrium bifurcation [5] can correspond to the dynamics of the stress system. The bifurcation model system can be expressed by the equation of stress S variation as

$$\dot{S} = \alpha_1 + \alpha_2 S + S^3. \quad (3)$$

The analysis of the equilibrium state shows that at $\alpha_2 > 0$ and arbitrary α_1, the system has a unique asymptotically stable state of equilibrium. At $\alpha_2 < 0$, the domain of values of α_1 exists, in which the system has three (one unstable and two stable) states of equilibrium, while the phase parameter space includes a structure called an assembly. On the basis of the relations between stress components, we can suppose that the coefficients in Eq. (3) have the following form:

$$\alpha_1 = \frac{S_h - S_V}{S_{max}}, \quad \alpha_2 = \frac{S_H - S_V}{S_{max}}, \quad (4)$$

where S_{max} is the maximal among the three stress components. Then, at any $\alpha_2 > 0$ and arbitrary α_1, the system is in an asymptotically stable equilibrium state, which characterizes the regime of lithospheric plate tectonics. When $\alpha_2 < 0$, the domain of the values of α_1 exists, in which the system has three equilibrium states, which characterize the rifting regime in the BRS. In this regime, the nonlinear behavior of the nonequilibrium geophysical medium in the BRS lithosphere leads to bifurcations (catastrophes) of stresses, resulting in the nonlinearity of seismogenesis and the generation of strong shocks. The level of some stress components can evidently increase or decrease, but the existence of a nonlinear nonequilibrium high-gradient state is necessary. It is likely that such states are related to fluid and thermal fluxes between the system and external medium, as well as to the difference between varying states S_j and S_{je}, where S_j and S_{je} are component parameters of the stresses in the system and medium, respectively. These differences have a transitional character, and they appear very quickly owing to the nonequilibrium phase transition. Later, they gradually relax as equilibrium is established between the system and the external medium.

The problem of forecasting the behavior of the dynamic system on the basis of time series is reduced to the interpolation problem. In our experiments, the number of attractors in the seismogenesis system does not exceed 3. If this is the complete spectrum of attractors in phase spaces, the system can return through them in the opposite direction by the hysteresis cycle. At present, we have data on the dynamic parameters of earthquake sources for the years 1968–1994 and we cannot describe the behavior of the system beyond these time limits. However, analysis of large earthquakes in the region revealed a pair of shocks in the Baikal region [6]: the South Baikal earthquake in 1999 in the southern part of Lake Baikal followed by the Kicherskoe earthquake at the northern edge of Lake Baikal. The similarity to the pair of earthquakes in 1981 allows us to suppose that these events are related to the transition of the system from the third attractor (formed in the 1990s) to the basin of attraction of the second attractor (distinguished in the 1980s). The mean time between transitions is ~10 yr. If this assumption is correct, the transition to the first attractor can occur within the next few years. Hence, the probability of the realization of large earthquakes of magnitude $M \approx 7$ in the Baikal region at present is rather high.

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