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BLOCK MODEL OF DYNAMICS OF THE LITHOSPHERE

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A model of the dynamic development of a system of lithospheric blocks manifested in an alternation of slow deformations and ruptures ("earthquakes") is proposed.

In geodynamics, and particularly in the problem of earthquakeprediction, mathematical models of the dynamics of the lithosphere are necessary, and, moreover, models sufficiently realistic reflecting its horizontal inhomogeneity and nonlinearity. When constructing such models it is useful to use the following fundamental property of the lithosphere: it consists of a hierarchy of blocks separated by boundary layers; compared with the blocks, these layers are relatively thin and less consolidated. In the literature these boundary layers are described under various names, depending on the rank of the structures being separated by them: transition zones, faults, slip surfaces, and so on right up to the grain boundaries of rock. The boundary layers themselves have an analogous hierarchical structure and can be regarded as systems of blocks of smaller scale. A block structure was examined in [1,2] for a broad range of geological bodies, including the lithosphere, on the basis of the general concept of their hierarchical organization. A particular determination of blocks of the lighosphere in mountainous territories at several steps of such a hierarchy is described in [3,4].

On the basis of this property we represent the lithosphere as a set of absolutely solid blocks separated in infinitely thin layers. The condition of absolute solidity of the blocks means that the moduli of elasticity in them is far greater than in the boundary layers, so that the bulk of the deformations of the medium is realized in the layers and not inside the blocks. More exactly, the model is applicable if $\Lambda/\lambda \gg L/h$, where Λ and λ are the characteristic values of the moduli of elasticity in the blocks and layers respectively; L is a characteristic dimension of the block; h is the characteristic thickness of the layer. The condition of thinness of the layer means that strains and stresses in it vary only along its trend.

The indicated representation of the lithosphere considerably simplifies models of its dynamics and, as we hope, without substantial loss of generality approximates them to reality. An analogous representation for engineering problems ("method of connected blocks") is proposed in [5].

The system of blocks is set in motion by external forces applied to the blocks directly or occurring as a result of given displacements of certain blocks. We will call such blocks "fixed" unlike the "free" blocks whose displacements are determined by the forces acting on them. Since the blocks are absolutely solid, all deformations related to their displacements occur only in the boundary layers. In this case stresses dependent on the magnitude and possibly also on the rate of strain occur in the boundary layers. This relation is continuous only so long as the stresses occurring are sufficiently small and do not exceed the strength thresholds. When these thresholds are reached fracture accompanied by stress drop occurs. We interpret such fractures as earthquakes.

An important feature of the model is the presence of three time scales in it. Only "slow" time corresponding to contemporary neotectonic processes is introduced explicitly. Changes in the external forces and movement of fixed blocks occur in this time. Slowness of the processes is expressed in the model by the following condition: at each instant of time the system of blocks is in a state of quasi-static equilibrium, i.e., for each free block the sum of the forces acting on it and the total moment of these forces are equal to zero.. Transition of the system of blocks from one state of equilibrium to another as a result of fracture occurs in "average" time, in which case "slow" time does not change.

During such a transition new fractures can occur. The series of fractures occurring upon transition of the system to a new state of equilibrium is interpreted as the main shock with foreshocks and aftershocks. Finally, "fast" time is the fracture propagation time. In this case the "slow" and "average" time are fixed, and the blocks do not move.

Healing of fractures, generally speaking, with a drop of strength, is also introduced into the model.

The given work is oriented toward modeling of a sequence of earthquakes in the seismically active lithosphere, i.e., in a system of blocks whose relative motion is at least partially realized through earthquakes. The main properties of the real sequences of earthquakes are as follows: 1) linear frequency law; 2) clustering, in which the most numerous clusters are determined by aftershocks; 3) migration of the foci along a system of faults; 4) remote interaction of earthquakes; 5) seismic cycle.

To them we can add "precursors," which indicate an increase of the probability of a strong earthquake. Such precursors include, 6) activiation and quiescence; 7) anomalous space-time clustering; 8) contrast of the distribution in space; 9) variation of seismic activity in time; 10 deviation from the long-term trend; 11) correlations at large distances. A definition of these precursors can be found in [6,7,8]. We are attempting to reproduce at least some of the enumerated properties on a model.

1. **Description of model.** We will describe here a two-dimensional model. All determinations are transferred without difficulty to the three-dimensional case.

Blocks and forces of interaction. A region on a plane with coordinates x-y divided into blocks - polygons with rectilinear boundaries-edges - is examined. The blocks can move as rigid bodies, retaining their shape and size. Movement of the i-th block is given by the vector of parallel transport (x_i, y_i) and angle of rotation ϕ_i. It is assumed that the movements are small compared with the size of the blocks. In this case the point $z = (x_0, y_0)$ belonging to the i-th block is displaced by the quantity $(x_i - y_0\varphi_i, y_i + x_0\varphi_i)$. If this point belongs to the boundary of the i-th and j-th blocks, then the relative movement of the blocks at this point is equal to

$$\delta(z) = (x_j - x_i - y_0(\varphi_j - \varphi_i),\ y_j - y_i + x_0(\varphi_j - \varphi_i)). \quad (1)$$

The vector $\delta(z)$ can be represented in the form

$$\delta(z) = \delta_\tau(z)\tau_{ij} + \delta_n(z)n_{ij}, \quad (2)$$

where τ_{ij} and n_{ij} are unit tangential and normal vectors to the boundary of the i-th and j-th blocks. The direction of τ_{ij} is selected so that on moving along the boundary in this direction the i-th block remains on the right and the j-th on the left. The normal n_{ij} is obtained from τ_{ij} by 90° counterclockwise rotation, i.e., n_{ij} is the outer normal for the i-th block and inner normal for the j-th.

We will consider that for small relative displacements the tangential and normal components of the force of interaction between blocks are proportional respectively to the tangential and normal relative displacement. Namely, the density $\sigma_{ij}(z)$ of the force acting on the i-th block from the side of the j-th block at point z is equal to

$$\sigma_{ij}(z) = \sigma_\tau(z)\tau_{ij} + \sigma_n(z)n_{ij}, \quad (3)$$

where

$$\sigma_\tau(z) = K_\tau\delta_\tau(z), \quad \sigma_n(z) = K_n\delta_n(z).$$

Here $K_\tau > 0$ and $K_n > 0$ are parameters of the model determining the rigidity of the boundary between the blocks of tangential and normal strains. They can be different on different edges. (Formula (3) will be modified later with consideration of sliding, see formula (9).)

We note that for the selected orientation of the tangential and normal vectors a positive value of $\sigma_\tau(z)$ corresponds to right slip and a negative to left slip, a positive value of $\sigma_n(z)$ corresponds to tension and a negative to compression.

It is easy to check that the quantity $\sigma_\tau(z)$ is constant along the edge, whereas $\sigma_n(z)$ changes linearly. For convenience of the calculations we will subsequently neglect this change and replace it by the average value on the edge. This is equivalent to replacing the force distributed along the edge by a force applied at the middle of the edge. To reduce the influence of this replacement, we can divide the boundary between blocks into several parts by additional points and consider each of these parts a separate edge. The calculations showed that the properties of the model change little upon such replacement.

The total force F_{ij} acting on the i-th block from the side of the j-th block is equal to the sum of the integrals σ_{ij} over the edges composing the boundary of these blocks, i.e.,

$$F_{ij} = \sum_{\alpha} L_\alpha \sigma_{ij}(c_\alpha),$$

where α is the number of the edge; L_α is its length; c_α is its middle. The moment of this force relative to the coordinate origin is equal to $M_{ij} = \sum_{\alpha} L_\alpha [c_\alpha, \sigma_{ij}(c_\alpha)]$, where $[c, \sigma] = c_1\sigma_2 - c_2\sigma_1$ for vectors $c = (c_1, c_2)$ and $\sigma = (\sigma_1, \sigma_2)$.

It follows from the definition that F_{ij} and M_{ij} linearly depend on the quantities $x_i, y_i, \varphi_i, x_j, y_j, \varphi_j$.

External forces and conditions of equilibrium. The blocks are divided into two types: "fixed" and "free." For the "fixed" block the value of its movement is assigned in the form $x_i = x_i^0 + x_i^1 t; y_i = y_i^0 + y_i^1 t; \varphi_i = \varphi_i^0 + \varphi_i^1 t$, where t is time, i is the number of block. For each free block the external force F_i^e and the moment of the external force M_i^e are assigned. The movement of such block is determined by the conditions of equilibrium:

$$\sum_j F_{ij} + F_i^e = 0; \sum_j M_{ij} + M_i^e = 0. \qquad (4)$$

Thus we obtain a system of 3 N linear equations (N is the number of free blocks) for 3 N unknowns (movements x_i, y_i, ϕ_i of these blocks). We note that in the three-dimensional case the corresponding system consists of 6 N equations for 6 N unknowns.

Fractures. We will call the edges on which the forces of interaction are determined by formula (3) elastic. We will consider that this formula holds as long as the strength thresholds are not exceeded, i.e.,

$$|\sigma_\tau(z)| < -A\,\sigma_n(z) + B; \qquad (5)$$

$$-D < \sigma_n(z) < C. \qquad (6)$$

Here A, B, C, D are parameters which can be different on different edges. Conditions (5) corresponds to the dry friction law [9]. As before, we will check these conditions for the average force on the edge, i.e., for z = c, where c is the middle of the edge. When these conditions are violated fracture of one of the following types occurs:

right slip, if $\sigma_\tau = -A\sigma_n + B,\ \sigma_n < 0$;

left slip, if $\sigma_\tau = A\sigma_n - B,\ \sigma_n < 0$;

underthrust, if $\sigma_n = -D$;

extension, if $\sigma_n = C$ or $|\sigma_\tau| = -A\sigma_n + B,\ \sigma_n > 0$.

The last condition means that fracture proper is caused by shear stresses, but normal stresses led to extension.

Underthrusts are introduced to investigate the situations when external effects cause the blocks to extremely draw together. In this case the normal stresses increase. In a three-dimensional medium then can be unloaded by movements along planes inclined to the direction of convergence; if it is horizontal, then this will be movements of the underthrust or overthrust type. In the two-dimensional model we introduce the corresponding stress drop, but we do not examine directly the stresses and strains perpendicular to the plane of the model.

After fracture the determination of the forces of interaction on that edge where the fracture occurred changes in the following way.

In the case of slip the normal component is determined, as before, by formula (3), and and the tangential component is proportional to the normal with coefficient a, $0 \le a \le 1$

$$\sigma_\tau = \pm(-a\sigma_n + b), \tag{7}$$

where the signs + and - refer respectively to right and left slip.

In the case of overthrust vector σ is proportional to the vector of elastic stresses at the time of fracture σ^-, and its normal component is equal to

$$\sigma_\tau = d\sigma_\tau^-/\sigma_n^-, \ \sigma_n = -d. \tag{8}$$

In the case of extension the forces of interaction disappear.

Three times scales. The change in the formulas for forces of interaction after fracture leads to violation of the conditions of equilibrium (4), as a result of which the system of blocks passes into a new position of equilibrium. We will consider that this transition occurs rather rapidly, so that the "slow" time T does not change in this case. During such a transition conditions (5), (6) can be violated on certain new edges, i.e., new fractures occur.

For determining the sequence of fractures we introduce the "average" time. Let X_- be the position of the system of blocks, i.e., the set (x_i, y_i, ϕ_i), immediately before fracture, and X_+ be the solution of system of equations (4) after fracture. We will consider that the system of blocks passes from position X_- to position X_+ linearly in "average" time $\theta \in [0,1]$, i.e., $X_\theta = X_- + \theta(X_+ - X_-)$ position at time θ. This movement continues until conditions (5), (6) are fulfilled on all elastic edges. If when $\theta = \theta_0$ conditions (5), (6) are violated on any edge, fracture of this edge occurs and the conditions of equilibrium (4) changes accordingly. Let X' be the solution of system (4) after the new fracture. We repeat the entire operation describe above, having replaced X_- by X_θ and X_+ by X', and we will do so until conditions (5), (6) are fulfilled on all elastic edges for all $\theta \in [0,1]$. In this case X_+ is the sought position of equilibrium of the system of blocks. The series of fractures obtained is interpreted as the main shock with foreshocks and aftershocks. The size of the unit fracture is equal to the length of one edge and, in particular, depends on the selected partition of the boundary between blocks into edges. To reduce this dependence, we introduce "fast" time in which the fracture upon fulfillment of the appropriate conditions can propagate to adjacent edges before the start of movement of the block, i.e., at a fixed "average" time. We proceed from the fact that as a result of fracture stress concentration occurs on its ends. In conformity with this, we check conditions (5), (6) on edges adjacent to the fractured edge, having multiplied the stress vector σ by a certain coefficient $q > 1$. We proceed in the following way. Let the fracture occur on an edge with vertices p_1 and p_2. Points p_1 and p_2 are declared the end of the fracture. For each elastic edge, one of the vertices of which coincides with p_1, we check conditions (5), (6), having multiplied vector σ by q. If in this case the conditions are violated on several such edges, then we select the edge for which the conditions are violated for the smallest value of q. We continue the fracture to this edge, considering its vertex not coinciding with p_1 to be the new end of the fracture. Thus an elongated fracture is obtained, with which the described procedure is repeated. The fracture is continued in exactly the same way toward its end p_2. Propagation of the fracture ends in one of two cases: a) if conditions (5), (6) are fulfilled for σ_q on all edges adjacent to the end of the fracture; b) if one of the edges adjacent to the end of the fracture is already fractured (not counting, of course, that edge which defines this end).

"Healing." After the series of fractures in "average" time is completed, recovery of the elastic state occurs on all edges except those where extension occurred. We tentatively call it healing. To determine the forces of interaction in the new elastic state, it is necessary to take into account sliding that occurred as a result of the fractures. The expressions for σ_τ and σ_n in formula (3) changes now in the following way:

$$\sigma_\tau = K_\tau(\sigma_\tau - \Delta_\tau); \ \sigma_n = K_n(\sigma_n - \Delta_n). \tag{9}$$

here Δ_τ and Δ_n are the tangential and normal components of sliding. The values of σ_τ and σ_n should not change during healing, since the position of equilibrium determined by them does not change. This condition permits determining the amount of sliding. As a result of slip only the value of Δ_τ changes. The new value of Δ_τ is selected from the condition of equality of stresses σ_τ in formulas (7) and (9)

$$K_\tau(\sigma_\tau - \Delta_\tau) = \pm(-aK_n(\sigma_n - \Delta_n) + b). \quad (10)$$

As a result of underthrust the new values of Δ_τ and Δ_n are selected from the condition of equality of stresses in formulas (8) and (9)

$$K_\tau(\sigma_\tau - \Delta_\tau) = d\sigma_\tau/\sigma_n, \; K_n(\sigma_n - \Delta_n) = -d. \quad (11)$$

Healing of extension occurs if during movement of the blocks the average normal component δ_n relative to the movement on the edge becomes equal to Δ_n (in the case of extension always $\delta_n > \Delta_n$). In this case only Δ_τ changes; the new value of Δ_τ is equal to δ_τ, so that in formula (9) $\sigma_\tau = 0$, just as before healing; the equality of σ_n to zero after healing is provided automatically by the condition $\delta_n = \Delta_n$.

Healing can occur also in "average" time. An extension is healed when $\delta_n = \Delta_n$, and slip and underthrust if on passing from X_- to X_+ the displacement along the edge should occur in the direction opposite to the initial.

In another variant of the model all fractures (except extensions) heal instantaneously, i.e., before the start of movement of the blocks, but in this case a reduced strength is established on the appropriate edges:

$$|\sigma_\tau| < -A'\sigma_n + B'; \; -D' < \sigma_n < C', \quad (12)$$

where $a < A' < A, b < B' < B, d < D' < D, 0 < C' < C$. The initial strength is recovered after completing the series of fractures in "average" time, i.e., before transition to "slow" time. This means, in particular, that in one series of fractures repeated fractures can occur on the same edges (foreshocks and aftershocks within the focus of the main shock).

Energy. The elastic energy on the edge with number α is determined by the formula

$$e_\alpha = L_\alpha(\sigma_\tau^2/2K_\tau + \sigma_n^2/2K_n), \quad (13)$$

where L_α is the length of the edge. By this same formula we determine the energy of the edge in a state of fracture: we consider it equal to that energy which this edge would have upon healing of the fracture. At the time of fracture - in fast time - the energy of the edge with number α decreases by the amount $de_\alpha > 0$, which we call the *energy release on the edge*.

We will determine the work of the external force on the i-th block by the formula

$$A_i = F_i^1 x_i + F_i^2 y_i + M_i^e \varphi_i, \quad (14)$$

where $F_i^e = (F_i^1, F_i^2)$ is the external force; M_i^e is the moment of the external force. It can be shown that the solution of system of equations (4), if there are no edges in a state of slip and underthrust, is the minimum of the function $\Phi = E - A$, where $E = \Sigma e_\alpha$ is the total work of the external forces (summation is carried out over the edges); $A = \Sigma A_i$ is the total work of the external forces (summation is carried out over the "free" blocks). Hence follows, in particular, that the matrix of system (4) is nonsingular if there is at least one "thick" block and the system of blocks is connected.

Let Φ_- be the value of function Φ immediately before a series of fractures and Φ_+ be its value after completion of the series. It can be shown that the quantity $dE = \Phi_- - \Phi_+$ is positive (and even greater than the sum of the energy releases on all edges in the series of fractures). This quantity is called the *energy release in the system*.

Calculations: simplest models of a sequence of earthquakes. Sequences of earthquakes were calculated for several simple variants of the described model. These variants represent the slip zone of the fault, consisting of one or three layers. Each layer is divided into rectangular blocks. Slip was created by movement of the "fixed" blocks along the margins of the fault zone. The direction of movement is indicated by arrows in the figures. Model analogues of the earthquake catalog, frequency graphs, and space-time distributions of earthquakes were examined for each variant.

Units of measurement. We will define the units of measurement for all parameters and variables occurring in the model. Our two-dimensional model simulates a certain three-dimensional medium. We denote by H the extent of this medium in a direction perpendicular to the plane of the model. Then in the preceiding account all quantities of force, moment, and energy should be referred to a unit length z. Their total values are obtained by multiplication by H.

The coefficients K_τ and K_n for calculating the elastic force are determined by a rheological model of a thin layer. In the particular case of a thin ideally and linearly elastic layer of thickness h with Lame constants λ and μ: $K_\tau = \mu/h, K_n = (\lambda + 2\mu)/h$. The remaining parameters and variables have the usual dimension: t is time; x, y, δ, Δ are the length; σ, B, b, C, D, d are stresses; ϕ, A, a, q are dimensionless.

We note that although the dimensions of the blocks, just as displacements, have the dimension of length, their characteristic scales are independent and different, so that the dimensions of the blocks are always far greater than displacements.

Values of the parameters. The following values of the parameters were used in the calculations: A = 0.6, B = 0.5, C = 1, a = 0, b = 0, K_τ = 0.6, K_n = 1, which are common for all edges. The parameters B, D, q were not assigned, since underthrusts and "fast" time were not introduced in the investigated variants. For the "fixed" blocks movement was assigned with a constant rate v - 1 in the directions indicated in the figures by arrows, as well as constant displacement toward the center of the model compressing the other blocks. The upper and lower blocks were displaced in the one-layer model by 0.5 and in the three-layer by 5. The side blocks are displaced in the one-layer model by 1 and in the three-layer by 5. Furthermore, in the three-layer model the side blocks rotate according to the displacement of the upper and lower blocks.

Results of calculations. The geometry of the one-layer model is shown in Fig. 1,a. The "fixed" blocks are hatched. The geometry and properties of this model are analogous to the Burridge-Knopoff model of masses and springs [10]. Figure 1, b represents the earthquake catalog: T is the time in arbitrary units, E is energy. All fractures occurring in "average" time are united into one *event*. Thus each event in Fig. 1,b is the unification of a "foreshocks-main shock-aftershocks" series. The energy E of such an event is the sum of energy releases de_α on all fractured edges. Figure 1,c shows the space-time distribution of earthquakes. Here X corresponds to the distance along the fault. Each line in Fig. 1,c indicates a series of edges that experienced fractures during the same event. The places where the first fracture occurred in the given series ("epicenters") are marked by dots. The frequency graph is shown in Fig. 1,d.

Figure 2 gives analogous calculations for the three-layer model of slip; Fig. 3 for the one-layer model with bending.

The calculations in Figs. 1-3 pertain to the case when dynamic friction is small (a = 0), i.e., as a result of fracture, shear stresses on its margins vanish.

Figure 4 shows analogous results for the maximum possible dynamic friction (a = A). Otherwise the model is the same as in Fig. 2.

We will discuss the results. As is seen from Figs. 1-4, the model gives an appoximately linear frequency law. We note that it is not incorporated in the model: it postulates only the conditions of fracture on elementary edges but not their unification. It is not even predetermined a priori that with an increase of energy the number of earthquakes decreases monotonically. The maxima energy is determined by the dimensions of the entire system, the minimum energy is related mainly to the dimensions of the smallest edge. The frequency graph is monotone and smooth only after a sufficiently strong earthquake. This is seen, for example, in Fig. 2, where with a decrease of the step with respect to E local extremes occur on the frequency graph. Such deviations from monotoneity were predicted in real catalogs and then found in [1] on the basis of concepts about the

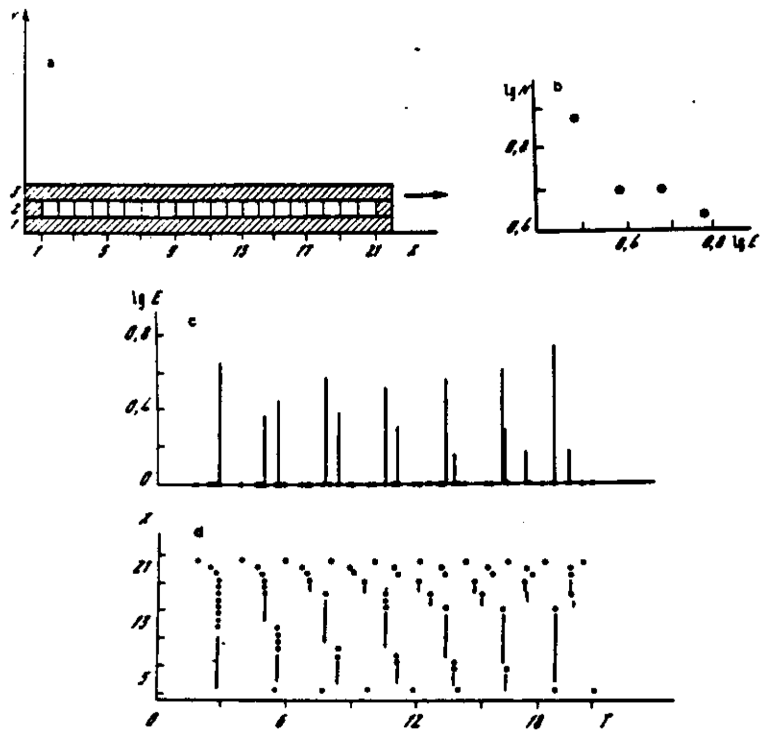

Fig. 1. One-layer model of slip: a) system of blocks; b) sequence of earthquakes; c) space-time distribution of fractures; d) frequency graph.

discrete hierarchical structure of the lithosphere. In certain cases (Fig. 4) a decrease of the E step causes a bend of the frequency graph in the region of small energies. An analogous bend is found in the real earthquake catalog. It is usually explained by insufficient information about weak earthquakes. The graph under consideration shows, however, that it can be partially explained also by physical causes.

The space-time distribution of earthquakes, just as in reality, is nonuniform. Thus, already in the simplest model (see Fig. 1) relatively numerous weak earthquakes dominate in the right side of the fault and more infrequent strong ones in the left side. This is explained by the fact that the immovable obstacle on the right lies on the path of movement, and local stress concentration is greater here. Therefore, strong earthquakes do not have time to be formed, and slipping is realized "by parts." It is interesting to note also the migration of weak earthquakes toward the future strong ones. Weak earthquakes in the right side of the fault as though prepare strong earthquakes in the left part. If we make the model symmetric, considering that the upper and lower blocks move at an equal rate in the opposite direction, then the indicated nonuniformity disappears. Both situations, apparently, are not precluded in nature. This result reminds us that when analyzing the dynamics of a fault one cannot always examine only the relative moment of its margins. After introducing bending the dominance of weak earthquakes in the right side was retained, although it decreased somewhat. There are no weak earthquakes at all in the zone of bending itself. On the whole the zone of bending plays approximately the same role as a barrier in Aki's model [11] or the zone of increased strength in Kanamori's model [12]. Precisely here occur relatively strong earthquakes. Their foci extend beyond the bend. We note that the introduction of bending without simultaneous introduction of underthrust makes our model transient. As the "fixed" blocks move the normal stresses on the bend will increase, which is why the earthquakes here will become increasingly more infrequent and stronger. In reality, this tendency will be disrupted by the formation of an underthrust. Thus the model (see Fig. 3) is applicable, perhaps, in the time interval between two overthrusts.

A characteristic space-time inhomogeneity is obtained in the three-layer model. Earthquaks occur as clusters now in one layer, now in another layer. At first the upper and lower parts of the zone are active, then activity shifts to the middle part, etc. Yet the

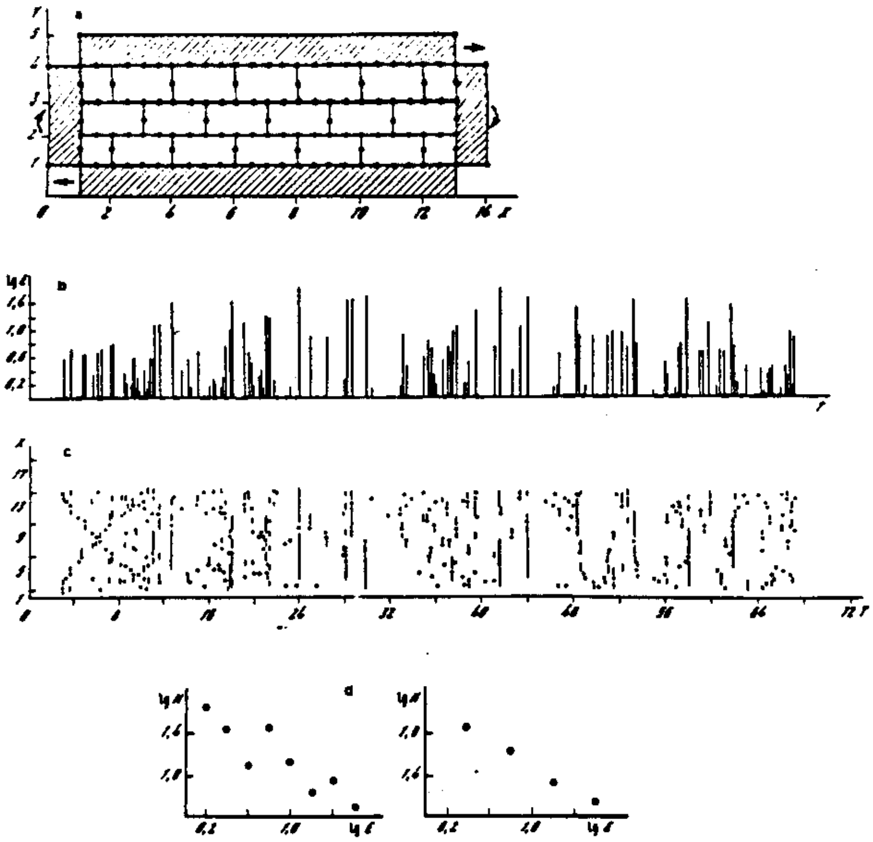

Fig. 2. Three-layer model of slip: a) system of blocks; b) sequence of earthquakes; c) space-time distribution of fractures; d) frequency graph.

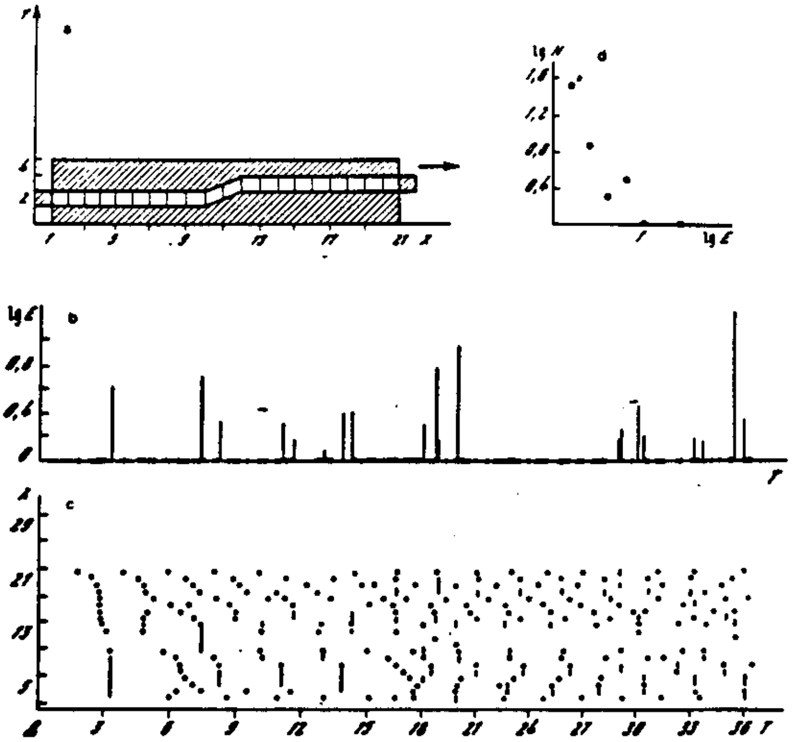

Fig. 3. One-layer model of slip with bending: a) system of blocks; b) sequence of earthquakes; c) space-time distribution of fractures; d) frequency graph.

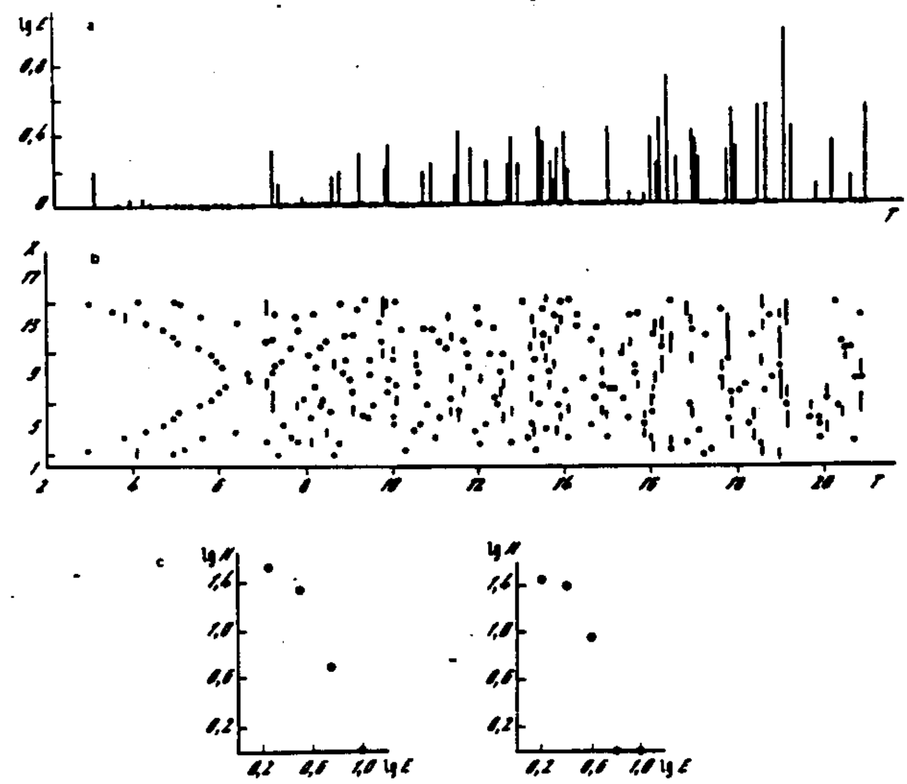

Fig. 4. Three-layer model (a = A): a) sequence of earthquakes; b) space-time distribution of fractures; c) frequency graph.

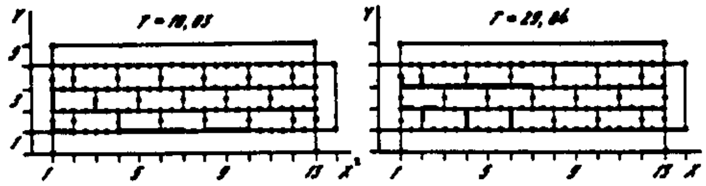

Fig. 5. Examples of the spatial structure of an individual event.

overall sequence looks rather regular. It is interesting also that strong earthquakes are preceded by periods of quiescence (the vacancies on the (x, t) graph). These vacancies most often begin to be filled from the margins.

A relative regularity of strong earthquakes is seen in Fig. 2. Weaker earthquakes are distinctly clustered; in this work we do not investigate clustering quantitatively.

In all investigated models strong earthquakes are often preceded by an increase of the number of weak earthquakes in individual parts of the zone of quiescence, especially along its margins. It would be premature to identify this phenomenon with known precursors.

We will stop on the spatial structure of an individual event. We note first of all that individual fractures in the event do not necessarily form a solid line. Several examples are given in Fig. 5. Partitioning of the events into foreshocks, main shocks, and aftershocks were not examined here. The next work will be devoted to this.

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