Modeling of large faults in zones of lithospheric extension and numerical constraints on deformation

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LARGE FAULTS IN ZONES OF LITHOSPHERIC EXTENSION: MODELING AND NUMERICAL ESTIMATES OF DEFORMATION

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A similarity-based physical model of faulting in zones of lithospheric extension simulated formation of fault systems in extended viscoelastic ductile material and their gradual coalescence into a single major suture. This process includes several stages that are marked by specific structural reorganization in fault systems and recorded in variations of their parameters (density, length, fractal dimensions, etc.). Structural reorganizations are evident in plots showing variations in fractal dimensions of fault systems, longest suture lengths, and fault density associated with deformation increase. In nature, the fractal dimensions of fault systems can be easily estimated from the known hierarchy of faults, which allows further estimation of the relative degree of deformation and the structural stage of evolution of major fault zones.

Ruptures, faults, fractures, parameters, physical modeling, fractal dimension, extension strain, structural changes

INTRODUCTION

The evolution of large lithospheric faults is regular in space and time [1–3] and most often consists in multistage growth of local faults and fractures, their structural arrangement and transformation into deep regional- or global-scale faults. This process, too long to be observed in nature, can be investigated experimentally [4, 5]. Simulated by physical models, fault evolution includes several discrete stages even at constant stress. Each stage reflects a qualitatively new structural setting and can be distinguished in experiments from changes in the pattern of small fractures, their density [1–3], and other factors controlling the geological and geophysical properties of faults and their dynamic influence. The identification of evolutionary stages in natural faults remains, however, a difficult problem.

In [1], this problem was approached from fracturing patterns inside faults, which in fact implies a qualitative solution. Reactivation of faults can be timed from isotopic ages of rocks, but these estimates do not necessarily correspond to structural stages. A quantitative solution requires a statistical geological basis, which is obviously unavailable. The necessary statistical data can be furnished by physical modeling based on the similarity principle. In this study, we apply physical modeling to simulate the multistage evolution of large faults in constant lithospheric extension, specifically the strain-dependent behavior of ruptures of various ranks and their structural settings.

METHODS

Physical modeling was carried out using the same method as in [1] with standard equipment called "Razlom" ("Fault"), which allows various combinations of stress loads on the model material. In our experiments, extensional stress was applied to the bottom of an argillic paste layer of a viscosity of 10^5 Pa·s. The experiments were based on the theory of similarity [5]:

$$\rho g L T/\eta = \text{const}, \quad (1)$$

where ρ is specific weight in g/cm^3, g is gravity acceleration in m/s^2, L is linear dimension in m, T is time in s, and η is viscosity in Pa·s.

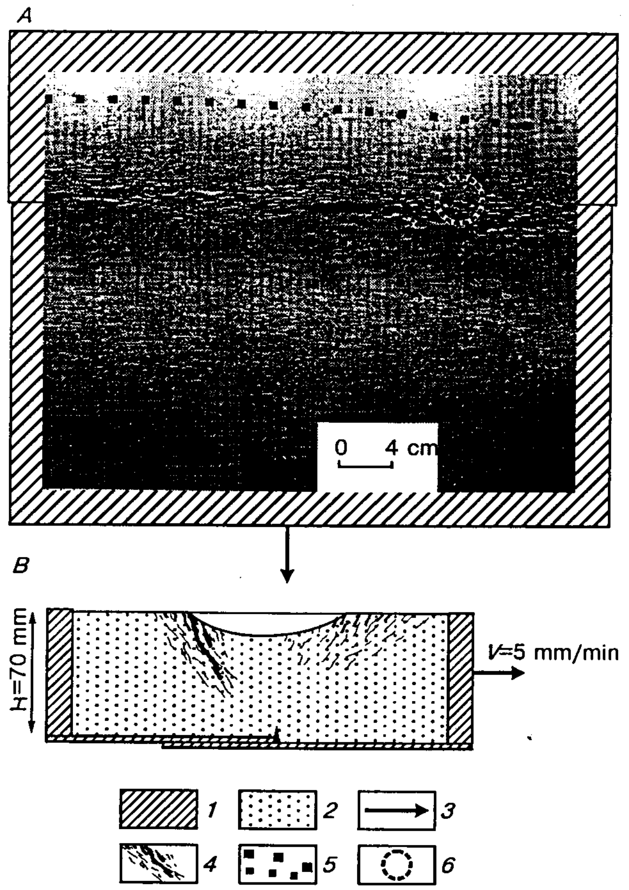

Fig. 1. Model of strain behavior on faulting. A — View from above; B — schematic cross section of modeled zone of extension. 1 — stamps; 2 — model material; 3 — direction of motion of mobile stamp; 4 — ruptures; 5 — zone of influence of large fault; 6 — window to estimate rupture density.

From (1) it follows that the similarity coefficients are related as

$$C_\eta = C_\rho \cdot C_g \cdot C_L \cdot C_T, \tag{2}$$

where C are the similarity coefficients, including specific weight coefficient $C_\rho = \rho_n/\rho_e$, gravity acceleration coefficient $C_g = g_n/g_e$, time coefficient $C_T = T_n/T_e$, and viscosity coefficient $C_\eta = \eta_n/\eta_e$. The subscripts "n" and "e" mean natural and experimental parameters, respectively.

The sought similarity coefficient of dimensions C_L is found from (2) as

$$C_L = C_\eta/C_\rho \cdot C_g \cdot C_T. \tag{3}$$

The similarity coefficients are calculated as ratios of natural to experimental values. In our case the natural parameters are 10^{23} Pa·s for the viscosity of continental lithosphere [6], 25 Ma for the time of Baikal rifting in a zone of lithospheric extension [7], 2.7 g/cm^3 for the mean specific weight of rocks, and 40–50 km for the thickness of the lithosphere in the Baikal rift beneath a fairly broad zone and 100 km beneath the Transbaikalian upland [8]. In the experiment, the model material of 10^5 Pa·s viscosity of and 2 g/cm^3 specific weight is strained under extension for 17 min at a rate of 5 mm/min. Thus, the experimental parameters are $C_\eta = 10^{18}$, $C_T = 7.5 \cdot 10^{11}$, $C_\rho = 1.35$, and $C_g = 1$, as the experiments were run in a constant gravity field. Substituting these coefficients into (3), we obtain $C_L = 10^6$. Therefore, 1 mm in the model corresponds to 1 km in nature, and 1 minute of experiment corresponds to 1.5 Ma of the geological history.

The strain dynamics associated with this destruction mechanism was discussed in detail in [2]. At the first modeling stage, strain produces a linear depression with fault zones emerging on both of its ends (Fig.

1), the widest at the beginning of the experiment and the narrowest at the final stage when they are transformed into a series of short local ruptures that coalesce into long faults. Thus active rupturing under continuing extension becomes concentrated in a narrowing zone and is shifted toward the depression to eventually form a single major fracture on its ends. It was noted that the rupturing proper, including rank changes and the formation of the major fracture, is faster and better pronounced in the passive flank of the model (on the fixed end). This most important and geologically longest stage of destruction was investigated in another series of experiments.

A 70 mm thick layer of argillic paste was spread uniformly on the plate. This thickness roughly corresponds to the pre-rifting thickness of the crust. During the experiment the layer was thinned to correspond to the rifted lithosphere beneath Baikal (40–50 km) [8]. The process of deformation was observed relative to markers (rings 14 mm in diameter) on the horizontal surface of the argillic layer. Extension strain was provided by monotonic motion of the plate at 5 mm/min. During the 18 min long experiment, we took 13 pictures from the onset of rupturing, for successive measurements of the necessary parameters, including lengths and density of ruptures and relative strain ε estimated from elongation of the marking rings [9] as

$$\varepsilon = \Delta d/d_0 \qquad (4)$$

where d_0 is the initial ring diameter and Δd is the diameter increment associated with transformation of the ring into an ellipse. The maximum strain in the axis of the forming large rupture was used in further calculations.

Each photograph allowed us to measure from 613 to 1448 ruptures of various ranks on the passive flank of the model. The density of ruptures was estimated as their number in a round window with a diameter equal to the half thickness of the model layer and a center in the zone of major rupturing. Successive measurements of lengths of some ruptures located at various distances from the major fault plane revealed the dynamics of elongation by strain. The rupture pattern associated with extensional strain and formation of a large fault was investigated using fractal analysis, with the equation [11]

$$N_i = aR^D \qquad (5)$$

where D is the fractal dimension, N_i is the number of destroyed pixels, R is the size of the system in pixels in an i-th iteration. A pixel was said destroyed if its two sides were crossed by a rupture.

RESULTS AND DISCUSSION

Physical modeling showed several stages in the formation of a large fracture recorded in structural changes which were observed and analyzed qualitatively in numerous earlier experiments [1–3]. The evolution of a large fracture involves elongation and coalescence of minor short ruptures and is accompanied by changes in their density and structural pattern within the influence of strain at certain stages. The changes in structural pattern mean that the strained model changes qualitatively which reflect the stages of evolution of a fault. The limits of stages were detected using the fractal analysis of the model rupture pattern.

Figure 2, *A* illustrates the dynamics of rupture growth during deformation. The rupture length vs. strain plot shows two branches, one corresponding to the major fracture and the other to all other shorter ruptures. The curve for the major fracture (Fig. 2, *B*), which reaches a length of 144 mm already at $\varepsilon = 0.5$, includes several segments that reflect its nonuniform elongation at uniform stress and strain rate. During the active growth of the major fracture, the elongation of other ruptures stops or slows down. The strain is inhomogeneous, being the greatest in the center of the model where the major fracture is forming and the smallest on the periphery in the region of minor fractures. Note again that we used the maximum strain values at the axial part of the major fracture.

Dynamics of rupture density reflects discontinuity of the destruction process. The modeling-based spatial distribution of the density of normal faults is described in [2], and here we pass over details of its variations along and across the zone of extension. The known regularities are as follows [2]: (1) density of ruptures increases toward the center of fault zone; (2) density maximums are spaced at roughly equal distances along the model and occur from the beginning to the end of the experiment; (3) number of active ruptures within a fault zone begin to decrease from a certain time. We were interested in absolute densities of ruptures within the region of the model where rupturing is observed throughout the experiment.

The changes in density of ruptures in this region observed in the course of the experiment (Table 1) reflect different stages associated with qualitative changes in the fault zone. At the first stage, the density increases as small ruptures emerge. The following stage of minor density changes corresponds to slower rupture

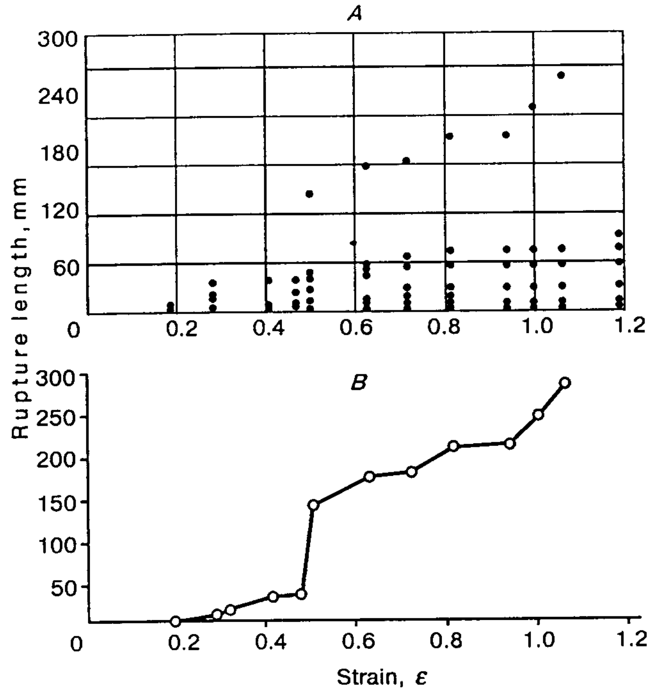

Fig. 2. Lengths of ruptures vs. strain. A — For ruptures within window; B — for major fracture.

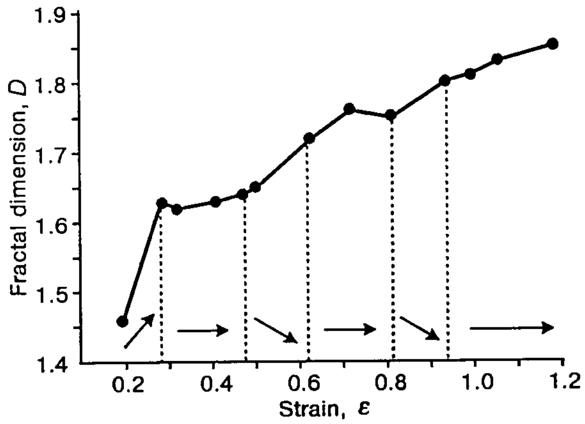

Fig. 3. Fractal dimensions of rupture network (D) vs. strain. Arrows pointing up, down, or right show increasing, decreasing, or constant density of ruptures, respectively.

growth before a critical structural change when some ruptures couple and thus become less dense. Then the process repeats at a hierarchically higher level.

The dynamics of lengths, density, and structural pattern of ruptures associated with the formation of an extension zone was investigated using fractal analysis. Figure 3 shows time-dependent fractal dimensions as a function of strain for all ruptures in the passive flank of the model. Comparing the degrees of complexity of the pattern with the lengths and density of ruptures (Table 1) we correlated the step-like shape of the fractal dimension plot with structural changes within the fault zone.

At the stage of inception of a fault network, at strain from 0.2 to 0.3, the model shows gradual complication of the rupture pattern associated with new ruptures and their slight elongation. This stage is followed by a period of quiescence with minor changes in rupture density and fractal dimensions of the network (Fig. 3) at strain from 0.3 to 0.5. Similar but shorter periods of quiescence are observed before the following structural

Table 1

Changes in Quantitative Parameters of Ruptures under Strain

No. of photo-graph	Time from onset of experiment, s	Extension strain in zone of major rupturing	Length of major fracture, mm	Number of ruptures in window	Fractal dimension, D
1	440	0.19	8	8	1.46
2	518	0.28	15	16	1.63
3	573	0.31	21	19	1.62
4	640	0.41	37	17	1.63
5	680	0.47	39	20	1.64
6	720	0.5	144	16	1.65
7	760	0.63	177	13	1.72
8	800	0.72	182	12	1.76
9	841	0.81	212	12	1.75
10	880	0.94	215	9	1.8
11	920	1.0	249	10	1.81
12	960	1.06	287	10	1.83
13	1000	1.19	>300	9	1.85

changes as well (Fig. 3). A major rupture emerges after $\varepsilon = 0.9$ and the zone of its active dynamic influence broadens due to new minor ruptures on the periphery. After the first structural change (at $\varepsilon = 0.5$), the largest elongating ruptures stand out from the total assemblage, which brings the fracture pattern to a stage of intense complication. The models demonstrate a hierarchic system of ruptures in which those that successively stop their coalescence and elongation coexist with longest ruptures that are still active. Therefore, changes in the fractal dimensions correspond to structural changes in the fault network.

Comparison of our results with the earlier modeling of an evolving shear zone [10] shows that increasing strain of any type causes discrete changes in the structural pattern of faults associated with gradient changes of fractal dimensions which reflect qualitatively new states of the model.

Therefore, the modeling experiments have demonstrated a regular relationship between strain, fracturing, and fractal dimensions of rupture networks in active fault zones. This regularity can be extrapolated onto natural processes. Fractal dimensions of faults of various ranks mapped on the Earth's surface can thus indicate relative strain and the stage of destruction preceding the formation of a large fault.

CONCLUSIONS

Physical modeling of rupturing associated with extensional strain showed a regular relationship between strain, rupture growth, and changes in rupture density during large-scale active faulting. Structural changes in the fault pattern preceding different stages of origin and evolution of a large fault are reflected in fractal dimensions which, in turn, are correlated with strain. Fractal dimensions can be easily estimated from the known hierarchy of mapped natural faults to infer the relative degree of rock deformation in the zones of large lithospheric faults. Studies of this kind have already been set up in the Baikal rift [12].

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REFERENCES

[1] S. I. Sherman, K. Zh. Seminskii, S. A. Bornyakov, in: *Faulting in the lithosphere. Shear zones* [in Russian], N. A. Logachev (Ed.), Novosibirsk, 1991.

[2] S. I. Sherman, K. Zh. Seminskii, S. A. Bornyakov, in: *Faulting in the lithosphere. Zones of extension* [in Russian], N. A. Logachev (Ed.), Novosibirsk, 1992.

[3] S. I. Sherman, K. Zh. Seminskii, S. A. Bornyakov, in: *Faulting in the lithosphere. Zones of compression* [in Russian], N. A. Logachev (Ed.), Novosibirsk, 1994.

[4] M. V. Gzovskii, *Fundamentals of tectonophysics* [in Russian], Moscow, 1975.

[5] S. I. Sherman, *Physical experiment in tectonics and theory of similarity*, Geologiya i Geofizika (Soviet Geology and Geophysics), vol. 25, no. 3, p. 8(6), 1984.

[6] V. K. Kuchai, *The recent dynamics of the Earth and the Pamir-Tien-Shan orogeny* [in Russian], Moscow, 1983.

[7] N. A. Logachev, S. V. Rasskazov, A. V. Ivanov, et al., in: *The lithosphere of Central Asia (Main scientific results obtained in the Institute of the Earth's Crust, Irkutsk, through 1992–96)* [in Russian], Novosibirsk, 1996.

[8] Yu. A. Zorin, E. Kh. Turutanov, V. G. Belichenko, et al., in: *Geophysical studies in East Siberia at the turn of the 21st century* [in Russian], Novosibirsk, p. 7, 1996.

[9] A. V. Mikhailova, in: *Tectonophysics and rock mechanics* [in Russian], Moscow, p. 38, 1971.

[10] S. A. Bornyakov, in: *Tectonics, geodynamics, and the processes of magmatism and metamorphism* [in Russian], Book 1, Moscow, p. 92, 1999.

[11] E. Feder, *Fractals* [Russian translation], Moscow, 1991.

[12] S. I. Sherman and A. S. Gladkov, *Tectonophysics*, vol. 308, p. 133, 1999.

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