ISSN 1028-334X, Doklady Earth Sciences, 2007, Vol. 415A, No. 6, pp. 944–949. © Pleiades Publishing, Ltd., 2007.
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GEOPHYSICS

Structure of the Epicenter Field of Earthquakes in the Baikal Region

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Presented by Academician G.S. Golitsyn October 27, 2006

Received October 19, 2006

DOI: 10.1134/S1028334X07060268

Methods of the fractal theory were applied to study the structure of epicenter fields of representative earthquakes (energy class $K_P \geq 8$) recorded from 1964 to 2002 in the Baikal region, including three subregions and six sectors. We show that the shock epicenter field in the Baikal region, subregions 2 and 3, and sectors 2, 3, and 5 is self-similar and similar, while the fractal estimates of the structure of the shock epicenter field in sectors 1 and 6 located at the flanks of the Baikal Rift Zone (BRZ) differ strongly. A tendency to a decrease in the cell dimension D_0 from southwest to northeast testifies to the transformation of quasi-areal distribution of epicenters of earthquakes to a quasi-linear structure. The chart of contour lines of D_0 characterizes the shock epicenter field in the BRZ as a structure formed predominantly in the regime of dynamic chaos.

The modern theoretical and numerical models of seismicity consider seismogenesis as evolution of complex dynamic systems with many degrees of freedom. They are developed mainly as a new basis for the prediction of strong earthquakes and investigation of the spatiotemporal and energetic structure of seismicity [1]. It is assumed that the available models of seismicity and their integration with the concepts about realization of earthquakes can facilitate to overcome the difficulties related to the lack of the corresponding fundamental equations and the impossibility of direct measurements in deep zones of the lithosphere, where earthquakes are generated. In the solution of these problems, commonly the five-dimensional space of kinematic parameters of seismicity is identified based on the joint analysis of the models and phenomenology: scaling, similarity, self-similarity, spatiotemporal correlation, responses to forcing, and predictability at different scales of averaging [2–4]. The study of energetics and dynamics of the natural seismicity in the Baikal region confirmed the possibility of implementation of such an approach for the investigation and fractal description of the spatiotemporal and energetic structure of seismogenesis system [5, 6]. The fractal properties of local fields of earthquake epicenters in the Baikal region observed over 30 years are estimated in [7, 8]. Significant acquisition of the database on the earthquakes in the region in the last decade allows us to expect refinement of the old data and gain of new information about the fractal structure of the shock epicenter field. In this work, we used the methods of fractal theory to study the structure of the epicenter field of representative earthquakes (energy class $K_P \geq 8$) recorded from 1964 to 2002 in the Baikal region, including three subregions. These three large geological subregions should be considered as two neighboring levels in the hierarchy of inhomogeneities of the lithosphere [9], which accommodate modern attractor structures of the riftogenesis system [10]. The division of the BRZ into regions and sectors gives a possibility to test similarity and self-similarity of the seismicity structure at different hierarchic levels. A chart of D_0 contour lines obtained on the basis of the data on earthquake epicenters in areas with size $2° \times 2°$ allows us to distinguish inhomogeneity zones in the structure of regional seismicity and compare it with the charts of the energetic structure and dynamics of the seismic process in the Baikal region.

In terms of seismicity, the most hazardous part of the Baikal region (φ = 48.0°–60.0° N, λ = 96.0°–122.0° E) is the rift zone that extends as a system of depressions from northern Mongolia along Lake Baikal to southern Yakutia. In the first visual approximation, the shock epicenter field can be presented as two triangles (Fig. 1). The earthquake epicenter field in the southwestern flank and central part of the BRZ makes up the first triangle. In the southwestern flank of the region (subregion 1, φ = 48.0°–54.0° N, λ = 96.0°–104.0° E), the shock epicenters are concentrated as sublatitudinal and submeridional bands (areal distribution of seismicity). In the central part of the BRZ (subregion 2, φ = 51.0°–54.0° N, λ = 104.0°–113.0° E), the epicenters are con-

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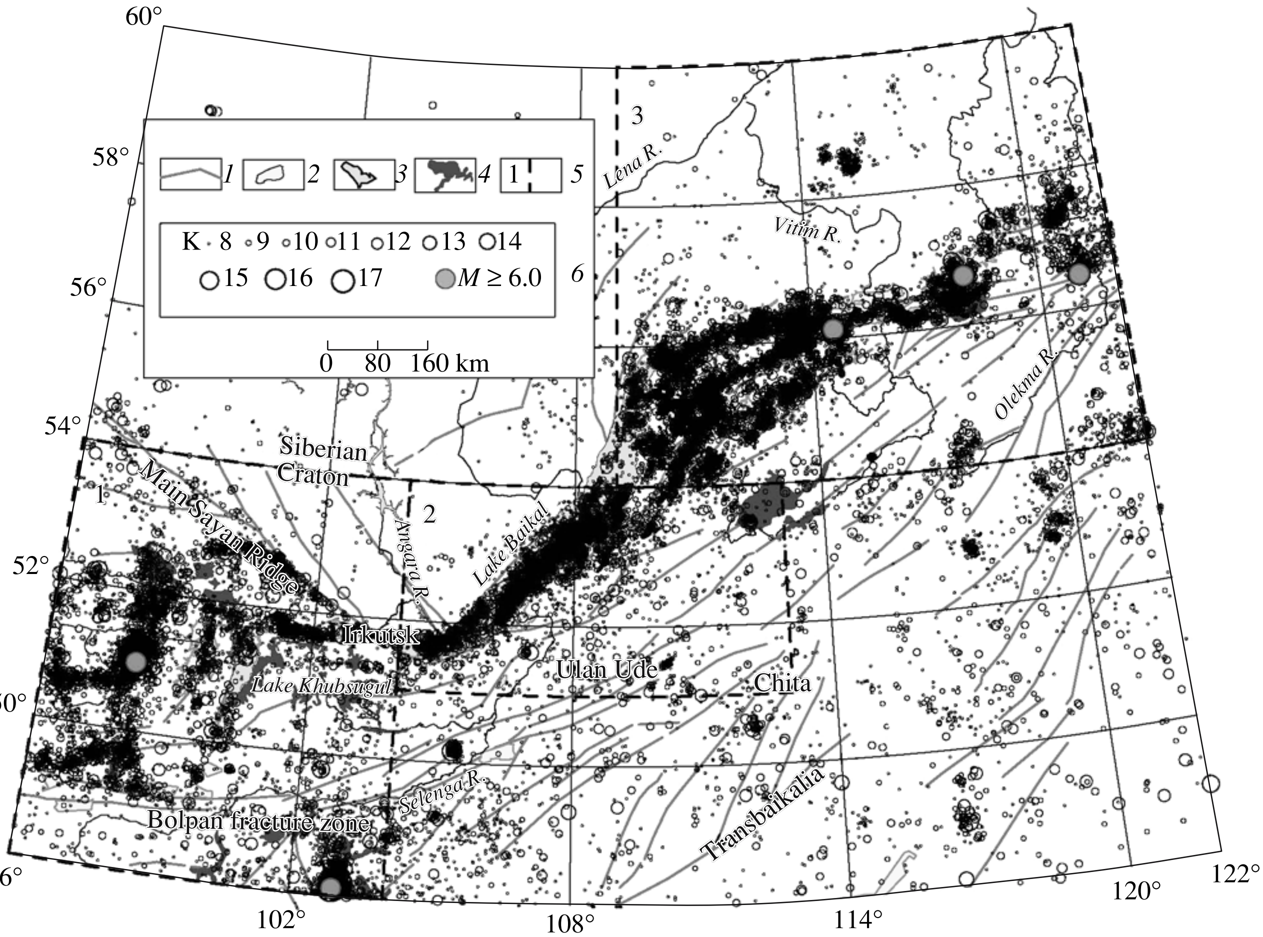

Fig. 1. Chart of epicenters of earthquakes ($K_P \geq 8$) in the Baikal region from 1964 to 2002. (*1*) Fractures, (*2*) depressions; (*3*) lakes; (*4*) basalts; (*5*) subregion numbers and boundaries; (*6*) energy class K_P according to the scale proposed by T.G. Rautian and epicenters of strong earthquakes with magnitude $M \geq 6$.

centrated predominantly in one wide NE-oriented band. In the northeastern flank of the BRZ (subregion 3, φ = 54.0°–60.0° N, λ = 109.0°–122.0° E), the epicenter field makes up the second triangle. In the west, the base of this triangle incorporates several NE-oriented bands of shock epicenters, while the vertex of the triangle includes one sublatitudinal band in the eastern part of the region. In order to scrutinize the structure of the epicentral field, we divided the subregions along longitudes 100.0°, 108.0°, and 116.0° into six sectors (nos. 1 to 6 starting from the southwestern boundary of the region). The local groups of high density of shock epicenters are formed mainly by aftershocks and swarm events. Therefore, the chart of the earthquake epicenters shows a discontinuous and nonuniform pattern. In terms of seismicity, the adjacent territories surrounding the rift zone differ strongly from the BRZ. The shock epicenter chart clearly shows a high-seismic zone limited by the almost aseismic Siberian Craton and low-seismic Transbaikalia (Fig. 1). In general, the seismicity of the region characterizes the system of seismogenesis as a fractal spatiotemporal and energetic structure.

The idea that fractal measure can be presented by interrelated fractal sets varying according to a power law with different exponents opens a new possibility for applying fractal geometry to geophysical systems of seismogenesis [3]. Fractal geometry can describe many of the irregular and fragmented forms in the environment and give birth to complete theories by determining a family of forms known as fractals [11]. The term fractal was introduced as a mathematical concept. However, it was soon widely applied in natural and humanity sciences. Thus, this term turned into a general scientific concept, which characterizes a self-similar network delicate system appearing in a cycle of nonlinear transitions of the system evolving from one state to another. The authors of [10] showed that the stress field in the lithosphere of the BRZ undergoes bifurcations of amalgamation. Multiple repeating of bifurcations is actually similar to iteration procedures generating fractal structures and images [11]. We believe that synergetic processes, which have taken place for millions of years since the end of the Upper Cretaceous–Paleocene (the time of the appearance of the South Baikal Depres-

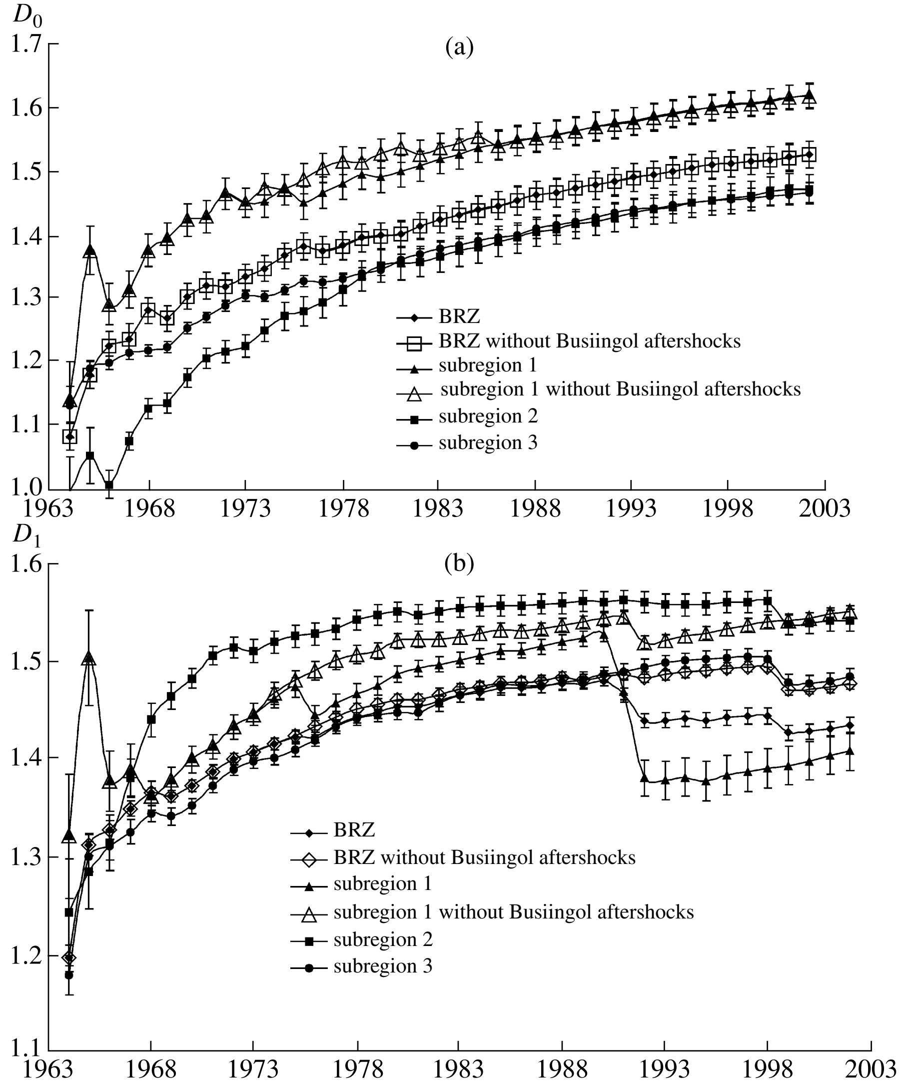

Fig. 2. (a) Grid and (b) information dimensions of the structure of the earthquake epicenter field in the Baikal region and three subregions with and without account for aftershocks of the three strong Busiingol earthquakes.

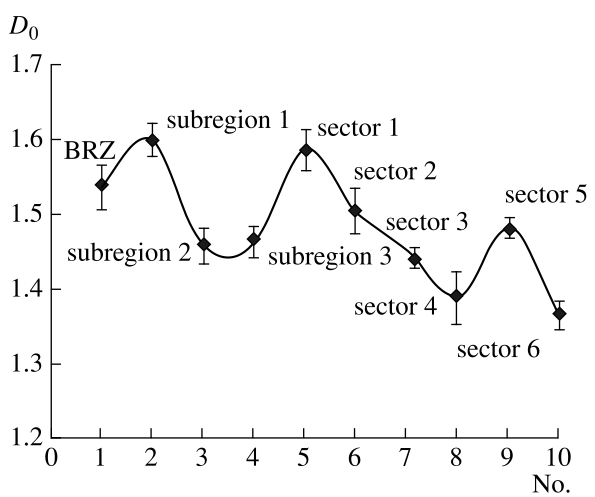

Fig. 3. Estimates of grid dimension D_0 of the structure of the earthquake epicenter field in the Baikal region, three subregions, and six sectors.

sion, the historical core of the Baikal Rift System [12]) in the lithosphere of the BRZ, make up natural spatiotemporal fractal structures including seismicity [5, 6]. The term "natural fractal" is used to denote natural structures, which can be presented as a fractal set for some purposes [11]. Such fractals tend to scale invariance, for which the degree of irregularity and fragmentation is invariant on all scales. Invariance with respect to multiplicative scale variations is caused by self-similarity of spatiotemporal and energetic processes. However, one can speak about self-similarity of the structure of the analyzed sampling only in the given scale range. As applied to random sets, self-similarity is not a strict concept because the parts in this case should not be exactly similar to the whole; it will be sufficient if the parts and the whole in decreased scale have the same distributions.

The present paper applies two versions of determining the fractal dimension of the structure of the earthquake epicenter field. In the first version, we calculated cell dimension D_0, which is determined on the basis of variations in the share of filled areas in the epicenter-hosting domain [13, 14]. The logarithm of the number of areas $C_0(h_q) = \ln N(h_q)$, which included at least one earthquake, was determined during sequential fractioning of the studied territory into a grid of areas with sides h_q (where $q = 1, 2, \ldots, k$ is the number of the iteration). In the second version, we used information dimension D_1, which was calculated from relation

$$C_1(h_q) = \sum_{i=1}^{m} I(i),$$

where $I(i) = p_i \ln p_i$, $p_i = \frac{n(i)}{N}$, $i = 1, 2, \ldots, m$ is the number of the sequential not-empty area; $n(i)$ is the number of earthquakes in this area; and N is the number of shocks in the sampling [14]. Based on the method of least squares, we calculated the equation of linear correlation, whose coefficient of proportionality corresponds to the sought dimension, for the obtained pairs $(\ln(h_q), C_k(h_q))$, $k = 0, 1$.

Figure 2 presents the graphs of variations in grid and information dimensions of the structure of the earthquake epicenter field in the Baikal region and three subregions. They were obtained for the total accumulated samplings of shocks ($K_P \geq 8$) with a step of one year. In order to study the influence of the groups of shocks on the estimate of the fractal dimension, we performed the calculations with and without account for the aftershocks of the three strong Busiingol earthquakes (November 29, 1974, $\varphi = 51.79°$ N, $\lambda = 98.47°$ E, $K_P = 14$; April 1, 1976, $\varphi = 51.15°$ N, $\lambda = 97.97°$ E, $K_P = 14$; December 27, 1991, $\varphi = 50.98°$ N, $\lambda = 98.08°$ E, $K_P = 16.2$), which occurred in sector 1 at the southwestern flank of the Baikal region. It is seen in Fig. 2a that the groups of aftershocks do not have any significant influence on the estimates of grid dimension D_0: the graphs obtained with and without account for the aftershocks actually coincide in the Baikal region. In the first subregion, the differences in the graphs caused by the influence of the aftershocks do not exceed the standard deviation. The information dimension behaves differently (Fig. 2b). The aftershocks of the three Busiingol earthquakes, South Baikal, and Kicher earthquakes in 1999 decrease notably the dimension of the corresponding area. The smaller the size of the studied territory, the stronger the variation of D_1. A similar effect is observed on the graphs obtained for the six sectors: the grid dimension is only slightly sensitive to the aftershocks, while the information dimension decreases significantly in the beginning of the series of aftershocks. These results introduce a certain correction to the study of the dimension of the structure of the earthquake epicenter field because it becomes clear that the grid dimension would monotonically increase up to a certain level in the course of time. Against the general background of increasing information dimension, it will decrease under the influence of a cluster of shocks. This decrease depends on the number of events in the group and the size of the study region. In this case, a comparison of dimensions is senseless because the information dimension is characterized by the response and long-term memory related to the groups of shocks. It would vary synchronously with the realization of strong earthquakes, which generate continuous series of aftershocks. Therefore, the further study of the structure of the earthquake epicenter field in the Baikal region is presented in this work as the estimates of the grid dimension.

In order to compare the fractal structure of the earthquake epicenter field, Fig. 3 presents D_0 values calculated for the shocks ($K_P \geq 8$) that occurred in the Baikal region, three subregions, and six sectors from 1964 to 2002. The structure of the earthquake epicenter field in subregion 1 and sector 1 is characterized by maximal dimension $D_0 \approx 1.60 \pm 0.02$, which suggests quasi-areal distribution of the shocks in these territories. The minimal value $D_0 \approx 1.36 \pm 0.02$ is observed in sector 6 and characterizes the distribution of epicenters of earthquakes in the northeastern Baikal region as a quasi-linear distribution. Figure 4 presents a chart which characterizes the structure of the earthquake epicenter field in the Baikal region as contour lines of D_0. The chart was obtained for samplings of earthquakes ($n > 100$, $K_P \geq 8$) recorded from 1964 to 2002 within areas of $2.0° \times 2.0°$. In order to show the influence of the groups of seismic events on the structure of the earthquake epicenter field, the chart shows 496 areas of different sizes marked by aftershocks, swarm shocks, and explosions in the Baikal region from 1967 to 2002. It is seen that the regions with high density of the groups of seismic events usually correspond to the zones with high D_0 values. This fact indicates the significant influence of the clusters of shocks on the structure of the epicentral field of regional seismicity. Increased values of dimension ($D_0 \geq 1.6$) are confined to large rift structures (Khubsugul and southern Baikal regions), while the maximum value ($D_0 \geq 7$) is localized in the northern part of the Barguzin depression. We can note that contour line $D_0 \approx 1.4$–1.5 covers the entire territory of the BRZ. It narrows in the central part and in the northeastern border of the region, while local regions with high D_0 values correspond to the zones of inhomogeneity in the charts of the energetic structure and dynamics of seismicity of the Baikal region [5, 6].

Thus, the shock epicenter field encloses inhomogeneities caused by the natural location of earthquake sources in the lithosphere of the region. Since the dimensions for the territories of the sectors, subregions, and the Baikal region are calculated with the superposition of the local fields of epicenters, the observed inhomogeneities make up the structures of the shock

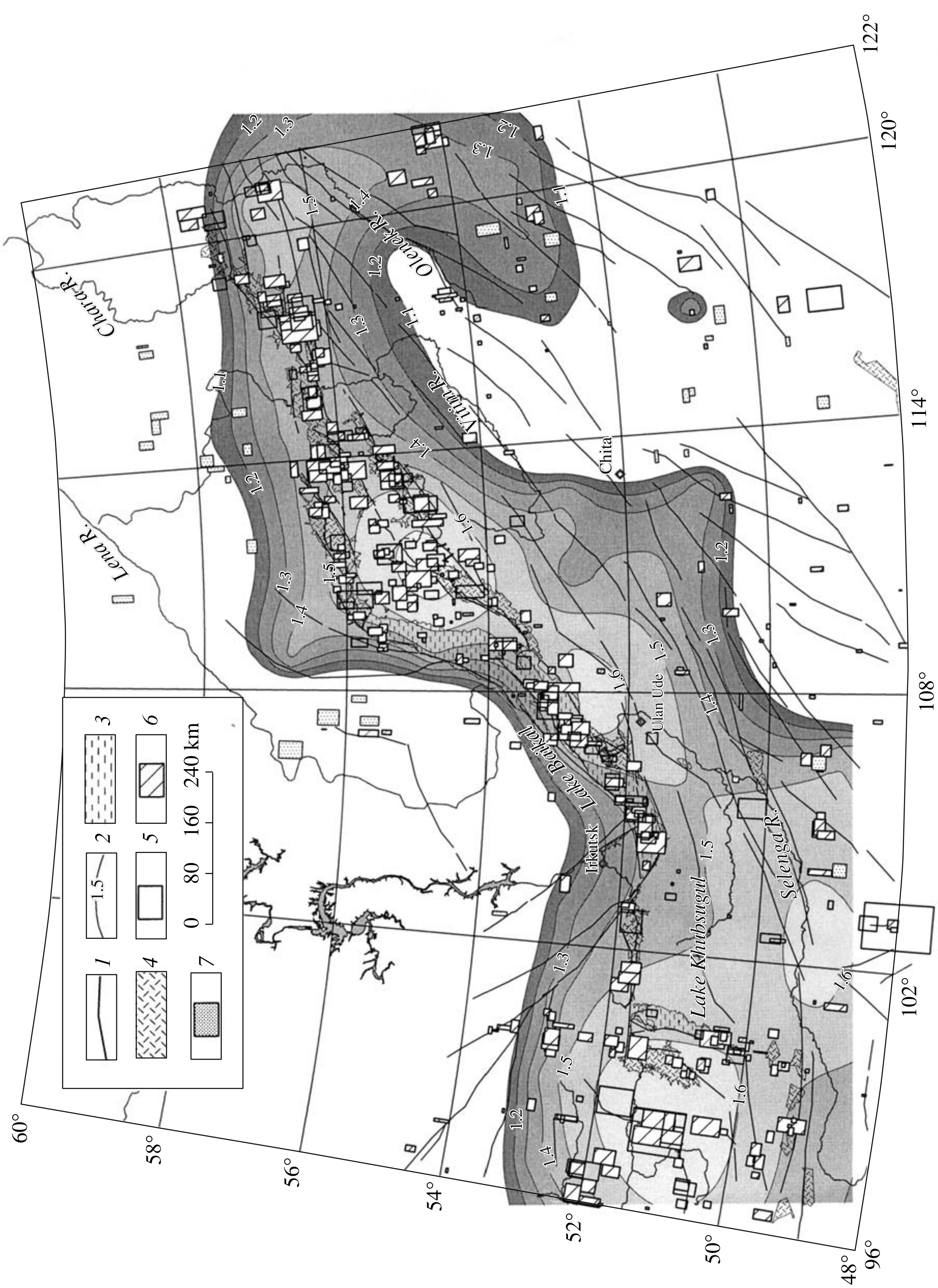

Fig. 4. Chart of grid dimension D_0 obtained from the data on the shocks ($K_P \geq 8$) recorded from 1964 to 2002 in areas $2° \times 2°$. (*1*) Major faults; (*2*) contour lines of grid dimension D_0; (*3*) lakes; (*4*) depressions; (*5–7*) areas of aftershocks, swarm shocks, and explosions, respectively.

epicenter fields of large territories as a multifractal and the obtained fractal estimates characterize the average distribution of the shock epicenters at the surface of these territories. Taking this effect into account in the first approximation, we can consider that the structure of the shock epicenter field is self-similar and similar in the Baikal region, subregions 2 and 3, and sectors 2, 3, and 5 at $D_0 \approx 1.45–1.55$. Therefore, we can characterize the earthquake epicenter field as a structure mainly related to dynamic chaos. The fractal estimates of the structure of the shock epicenter field in sectors 1 and 6 located at the flanks of the BRZ differ strongly, indicating the influence of some factors on the formation of the shock epicenter field. In general, the Baikal region shows a tendency of decrease in the dimension of D_0 from southwest to northeast. This fact characterizes the transition from quasi-areal to quasi-linear distribution of the earthquake epicenters.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research, project nos. 05-05-97206 p_Baikal, 06-05-64120-a.

REFERENCES

1. *International Handbook of Earthquake and Engineering Seismology* (Academic Press, Amsterdam, 2002), Part A.
2. I. R. Stakhovskii, Izv. Phys. Solid Earth **40** (10), 849, (2004) [Izv. Akad. Nauk, Fiz. Zemli, No. 10, 73 (2004)].
3. V. G. Kosobokov and A. K. Nekrasova, Vychislit. Seismol., **35**, 160 (2004).
4. V. B. Smirnov, A. V. Ponomarev, Quian Jiadong, and A. S. Cherepantsev, Izv. Phys. Solid Earth **41** (6), 428, (2005) [Izv. Akad. Nauk, Fiz. Zemli, No. 6, 6 (2005)].
5. A. V. Klyuchevskii, Dokl. Earth Sci. **408**, 559 (2006) [Dokl. Akad. Nauk **408**, 96 (2006)].
6. A. V. Klyuchevskii and F. L. Zuev, Dokl. Earth Sci. **409**, 831 (2006) [Dokl. Akad. Nauk **409**, 248 (2006)].
7. A. V. Solonenko and E. A. Shteiman, in *Seismicity and Seismic Zoning of Northern Eurasia* (OIFZ RAN, Moscow, 1995), No. 2/3, pp. 344–353 [in Russian].
8. S. I. Sherman and A. S. Gladkov, Dokl. Earth Sci. **361**, 872 (1998) [Dokl. Akad. Nauk **361**, 685 (1998)].
9. M. A. Sadovskii, Dokl. Akad. Nauk SSSR **247**, 829 (1979)].
10. A. V. Klyuchevskii and A. A. Klyuchevskaya, Dokl. Earth Sci. **414**, 1317 (2007) [Dok. Akad. Nauk **414** (2), 4465 (2007)].
11. B. Mandelbrot, *Fractal Geometry of Nature* (Freeman, New York, 1983; IKI, Moscow, 2002).
12. N. A. Logachev, Geol. Geofiz. **44** (5), 91 (2003).
13. J. Feder, *Fractals* (Plenum Press, New York, 1998).
14. S. V. Bozhonkin and D. A. Parshin, *Fractals and Multifractals* (NITS RHD, Izhevsk, 2001) [in Russian].