ISSN 1028-334X, Doklady Earth Sciences, 2006, Vol. 409, No. 5, pp. 831–835. © Pleiades Publishing, Inc., 2006.
Original Russian Text © A.V. Klyuchevskii, F.L. Zuev, 2006, published in Doklady Akademii Nauk, 2006, Vol. 409, No. 2, pp. 248–253.

GEOPHYSICS

Investigation of Seismicity Dynamics in the Baikal Region

A. V. Klyuchevskii and F. L. Zuev

Presented by Academician G.S. Golitsyn January 23, 2006

Received November 18, 2005

DOI: 10.1134/S1028334X06050345

For the first time, the methods of fractal theory were applied to the study of seismicity dynamics of the Baikal region and its three areas. Estimates of the Hausdorff dimensionality (*D*) show self-similarity of the seismic process in 1967–2002 with a 10% significance level. The most prominent Hurst index (*H*) and *D* variations correspond with the aftershock series of strong earthquakes, while regions of high *H* and *D* values are congruent with the concentration zones of earthquake groups, suggesting a high influence of shock clusters on the regional seismicity. In general, the Baikal region and its three areas are characterized by a persistent seismic process with long-term memory.

Modern theoretical and numeric simulations of seismicity are developing as a new basis for the study of spatiotemporal and energy structure of seismicity and prediction of strong earthquakes [1]. These models provide for an expansion of principal features of seismicity diagnostics by the joint analysis of models and phenomenology: scaling, similarity, self-similarity, and predictability on different averaging scales. It is well known that invariance relative to multiplicative scaling is governed by the self-similarity of spatiotemporal processes [2]. Self-similarity in application to random sets is not a rigorous concept, because parts in such a case must not be inevitably and exactly similar to the whole and is sufficient if parts and the scaled down whole have the same distributions. Notwithstanding their fundamental importance, such procedures of the diagnosis of a natural seismicity pattern were practically never applied for investigating the structure of seismicity dynamics (seismic process) in the Baikal region. Analysis of the seismic regime made it possible to identify periods of high seismic activity in the region [3]. During the instrumental observation period, the strongest earthquakes (energy class $K_P \geq 14$) generally followed geodynamic activation in some parts of the region and represented responses to the geophysical medium excitation owing to the stress field inversion during the self-organization of the Baikal rift system (BRS) [4, 5]. Excitation of the active geophysical medium was accompanied by an increase in the number of seismic event groups and shocks in earthquake swarms. The abundance of aftershocks and swarm events in the BRS lithosphere ([6, 7]) predetermines a priori the complicated spatiotemporal relationship of the seismic process with earthquake clusters and complicates analysis of dynamics of the regional seismicity, because estimation of the influence of shock groups of various energy classes on its variations becomes the priority issue.

The most hazardous (in terms of seismicity) area of the Baikal region is represented by the rift zone extending as a depression system from northern Mongolia along Lake Baikal to southern Yakutia [4]. Earthquake epicenters are mainly concentrated as sublatitudinal and NE-oriented bands, while local high-density shock groups are most often related to aftershock and swarm shock activity. Figure 1 shows the distribution of the annual number of representative $K_P \geq 8$ earthquakes registered in 1967–2002 in the Baikal region (φ = 48.0°–60.0° N, λ = 96.0°–122.0° E), along with the southwestern (area 1, φ = 48.0°–54.0° N, λ = 96.0°–104.0° E) and northeastern (area 3, φ = 54.0°–60.0° N, λ = 109.0°–122.0° E) flanks and the central part (area 2, φ = 51.0°–54.0° N, λ = 104.0°–113.0° E) of the BRS. These large geological areas can be considered two adjacent hierarchical levels of lithospheric inhomogeneities [8] marked by recent structure-attractors of riftogenesis [4, 5]. It is obvious from Fig. 1 that the majority of earthquakes occur in area 3. The maximum number of annual shocks were recorded in 1991–1992 (area 1) and 1999 (areas 2 and 3). They were governed by aftershocks of the Busiingol (December 27, 1991; K_P = 16.2; φ = 50.98° N, λ = 98.08° E), South Baikal (February 25, 1999; K_P = 14.6; φ = 51.64° N, λ = 104.82° E),

Institute of the Earth's Crust, Siberian Division, Russian Academy of Sciences, ul. Lermontova 128, Irkutsk, 664033 Russia; e-mail: akluchev@crust.irk.ru

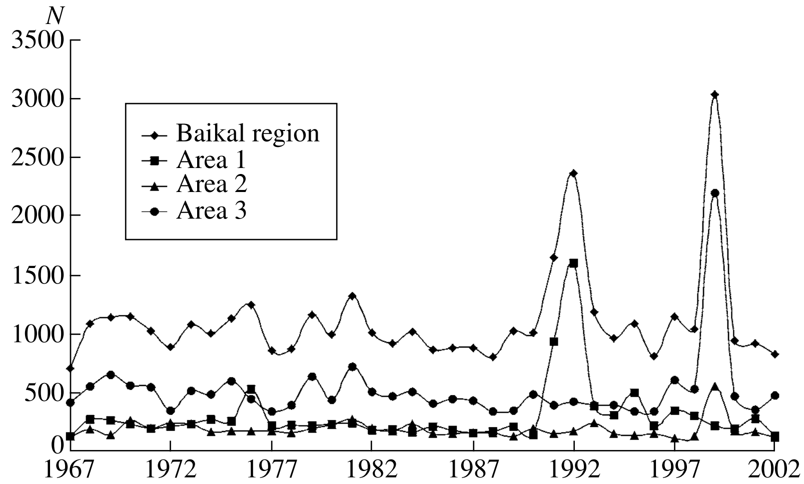

Fig. 1. Distribution of annual counts N of representative $K_P \geq 8$ earthquakes registered in the Baikal region and its three areas in 1967–2002.

and Kichera (March 21, 1999; $K_P = 14.5$; $\varphi = 55.83°$ N, $\lambda = 110.34°$ E) earthquakes.

The fractal measure can be represented by interrelated fractal sets with different indices depending on the power law. This concept offers new opportunities for the application of fractal geometry to geophysical seismogenerating systems [9]. We believe [4, 5] that long-term (millions of years) synergic processes, which started at the terminal Late Cretaceous–Paleocene (since the origin of the South Baikal Depression, the historical BRS core [10]) in the rift zone lithosphere, create natural spatiotemporal fractal structures. The term *natural fractal* is applied for denoting natural structures that can be represented as a fractal set for some purpose [2]. Natural fractals incorporate an element of randomness, and their regularity and/or irregularity obeys statistical laws. The R/S analysis shows that experimental signals from many natural phenomena have a fractal time dependency [11]. The fundamental characteristics of a stochastic time process are the Hurst index (H) and Hausdorff dimensionality (D) [2]. We calculated these parameters using methods of the index of dispersion for IDC counts [12] and cell counts [11]. For the specified time interval t, IDC is determined as the ratio of the dispersion of the number of earthquakes (N_t) for this interval to the statistical expectation of N_t. In the process of scaling, self-similar processes yield monotonously increasing IDC of type $m^{-1}t^2H^{-1}$. Having drawn the $\log \mathrm{IDC}(t)$–$\log(t)$ plot, we obtain a straight line with a $2H$–1 inclination. The cell count method is based on analysis of variation in the share of filled cells in the object-hosting domain. For each t, the number of filled cells $C[t]$ is estimated upon the following condition: a cell shall be considered filled if the number of earthquakes therein exceeds one-half of the average number; otherwise, the cell is considered empty. Having drawn the $\log C[t]$–$\log(t)$ plot, we obtain a straight line, the inclination of which is the fractal Hausdorff dimensionality (D). Dimensionality D is applied to evaluate the self-similarity of seismic process in the Baikal region, while index H makes it possible to evaluate the impact and role of seismic event groups of various energy classes in the regional seismicity dynamics.

Figure 2 shows variations of H and D values obtained in 1967–2002 for annual earthquake samplings of $K_P \geq 6$, $K_P \geq 7$, $K_P \geq 8$, and $K_P \geq 9$ in the Baikal region. It is obvious that the time variations of H in general have the same trends for shock samplings of different classes. However, the H level decreases in stronger earthquake samplings. For shocks of $K_P \geq 9$, the average $H \approx 0.5 \pm 0.1$ and the seismic process is close to deterministic chaos [13]. The maximum level of $H \approx 0.88$ recorded in 1992 for shock samplings of $K_P \geq 6$ correlates with the most active aftershock phase of the Busiingol earthquake (Fig. 1). It is worth noting that time variations of H in the studied areas have in general similar trends, despite a higher scatter of data points and standard deviations owing to a lesser number of shocks in the respective data array. In plots showing D variations, the trends mentioned above are less obvious: the D level decreases insignificantly for higher classes and is equal to ~0.8 ± 0.1 for shocks of $K_P \geq 9$. It is noteworthy that parameter D is more stable in time than index H. Moreover, D and H poorly correlate, although both parameters responded to the aftershock series of the 1991–1992 and 1999 strong earthquakes.

Since index H inversely correlates with K_P and has a maximum level at $K_P \geq 6$, clusterization of seismicity intensifies when the range of energy classes is expanded toward weaker shocks. For shocks of $K_P \geq 9$, $H \approx 0.5$; i.e., the clusterization is weak and independent events predominate in the seismicity pattern. Therefore, in order to characterize the seismicity dynamics at the flanks and in the central part of the BRS at a minimized

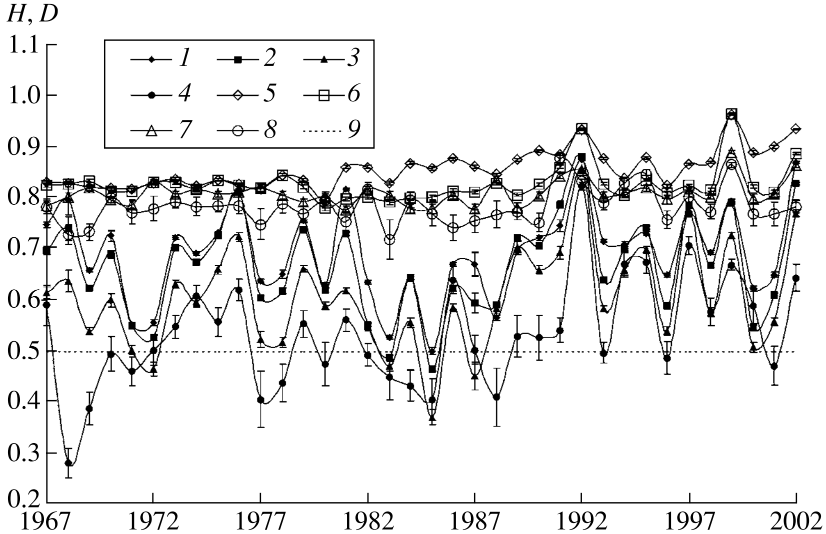

Fig. 2. Annual variations of the Hurst index (*H*) and Hausdorff dimensionality (*D*) of seismic process in the Baikal region. (*1–4*) *H* value of earthquake samplings of $K_P \geq 6$, $K_P \geq 7$, $K_P \geq 8$, and $K_P \geq 9$, respectively; (*5–8*) *D* value of the same earthquake samplings; (*9*) $H = 0.5$ level characterizing the seismic process stability.

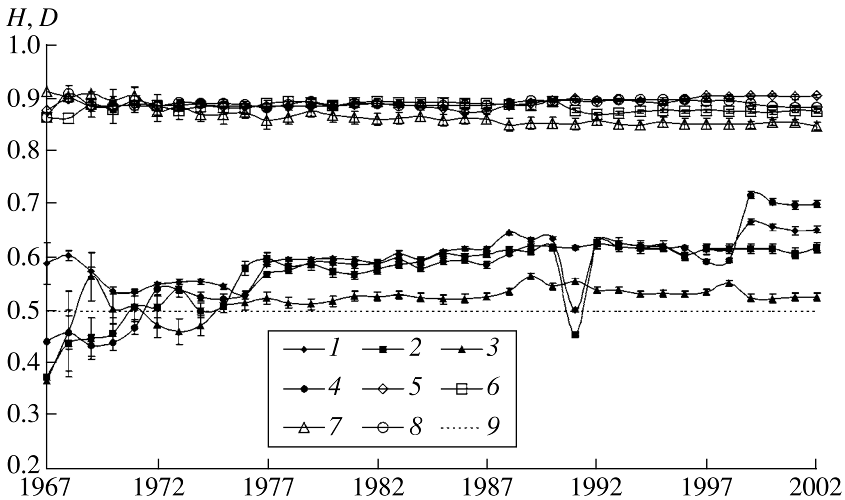

Fig. 3. Variations in the Hurst index (*H*) and Hausdorff dimensionality (*D*) values of cumulative seismic process with $K_P \geq 9$ in the Baikal region and its three areas: (*1–4*) *H* value of earthquake samplings of $K_P \geq 9$ in the Baikal region, area 1, area 2, and area 3, respectively; (*5–8*) *D* value of the same earthquake samplings; (*9*) $H = 0.5$ level characterizing the seismic process persistence.

level of available data clusterization, Fig. 3 presents *H–D* variation plots for cumulative (1-yr interval) samplings of $K_P \geq 9$ earthquakes recorded in 1967–2002 in the Baikal region and its three areas. It is obvious that the plots of *H* variations in the three areas up to the mid-1970s show random wandering with high standard deviations, probably, caused by a low representativeness of data. However, this time interval also shows a close correspondence of *H* plots for areas 1 and 3 and their substantial difference relative to the area 2 plot. *H* plots for areas 1 and 3 subsequently maintain the similarity trend and resemble *H* plots for the Baikal region. In these years, the average level of index *H* on these plots is $H \approx 0.6$, indicating the presence of shock swarms in the cumulative seismic series. The correlation coefficient varies from $\rho \approx 0.80$ (areas 1 and 3) to $\rho \approx 0.50$ (areas 2 and 3). The significant decrease recorded in 1991 in area 1 ($H \approx 0.46$) and the Baikal region ($H \approx 0.5$) coincided with the start of the aftershock series of the Busiingol earthquake. Such an extraordinary decrease is noteworthy, because other aftershock series of strong earthquakes reflect the intensification of clusterization and correlate with the *H* increase. This effect can be explained in the following

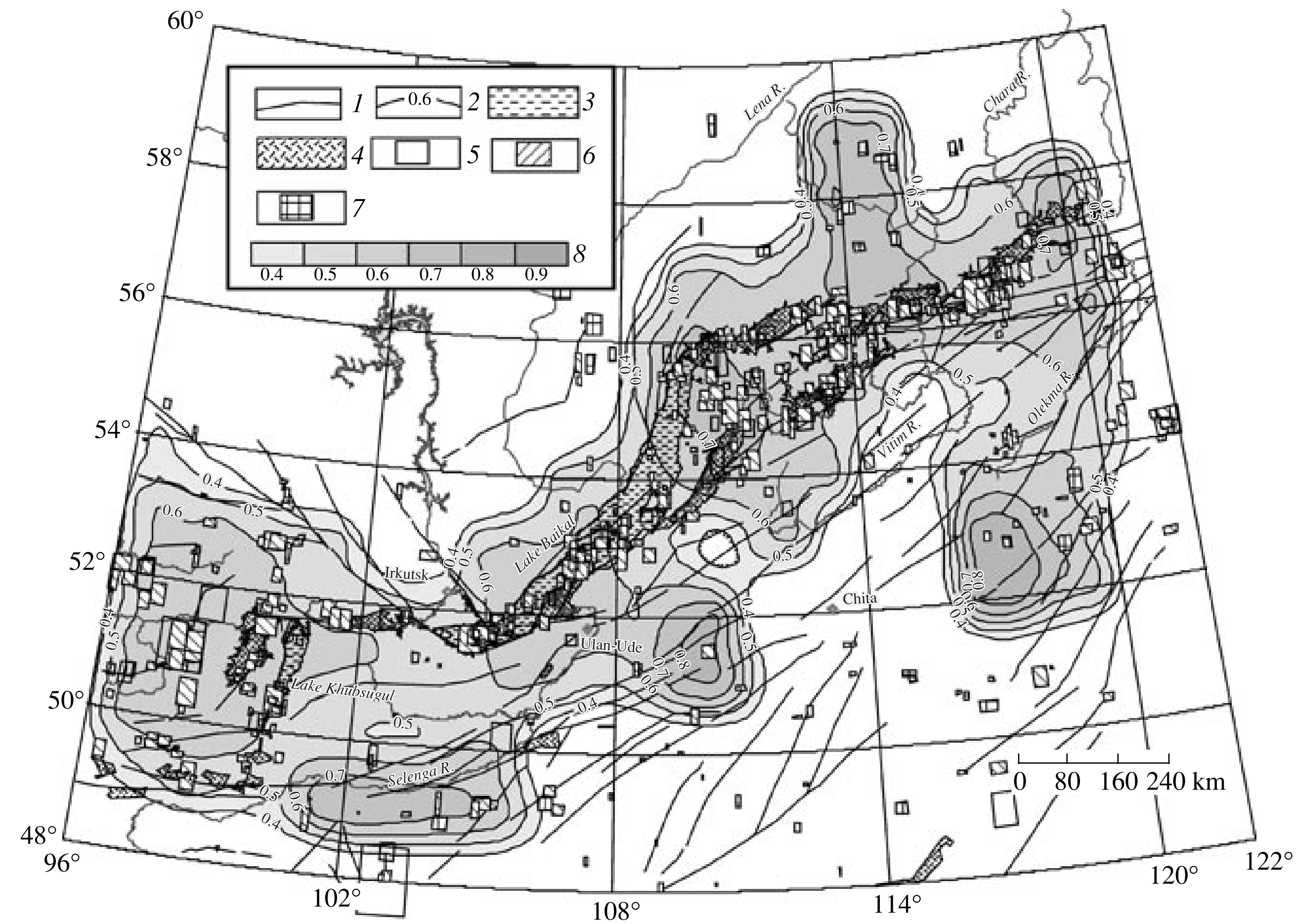

Fig. 4. Spatial structure of seismicity dynamics of the Baikal region in the Hurst index (*H*) isolines: (*1*) major faults; (*2*) *H* isolines; (*3*) lakes; (*4*) depressions; (*5–7*) sites of aftershocks, shock swarms, and explosions, respectively, (*8*) *H* scale.

way: aftershock series of the Busiingol earthquake do not correspond to seismicity dynamics of the Baikal Rift and the southwestern flank of the BRS [4] or the velocity of shock series that exceeded the maximum level for this process and the system ceased to respond. In the northeastern area, the Hurst index achieved a maximum value ($H \approx 0.72$) in 1999. This event contemporizes with the aftershock series of the Kichera earthquake. The high *H* level maintained in subsequent years indicates the presence of a long-term memory of this aftershock series of earthquakes in the Baikal region and area 3. In the central BRS, the average level of *H* varied within 0.51–0.53 from the mid-1970s; i.e., the seismic process in this territory was generally close to deterministic chaos. Significant *H* increases observed in 1989 and 1998 are likely to be a consequence of the North Mongolian (May 13, 1989; $K_P = 15$; $\varphi = 50.17°$ N, $\lambda = 105.34°$ E) and a forerunner of the South Baikal earthquakes. The possibility of a predicting sign is based on the effect of seismic calm within the source zone [14] and the increase of the average velocity of earthquake series within a vast area around an expected strong shock [15]. This was typical for the North Mongolian earthquake with its epicenter situated beyond area 2. In the central BRS, no earthquake groups were registered in 1989 and 1998. Therefore, *H* maximums in these years could not have been caused by clusters situated in this territory. Thus, the most significant variations of the *H* value of the seismic process in the Baikal region and its three areas correlate in time with aftershock series of strong earthquakes (Fig. 1). However, shock groups show different patterns of variation in parameter *H*. In 1967–2002, Hausdorff dimensionality changed from $D \approx 0.92$ to $D \approx 0.85$, and the annual *D* variation did not exceed the standard deviation. In general, differences in the Hausdorff dimensionality in the studied period at the flanks and central part of the BRS did not exceed two standard deviations, thus indicating self-similarity of seismic process in the Baikal region with a 10% confidence level.

Figure 4 shows a map of *H* isolines characterizing the spatial structure of seismicity dynamics in the Baikal region. The map was compiled for $n > 100$ shock samplings of $K_P \geq 8$ recorded from 1967 to 2002 within $2.0° \times 2.0°$ grids. Data were smoothed with 1° spacing along latitude and longitude, and the *H* values were attributed to the grid centers. For the sake of demonstrating the impact of earthquake groups on seismicity dynamics, the map shows 496 different-size grids with records of aftershocks, shock swarms, and explosions in the Baikal region in 1967–2002 [7]. It is obvious that sites of increased density of earthquake groups generally correspond to high H zones, thus testifying to the strong impact of earthquake clusters on the seismic process of the Baikal region. A similar pattern is seen on the map characterizing the spatial structure of seismicity dynamics of the Baikal region in D isolines.

In theoretical studies, the $0.5\ H \le 1.00$ range implies a persistent (stable) time series characterized by long-term memory effects; i.e., processes of the present time will influence the future [2, 11]. Persistent time series are the most common natural processes. The $0 \le H < 0.50$ range shows a time series antipersistence characterized by unstable wanderings of the system. If we look at seismicity dynamics of the Baikal region from this point of view, antipersistence appears in the case of a low representativeness of initial data. Generally, the seismic process of the Baikal region and its three areas is a persistent process with effects of long-term memory about the most significant earthquake groups. Therefore, the seismic process has a persistent statistical multiplexing formed by superposition of aftershocks coupled with swarm and background shocks. Their superposition produces an integrated self-similar process. However, velocity jump in the shock series in the beginning of an aftershock series will produce an additional nonlinearity with possibilities of various styles of dynamic behavior of the geophysical system of seismogenesis reflected in parameters D and H.

ACKNOWLEDGMENTS

This work was supported in part by the Russian Foundation for Basic Research.

REFERENCES

1. *International Handbook on Earthquake and Engineering Seismology,* Ed. by W. H. K. Lee, H. Kanamori, P. C. Jennings, and C Kisslinger (Acad. Press, Amsterdam, 2002).
2. B. Mandelbrot, *The Fractal Geometry of Nature* (WH Freeman and Co., New York, 1982; IKI, Moscow, 2002).
3. S. I. Golenetskii, J. Geodyn. **11**, 293 (1990).
4. A. V. Klyuchevskii, Vulkanol. Seismol., No. 5, 65 (2003).
5. A. V. Klyuchevskii, Dokl. Akad. Nauk **403**, 96 (2005) [Dokl. Earth Sci. **403**, 785 (2005)].
6. N. V. Solonenko and A. V. Solonenko, *Aftershock Series and Earthquake Swarms in the Baikal Rift Zone* (Nauka, Novosibirsk, 1987) [in Russian].
7. A. V. Klyuchevskii, in *The Mode of Deformation and Seismicity of Lithosphere* (Sib. Otd. Ross. Akad. Nauk, Novosibirsk, 2003), pp. 332–335 [in Russian].
8. M. A. Sadovsky, Dokl. Akad. Nauk SSSR **247**, 829 (1979).
9. V. G. Kosobokov and A. K. Nekrasova, Vychisl. Seismol. **35**, 160 (2004).
10. N. A. Logachev, Geol. Geofiz. **44** (5), 91 (2003).
11. J. Feder, *Fractals* (Plenum, New York, 1988; Mir, Moscow, 1991).
12. O. I. Shelukhin, A. M. Tenyakshev, and A. V. Osin, *Fractal Processes in Telecommunications* (Radiotekhnika, Moscow, 2003) [in Russian].
13. G. G. Malinetskii and A. B. Potapov, *Current Problems of Nonlinear Dynamics* (URSS, Moscow, 2003) [in Russian].
14. G. A. Sobolev, Vulkanol. Seismol., No. 4/5, 63 (1999).
15. V. I. Keilis-Borok, L. Knopoff, I. Rotwain, and C. R. Allen, Nature **335** (6192), 690 (1988).