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Research paper

Coupled large earthquakes in the Baikal rift system: Response to bifurcations in nonlinear resonance hysteresis

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ABSTRACT

The current lithospheric geodynamics and tectonophysics in the Baikal rift are discussed in terms of a nonlinear oscillator with dissipation. The nonlinear oscillator model is applicable to the area because stress change shows up as quasi-periodic inharmonic oscillations at rifting attractor structures (RAS). The model is consistent with the space-time patterns of regional seismicity in which coupled large earthquakes, proximal in time but distant in space, may be a response to bifurcations in nonlinear resonance hysteresis in a system of three oscillators corresponding to the rifting attractors. The space-time distribution of coupled $M_{LH} > 5.5$ events has been stable for the period of instrumental seismicity, with the largest events occurring in pairs, one shortly after another, on two ends of the rift system and with couples of smaller events in the central part of the rift. The event couples appear as peaks of earthquake 'migration' rate with an approximately decadal periodicity. Thus the energy accumulated at RAS is released in coupled large events by the mechanism of nonlinear oscillators with dissipation. The new knowledge, with special focus on space-time rifting attractors and bifurcations in a system of nonlinear resonance hysteresis, may be of theoretical and practical value for earthquake prediction issues. Extrapolation of the results into the nearest future indicates the probability of such a bifurcation in the region, i.e., there is growing risk of a pending $M \approx 7$ coupled event to happen within a few years.

1. Introduction

Intermediate, and especially, short-range earthquake prediction is still a challenge though considerable progress has been achieved in seismology in the last two decades. The current prediction practice focuses mostly on statistics of local seismicity and preseismic geological and geophysical changes in seismogenic crust. The preseismic processes have been explained in terms of crack nucleation based on the hierarchical structure of slip bands, grain boundary sliding, dislocation pile-ups, dislocation-to-crack transition, and microcrack formation (Zhurkov et al., 1981; Sobolev, 1993; Teisseyre and Majewski, 2002). On a large scale, the existing approaches proceed from the idea that an earthquake represents a fluctuation about the long-term motion of the plates (Rundle, 1988), or that prominent heterogeneities in fault zones act as barriers affecting seismicity and rupture arrest (Das and Aki, 1977). A number of intermediate-range earthquake prediction algorithms were developed based on pattern recognition (Keilis-Borok and Kossobokov, 1990) including quiescence, closer clustering of events, and changes in aftershock statistics. Several authors (Sykes and Jaume, 1990; Knopoff et al., 1996) proposed systematic increase in intermediate-level seismicity prior to a large earthquake. There were a number of positive aspects to these approaches, but there is certainly no general consensus on the efficacy of intermediate-range forecasts (Turcotte and Malamud, 2002). It is hard to find reliable prediction criteria for specific seismic areas because of local, diverse and changeable geological and geophysical conditions while the exact knowledge of physical processes in the lithosphere remains limited.

It appears reasonable to view the problem in the more general perspective of the complexity theory (Nicolis and Prigogine, 1989)

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and investigate basic evolution trends of a seismic area as a self-organized complex system. Some aspects of the theory of complexity are beginning to have a major impact on the understanding of earthquake faulting, rock fracture, and, more generally, tectonophysics and geodynamics of the lithosphere (Lee et al., 2002). Recent studies have brought out a revival model of self-organized space-time structure and criticality in earthquakes (Bak and Tang, 1989). It has become increasingly evident that evolution of a seismic area is among numerous examples of geophysical systems where spatial, temporal, or spatiotemporal structures arise out of chaotic states (Keilis-Borok, 1990; Sornette et al., 1990). Such spontaneously developing systems, which exchange energy and matter with the environment, may undergo three stages of evolution, besides thermodynamic instabilities: organization, self-organization, and chaos (Majewski and Teisseyre, 1997). Large systems of this kind demonstrate consistency between entropy production, progressive differentiation, increase in complexity, and self-organization (Nicolis, 1986). Self-organization of a system implies that it can replicate its environment or parts of it (lower hierarchic levels), and is logically related to the properties of attractors within the system.

We apply the theory of complex self-organizing systems and their nonlinear dynamics to study the seismic process and stresses in the rifted crust of the Baikal region. Thus we have tried to highlight basic trends in the space and time patterns of stress as the main physical proxy of lithospheric forces related to heat sources, deformation, and earthquakes (Zoback, 1992).

The history of instrumental seismicity in the Baikal rift system (BRS) includes several spells of high activity with several $M_{LH} > 5.5$ earthquakes (Golenetsky, 1990), which we correlate to reversals of lithospheric stress (Klyuchevskii, 2003, 2007). The stress change events were recognized in patterns derived from fault radii and seismic moments of more than 70,000 $M_{LH} \geq 2.0$ local shocks (Klyuchevskii, 2004); these were analyzed jointly with the focal mechanisms of 265 $M_{LH} \geq 3.5$ local earthquakes for the period from 1968 to 1994. Using the ample database of seismic moments of $M_{LH} \geq 2.0$ earthquakes was a major step forward relative to the previous BRS stress reconstructions with only $M_{LH} \geq 3.5$ earthquake mechanisms (Doser, 1991; Solonenko et al., 1997). Analysis of small events has significantly improved the resolution of the regional stress pattern and its space-time variations. The regional stress history between 1968 and 1994 which was thus analyzed, with three significant stress events distinguished in this study, was interpreted as a scenario of nonlinear evolution with triple equilibrium bifurcation (Klyuchevskii, 2010a). The stress events were noted to localize in zones of predominantly vertical stress in the center and on the flanks of the rift system. These zones, where most earthquakes of different magnitudes had normal-slip mechanisms, correspond to local highs of strain anisotropy. By analogy with attractors related to structure formation in classical self-organized systems (Nicolis and Prigogine, 1989; Majewski and Teisseyre, 1997), we interpret the zones of vertical stress and strain anisotropy as rifting attractor structures (RAS) which are the key agents in the current BRS tectonics and seismicity (Klyuchevskii, 2005, 2010a, 2011a, b).

The time span considered for this study is million times shorter than the Mesozoic–Cenozoic period in the history of rifting in Central Asia (Logatchev and Florensov, 1978; Ma and Wu, 1987; Logatchev, 1993; Liu et al., 2004; Zhao et al., 2006, 2007; Mats and Perepelova, 2011). Taking into account the spontaneously developing nonlinear systems, this difference in characteristic times allows one to move away from the question of origin and driving forces of the Baikal rifting (Molnar and Tapponnier, 1975; Logatchev and Zorin, 1987), and instead to highlight the pulse-like quasi-periodic regional perturbations arising at RAS on the background of global stress (Klyuchevskii, 2010a, 2011a, b). With this in mind, we are developing an approach to explain a striking regularity observed in several $M_{LH} > 5.5$ earthquakes that occurred periodically in couples, one shortly after another, in the same locations at two ends of the rift system (Klyuchevskii, 2003). We explore the origin, distribution, and periodicity of the coupled events which are considered as a response to stress reversal generated by the rifting attractors. Furthermore, we suggest a general perspective of the current geodynamics of the rift lithosphere, using a model of nonlinear oscillators with dissipation in the phase space of energy (Klyuchevskii, 2007, 2010a). The rifting attractors are simulated by nonlinear oscillators which operate jointly in a single system. Inasmuch as the stress reversals at rifting attractors cause quasi-periodic perturbations to the lithosphere, we assume that the couples of $M_{LH} > 5.5$ events distant in space but proximal in time may correspond to energy change events in nonlinear oscillators associated with bifurcations (catastrophes) in nonlinear resonance hysteresis.

This approach is the first attempt at synthetic modeling of the physics of continental lithosphere in the Baikal rift. We expect that this would provide new insights into the basic trends of the regional seismicity and would have valuable theoretical and practical earthquake prediction implications.

2. Method

The energy evolution of the seismic process is modeled here, proceeding from the analogy with an oscillating nonlinear pendulum, the most spectacular and best known specific case in the theory of catastrophes (Poston and Stewart, 1978; Arnold, 1983). The energy exchange of an oscillating system with its environment is the key parameter of sustained nonlinear dissipative oscillations. The total stored energy changes slowly when the oscillator and the exciting agent interact weakly, because energy changes only slightly within each period. However, the energy change can be very rapid if the interaction is strong, as in the case of nonlinear resonance oscillations (Nicolis, 1986).

Nonlinear resonance in a dissipative oscillator with, say, a cubic nonlinearity, can be expressed as (e.g., Arnold, 1983; Kuznetsov et al., 2005)

$$\ddot{x} + \omega_0^2 x = -2\gamma\dot{x} - \beta x^3 + f\cos\omega t \tag{1}$$

where x is the displacement of the oscillator relative to its equilibrium and ω_0 is its natural frequency, γ is the dissipation constant, and β is the nonlinearity constant; f and ω are the amplitude and the frequency of the exciting force. Thus, the terms on the right-hand side are responsible for dissipation, nonlinearity, and excitation. After transformation, (1) becomes the equation of a resonance curve,

$$(\gamma a_0)^2 + a_0^2\left(\delta - \frac{3\beta a_0^2}{8\omega_0}\right)^2 = \frac{f^2}{4\omega_0^2} \tag{2}$$

where a_0 is the equilibrium amplitude of oscillations, and $\delta = \omega - \omega_0$ is the frequency mismatch (resonance detuning). The nonlinearity parameter β is assumed to be positive, for the sake of certainty, and several dimensionless parameters are additionally introduced: $P = (3\beta f^2)/(32\gamma^3\omega_0^3)$ responsible for the excitation intensity, $X = (3\beta a_0^2/(8\gamma\omega_0)$ responsible for the intensity of the excited oscillations, and the nondimensional detuning $\Delta = \delta/\gamma$. Then (2) becomes

$$X = \frac{P}{(X-\Delta)^2 + 1}. \tag{3}$$