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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

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

Assigning different values to the excitation intensity P, one can obtain a family of curves $X = X(\Delta)$, which are the resonance curves of a nonlinear oscillator in the dimensionless coordinates X and Δ (Fig. 1a). If the excitation is small,

$$X = \frac{P}{\Delta^2 + 1} \tag{4}$$

and the corresponding curve has a bell shape typical of linear resonance. As P grows, the amplitude of the excited oscillations increases, and the upper part of the resonance curve gradually bends to the right making the curve ever more asymmetrical, to eventually acquire a prominent 'appendix' (Fig. 1b).

In the analysis of bifurcations, the resonance curve (Eq. (3)) is differentiated along X to obtain:

$$(\Delta - X)^2 + 2X(\Delta - X)\left(\frac{\partial\Delta}{\partial X} - 1\right) + 1 = 0. \tag{5}$$

3. Models of nonlinear oscillators

The behavior of the system is analyzed in terms of a phase portrait (Khlebopros et al., 2007; Klyuchevskii, 2007, 2010a) in the phase space of energy. The phase space in the coordinates Δ–X ($-\omega_0/\gamma < \Delta < \infty$) is divided into three domains, and the resonance curve, correspondingly, has three branches with the boundaries between them being defined according to the condition $\partial\Delta/\partial X = 0$: from $-\omega_0/\gamma$ to Δ_1, from Δ_1 to Δ_2, and from Δ_2 to ∞ (Fig. 2). The domains from $-\omega_0/\gamma$ to Δ_1 and from Δ_2 to ∞ are the same as the ascending left-hand and descending right-hand branches of the linear oscillator, while the domain from Δ_1 to Δ_2 deserves special attention. The resonance curve that forms at a rather large excitation amplitude includes, within this domain, an ascending (1) and a descending (3) branch, and branch 2 between them. Branches 1 and 3 lie one above another and thus can be called an upper and a lower branch, respectively. The intermediate branch of the resonance curve corresponds to unstable equilibrium and is a divide in the phase space between the two branches (1) and (3) which represent two stable states of the system (Fig. 2).

Gradual increase in the excitation frequency applied to the system, which is originally far from the resonance, is plotted as the motion of the system along the left (upper) branch of the resonance curve. As the excitation frequency increases, the oscillation amplitude increases proportionally, and soon after the peak there follows a sudden change (a hard transition or a catastrophe). The excitation amplitude drops to some minor value, whereby the energy of the nonlinear oscillator drops abruptly, and the system falls on the right-hand (lower) branch of the curve. At this end the system can follow either of the two possible evolution scenarios. In one extreme case, it falls at some small starting energy point and resumes its evolution in the domain from $-\omega_0/\gamma$ to Δ_1 to arrive again at the domain between Δ_1 and Δ_2 as a result of numerous stochastic pulses. In this case events occur along the upper branch of the curve, and the energy of the system builds up monotonously within the deterministic component (from ω_0/γ to Δ_2), until a catastrophe happens. In the other extreme case, as the excitation frequency decreases, the system, instead of falling to initial small energy level, moves toward greater energy along the right-hand (lower) branch, including the bandwidth where large-amplitude oscillations occurred before (Fig. 2). The oscillation amplitude increases gradually (while the excitation amplitude remains invariable and large enough), and another catastrophe happens at some point. This catastrophe is associated with a jump-like transition to high-amplitude oscillations and extremely rapid increase in the oscillator's energy (unlike the previous catastrophe in which the energy decreased); thereby the system returns to the left-hand (upper) branch of the resonance curve. Thus, a change in the

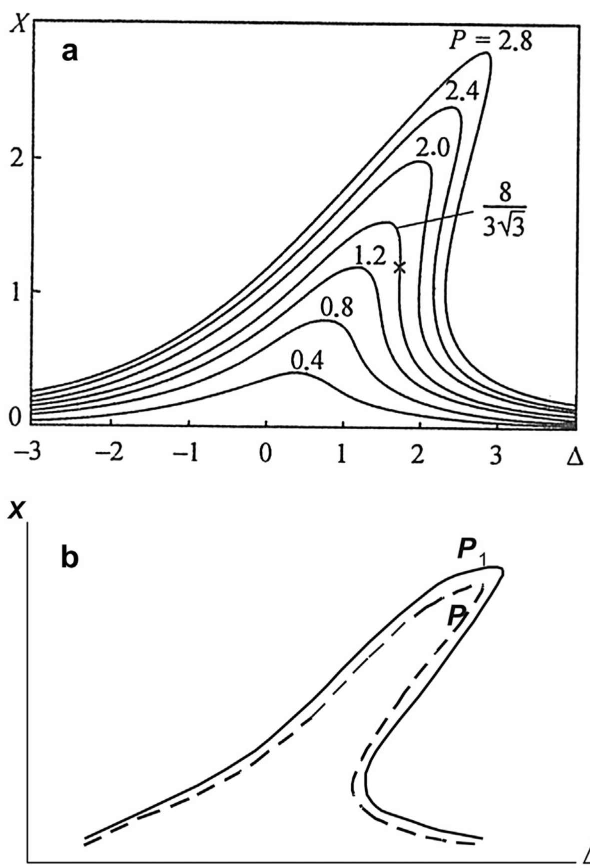

Figure 1. Family of resonance curves of a nonlinear oscillator with dissipation. a: Each curve shows dependence of X (intensity of excited oscillations) on Δ (nondimensional detuning) at a fixed excitation amplitude defined by P (see Eq. (3)). The cross marks the point corresponding to the first appearance of the vertical tangent (the coordinates of the cusp point: ($P = 8/(3\sqrt{3})$, $\Delta = \sqrt{3}$, $X = 2/\sqrt{3}$), after (Kuznetsov et al., 2005). b: As P grows ($P_1 > P$), the amplitude of the excited oscillations increases, and the upper part of the resonance curve gradually bends to the right making the curve ever more asymmetrical to eventually acquire a prominent 'appendix'.

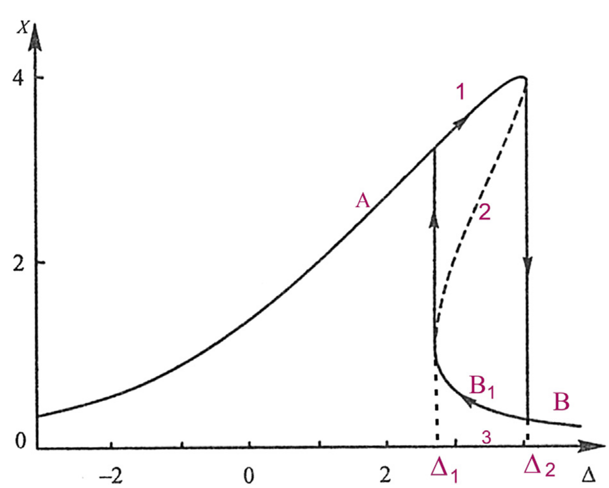

Figure 2. Nonlinear resonance hysteresis. Arrows show direction of motion along the resonance curve in the case of slow change in excitation frequency, modified after (Kuznetsov et al., 2005). See text for explanation.

excitation frequency at quite a large excitation amplitude and small dissipation leads to hysteresis of the nonlinear resonance. In the domain of hysteresis, the nonlinear oscillator is bistable, which corresponds to coexistence of two attractors in the phase space: one related to a small excitation amplitude and the other to a large one.

More complicated processes occur in a system of two interacting nonlinear oscillators (1 and 2). The oscillators are located at some distance from one another and are commensurate in their natural (resonance) frequencies and excitation amplitudes, as well as in the nonlinearity and dissipation parameters. The two oscillators are related in a specific way: their interaction becomes especially active only when one of them arrives at a catastrophe (a jump from one curve branch to the other). Although one oscillator lags behind the other in the phase, the two have similar phase portraits. Thus we may assume that the phase curves of two nonlinear oscillators coincide and use a single phase portrait (Fig. 2). Let one oscillator (oscillator 1) be located at the point A on the upper branch of the phase curve and move slowly along it to the right while the other (oscillator 2) be at the point B on the lower curve branch and move slowly to the left. As the system arrives at Δ_2, oscillator 1 experiences a catastrophe with a large energy release, and both oscillators come to be located on the lower branches of their phase curves (shown as a single curve in Fig. 2). While the system is moving slowly from A to Δ_2, oscillator 2 moves from B toward Δ_1 (point B_1).

If the distance between B_1 and Δ_1 is not very large, oscillator 2 jumps it over and achieves a catastrophe whereby it almost instantaneously moves from the lower curve branch to the upper one. Then oscillator 1, which again is moving slowly along the lower curve branch, arrives at Δ_1 and jumps up to the upper branch, and the two again stay on the same branch for a short while. If at that time oscillator 2 is close enough to Δ_2, oscillator 1 pushes it toward this critical point and thus triggers a catastrophe in No. 2. Note that each oscillator, when being pushed by its counterpart, moves orders of magnitude faster than in the absence of that propulsive action. However, if the distance from B_1 to Δ_1 is greater than some critical value, the catastrophe in oscillator 2 occurs much later, i.e., the arising regularity may stochastically break down.

This dynamics realizes at some quasi-periodicity and can generate one or two catastrophes. The stochastic component in the periodicity is due to the difference in the velocities of the moving oscillators in the absence of interaction and to the phase lag in the beginning of the interaction. In a system of three synchronized nonlinear oscillators (1, 2, 3), a catastrophe occurs as two oscillators move along the upper phase curve branch and have the same natural frequencies; another catastrophe takes place as the frequency of oscillator 3 coincides with that of 1 and 2 jointly. Inasmuch as the frequency of No. 3 lags slightly behind that of No. 2, there is some time lag in their frequencies, and another catastrophe can break in a while. The behavior of the system moving along the lower curve is similar to the above pattern, but the energy of the lower branch is low, and the generated events are slightly smaller than those associated with the drop from the upper branch.

4. Data and results

In this section we analyze relevant earthquake data from the Baikal rift system to see whether the above models with one to three nonlinear oscillators can apply. The map in Fig. 3 shows locations and magnitudes of $M_{LH} \geq 5.5$ events that have occurred in the Baikal region since 1950 when continuous recording became possible due to a newly developed regional seismological network of permanent stations. Location errors in the 1950s were within 50 km. By the mid-1960s, the network had approached its present

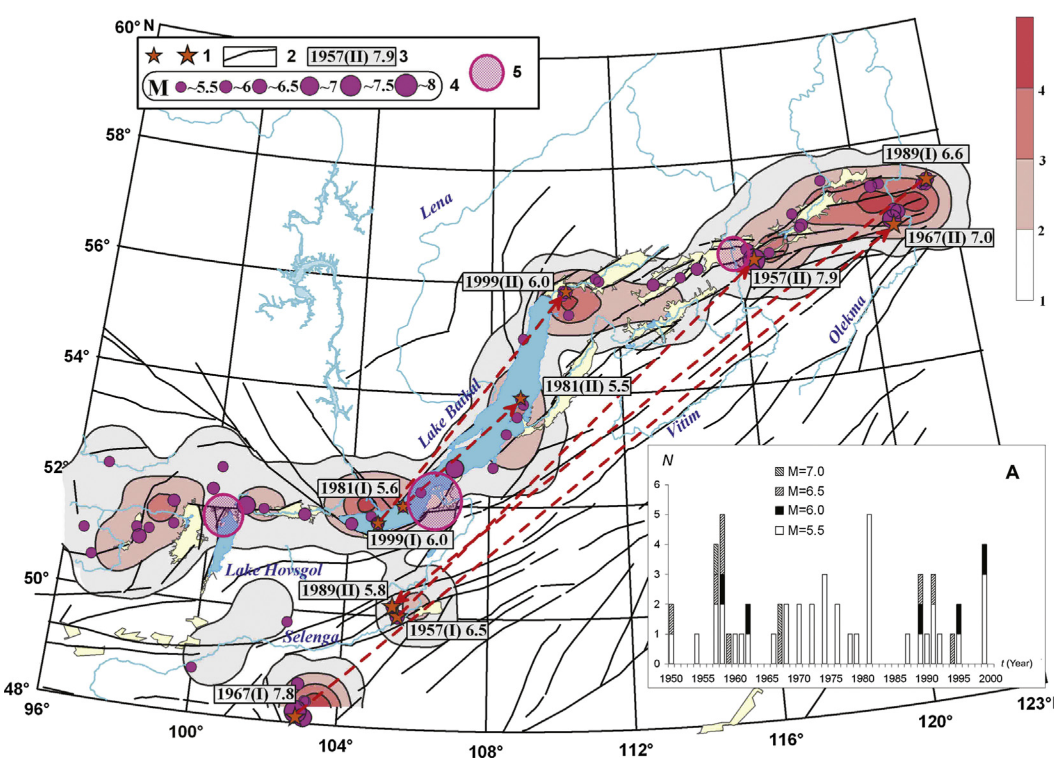

Figure 3. Map of earthquakes and density of $M_{LH} \geq 5.5$ earthquakes in the Baikal region since 1950. 1 = couples of $M_{LH} \geq 5.5$ earthquakes; 2 = large faults; 3 = year and order of events (I is earlier event, II is later event; dashed line connects the coupled events; arrow is directed from earlier shock to later shock), and the shock magnitudes; 4 = $M_{LH} \geq 5.5$ earthquakes, circle sizes are proportional to earthquake magnitudes; 5 = rifting attractor structures (RAS) (the structure size in the map approximately corresponds to its surface area and lifetime). Inset A gives frequency histogram (annual numbers) of $M_{LH} \geq 5.5$ earthquakes in the Baikal region since 1950.

Table 1
Couples of instrumentally recorded large earthquakes in the Baikal rift system.

Coupled events	No.	Earthquake	Date	Lat. (° N)	Long. (° E)	M
Couple I	1	Kyakhta	1957.02.06	50.0	105.5	6.5
	2	Muya	1957.06.27	56.1	116.4	7.9
Couple II	3	Mogod	1967.01.05	48.0	103.0	7.8
	4	Tas-Yuryakh	1967.01.18	56.6	121.8	7.0
Couple III	5	Unnamed	1981.05.22	51.96	105.52	5.6
	6	Unnamed	1981.05.27	53.94	108.92	5.5
Couple IV	7	South Yakutia	1989.04.20	57.17	122.31	6.6
	8	North Mongolia	1989.05.13	50.17	105.34	5.8
Couple V	9	South Baikal	1999.02.25	51.64	104.82	6.0
	10	Kichera	1999.03.21	55.83	110.34	6.0

configuration and could record continuously $M_{LH} \geq 2.5$ earthquakes, while the location errors reduced to 5–10 km (Golenetsky, 1990).

Data on five couples of large instrumental events in the Baikal rift system is given in Table 1. There were three coupled events between 1967 and 1994 (in 1967, 1981, and 1989) in the Baikal region (Klyuchevskii, 2003), which were distant in space but proximal in time (Fig. 3, Table 1). Note that all three earthquake couples followed stress change events within the rifting attractor structures (Klyuchevskii, 2010a, 2011a). The statistical significance of this series increases as it is extended with the earthquake couple of the Kyakhta event of 06.02.1957 (20-34-58; $M = 6.5$; $\varphi = 50.0°$ N, $\lambda = 105.5°$ E) south of Lake Baikal and the Muya event of 27.06.1957 ($M = 7.9$; $\varphi = 56.1°$ N, $\lambda = 116.4°$ E) in the northeastern flank of the rift system (Fig. 3, Table 1). The same spatial combination of the events repeated in 1967, when the Tas-Yuryakh earthquake in the northeastern flank of the rift (18.01.1967; $M = 7.0$; $\varphi = 56.6°$ N, $\lambda = 121.8°$ E) followed the Mogod one in northern Mongolia (05.01.1967; $M = 7.8$; $\varphi = 48.0°$ N, $\lambda = 103.0°$ E), and then in 1989 with the South Yakutian earthquake of 20.04.1989 ($M_{LH} = 6.6$; $\varphi = 57.17°$ N, $\lambda = 122.31°$ E) preceding another event in northern Mongolia (13.05.1989; $M_{LH} = 5.8$; $\varphi = 50.17°$N, $\lambda = 105.34°$ E). There is obviously a striking regularity in these couples of earthquakes that occurred south of Lake Baikal and in the northeastern part of the rift system (Fig. 3) and had a magnitude difference of about a unity (Table 1). A couple of smaller events shook the central part of the rift in 1981 (22.05.1981; 09-51-20.5; $M_{LH} = 5.6$; $\varphi = 51.96°$ N, $\lambda = 105.52°$ E) and (27.05.1981; 21-26-07.8; $M_{LH} = 5.5$; $\varphi = 53.94°$ N, $\lambda = 108.92°$ E). In 1999 there was another couple: the South Baikal earthquake of 25.02 beneath southern Baikal (18-58-29.9; $M_{PSP} = 6.0$; $\varphi = 51.64°$ N, $\lambda = 104.82°$ E) followed soon by a shock on the northern Baikal end (the Kichera earthquake of 21.03.1999, 16-16-03.1; $M_{PSP} = 6.0$; $\varphi = 55.83°$ N, $\lambda = 110.34°$ E) (Fig. 3, Table 1). The four events likewise show systematic distributions in space and time and in magnitudes. Note that no coupled earthquakes have yet been recorded after 1999 in the Baikal region, but a single event occurred in the south of Lake Baikal near Kultuk village (27.08.2008; $M_W = 6.3$; $\varphi = 51.62°$ N, $\lambda = 104.06°$ E).

The epicentral field in the map of Fig. 3 extends from the southwest to the northeast along the basins and ranges of the rift zone. The largest events tend to be along the rift flanks, and earthquakes in the central part have smaller magnitudes; several large shocks appear south of Lake Baikal. There are three domains of high earthquake density on the 100 km × 100 km grid (at the flanks and at the center of the rift) which match the areas of the rifting attractor structures in the lithosphere (Klyuchevskii, 2011a). The annual $M_{LH} \geq 5.5$ earthquake frequency histograms since 1950 show three major peaks at 1957, 1981, and 1999, and all $M_{LH} \geq 6.0$ events occur in couples (Fig. 3A). This feature is illustrated numerically in Fig. 4 as a plot of mean 'migration' rate of $M_{LH} \geq 5.5$ earthquakes. The rate V is found as a ratio of the distance between earthquakes to their time spacing. The migration rates of coupled events are much above the average in the late 1950s, 1960s, and 1980s, as well as in 1981 and 1999, the peaks having a ~10 year periodicity.

5. Discussion

In the case of detuning, when the resonance linearity fails, there arise forced oscillations of a relatively small amplitude a_1 (Fig. 5a) (Kuznetsov et al., 2005). The same external force F applied to an oscillator of an originally large amplitude, which then has its natural frequency about that of the exciting action, will push the oscillator to oscillate in time with this action and to swing at the ever larger amplitude a_2 (Fig. 5b). Thus oscillators can become synchronized in frequency and phase in the conditions of nonlinear resonance. An intermediate amplitude corresponds to an unstable state: any minor increase or decrease in the amplitude of oscillations, after a transition, pushes the oscillator to the states a_1 or a_2, i.e., to one of its attractors. It is important for our consideration that, according to Nicolis (1986), the total energy density in a system of n synphase oscillators is proportional to n^2, and the system operates coherently. Otherwise, if the phases are random and distributed uniformly over some 2π interval, the total energy density of the system is proportional to n, and the energy release is incoherent. Furthermore, interaction of linear related oscillators leads to energy exchange between their amplitudes but does not involve their phases or frequencies. Yet, if the oscillators are nonlinear, there is interrelation between their amplitudes and phases (or amplitudes and frequencies). Two coupled nonlinear oscillators begin to interact (when their oscillation amplitude is small) and exchange

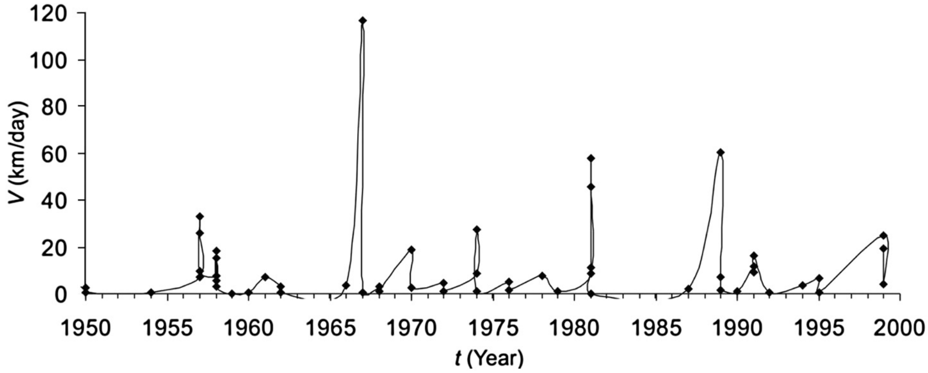

Figure 4. Mean "migration" rate V of $M_{LH} \geq 5.5$ earthquakes.

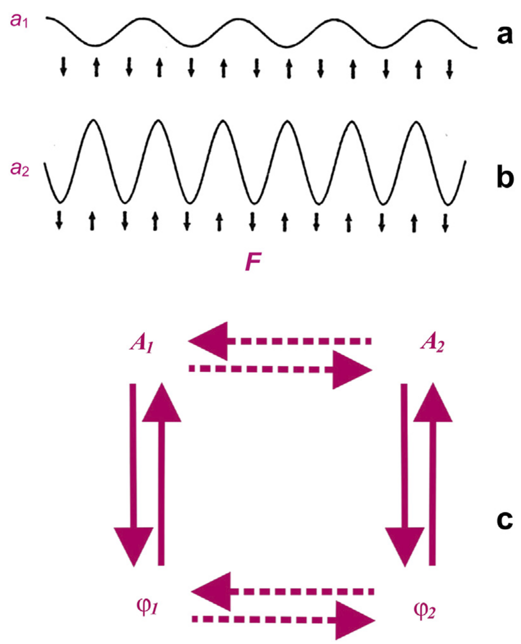

Figure 5. Amplitude interactions among related nonlinear oscillators transposed to phase relationship, modified after (Nicolis, 1986; Kuznetsov et al., 2005). See text for explanation.

energy between their amplitudes A_1, A_2 (Fig. 5c). However, by the relationship $A_1 \leftrightarrow \varphi_1$, $A_2 \leftrightarrow \varphi_2$, the energy exchange between the amplitudes leads to the phase relationship $\varphi_1 \leftrightarrow \varphi_2$ of the oscillators, and, besides anharmonicity, there appears a relationship of the amplitudes with the main frequency. Thus the energy interaction between the amplitudes of anharmonic oscillators gives rise to the frequency (or phase) relationship and thereby opens a way for phase coherence of three oscillators, which causes instability and nonlinear resonance bifurcations. This very combination of factors likely maintains the most 'efficient' way of system energy release in extreme states.

Another essential theoretical point is that a nonlinear oscillator always becomes excited, to the probability $P \approx 1$, when the mean square deviation of the imposed fluctuations exceeds some critical value (Nicolis, 1986). This excited oscillator then reaches its limit period with the main frequency ω_0 and a large amplitude. Depending on the threshold relation coefficients (governing parameters) μ, the set of mean square amplitudes ε of the excited concurrent modes, and the imaginary parts of the eigenvalues of the latter (their threshold frequencies Ω), one can observe some interesting dynamic regimes in such a multi-mode oscillator. Specifically, spontaneous mergence (uptake) of some frequencies if the frequencies Ω of the concurrent modes are similar enough and the amplitudes ε_i of some of them exceed a certain threshold can be observed. Once this happens, the whole system oscillates at one combined frequency which can change (as a function of intensity and topology of the relationship) from the arithmetic $\sum_{i=1}^{K} \Omega_i/K$ or geometric $(\sum_{i=1}^{K} \Omega_i)^{1/K}$ means to the weighted mean frequency

$$\left(\frac{\sum_{i=1}^{K} \varepsilon_i^2 \Omega_i^2}{\sum_{i=1}^{K} \varepsilon_i^2}\right)^{1/2}$$

where K is the number of the excited modes. This behavior is obviously self-organizing and features high order, though low complexity, and is typical of homeostasis-maintaining systems. In this case, all oscillators oscillate synchronously and the system is functionally uniform.

This very synchronicity applies in the suggested model of nonlinear oscillators, which appears to explain the generation of some earthquakes associated with nonlinear geodynamics of the Baikal rift lithosphere. In the simplest case, one nonlinear oscillator periodically generates single events of roughly similar magnitudes within the hysteresis of the nonlinear resonance. In the case of several coupled and interacting oscillators, the system moves along the lower branch of the phase curve toward lower excitation frequencies and the catastrophes are realized as the system jumps up to the upper branch. In terms of the seismic process this indicates some cyclicity of large events: frequency build-up – a catastrophe (a large or great event) – frequency decay – a catastrophe (slightly smaller event), etc. The cyclicity may be interrupted (apparently, by period duplication) if, after the catastrophe, the events follow the former scenario of frequency growth.

The interaction of two or three related nonlinear oscillators, similar in size and oscillation (dissipation) parameters, can account for the synchronization of coupled events corresponding to stress reversal in three geographically dispersed areas which fall in the zones of rifting attractors (Klyuchevskii, 2011a). In our assumption they are, specifically, the rifting attractor structures (Fig. 3) distinguished on the basis of $M_{LH} \geq 2.5$ statistics of fault radii and seismic moments (Klyuchevskii, 2004, 2005, 2007). The coupled $M_{LH} \geq 5.5$ earthquakes occurred exactly within those areas: the largest shocks of $M_{LH} \geq 6.0$ on the rift flanks in 1957, 1967, and 1989 and $M_{LH} \approx 5.5$ couples in 1981 and 1999 in the central part of the rift system south of Lake Baikal. In terms of the above model, the events on the rift flanks may correspond to drops to the lower branch of the hysteresis while those in the rift center may fit the jumps up to the upper branch of the phase curve.

The specific subsurface physical mechanisms that govern the operation of the nonlinear oscillating system remain unclear and require further studies. The thermal and gravity instability that maintains rifting within the rifting attractor structures (domains of high stress and strain anisotropy) may be associated with different lithospheric and sublithospheric processes: rise of melts or hot fluids through the highly permeable rifted lithosphere, decompression-related gas-to-liquid phase change transitions, metamorphic reactions, etc (see, for example, Letnikov, 1992, 2006; Logatchev, 1993; Golubev and Zubkov, 2006; Klyuchevskii, 2011a, b). What is important, is that the responses of the system are obviously nonlinear, and catastrophes (bifurcations) are the optimal way of abrupt energy release in extreme states for the sake of system's conservation. This is exactly the 'efficiency' principle (see above) which appears to work in the hierarchy of earthquakes as the greatest amount of strain energy built-up slowly in the source area releases instantaneously in a single large shock (Zhurkov et al., 1981; Sobolev, 1993).

Thus, at least a part of $M_{LH} \geq 5.5$ events in the Baikal rift system are associated with its nonlinear geodynamics. This inference has important implications for intermediate-range earthquake prediction based on fault radius and seismic moment statistics of $M_{LH} \geq 2.5$ earthquakes (Klyuchevskii, 2004, 2005, 2007). Extrapolating the results into the nearest future, and bearing in mind the decade-long periodicity of the pulses, one may expect a bifurcation to approach, i.e., there is growing risk that $M \approx 7$ coupled events may happen in the region within a couple of years.

A number of other relatively large earthquakes in the area fail to fit the suggested model. The reasons may be in some unknown lithospheric tectonophysical effects in the Baikal rift and/or in their interplay with processes in neighboring active seismic areas of Mongolia, Yakutia, and Altai-Sayan which may affect the Baikal regional seismicity. Inasmuch as changes in lithospheric stress in the Baikal rift affect seismicity in the neighboring regions (i.e., local seismicity in Mongolia (Klyuchevskii, 2010b)), prediction of large earthquakes requires further investigation into nonlinear geodynamic and tectonophysical processes in Central Asia.

6. Conclusions

The space-and-time patterns of $M_{LH} > 5.5$ earthquakes in the Baikal rift system hold over the entire period of instrumental seismicity and reflect the origin, energy, and activity time of the causative phenomena. These patterns are interpreted in terms of nonlinear resonance hysteresis associated with pulse-like perturbations at three rifting attractor structures. The model presents the stress evolution in the rifting attractor zones as operation of a dissipative system of interacting nonlinear oscillators. Periodic catastrophes (bifurcations) in this system provide the most efficient way of energy release for the sake of system conservation. The bifurcations show up as stress reversals with the ensuing couples of earthquakes that happen alternately on the two flanks of the rift system, one shortly after another. Thus, at least a part of $M_{LH} \geq 5.5$ events in the Baikal region must be associated with nonlinear geodynamics of the rift system. This inference has important implications for intermediate-range earthquake prediction based on fault radius and seismic moment statistics of $M_{LH} \geq 2.5$ earthquakes. Extrapolating the results into the near future, and bearing in mind the decade-long periodicity of the seismicity pulses, one may expect a bifurcation to approach. That is, there is growing risk that coupled events of $M \approx 7$ may occur in the region within a few coming years.

This interpretation of the current geodynamics and tectonophysics of the Baikal rift system using the model of a nonlinear oscillator with dissipation is the first attempt to synthesize the physics of continental lithosphere. We expect this to provide new insights into the regional seismicity and to be of theoretical and practical value for earthquake prediction issues. Better understanding of the controls of stress evolution and seismicity requires further investigation into nonlinear processes of the whole Central Asian geodynamics and tectonophysics.

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