GEODYNAMICS & TECTONOPHYSICS

PUBLISHED BY THE INSTITUTE OF THE EARTH'S CRUST
SIBERIAN BRANCH OF RUSSIAN ACADEMY OF SCIENCES

2017 VOLUME 8 ISSUE 4 PAGES 989–998 ISSN 2078-502X

https://doi.org/10.5800/GT-2017-8-4-0328

Tectonophysics

DIAGNOSTICS OF META-INSTABLE STATE OF SEISMICALLY ACTIVE FAULT

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Abstract: Based on the results of a laboratory simulation of the seismic fault reactivation by "stick-slip" process, it was shown that the system of two blocks just before an impulse offset goes through the meta-instable dynamic state, with early and late stages of meta-instability [*Ma et al., 2012*]. In the first stage the offset begins in slow stationary mode with slow stresses relaxation on contact between blocks. In the second stage of the "accelerated synergies" strain rate increases and, subsequently, the deformation process through a process of self-organization came to dynamic impulse offset. The experimental results were used for interpretation of the results of spectral analysis of the deformation monitoring data. The data were held within the southern part of Lake Baikal, where Kultuk earthquake (27.08.2008, Ms=6.1). took place. Its epicenter was located in the South end zone of the main Sayan fault. Monitoring of deformations of rocks was carried out from April to November 2008 in tunnel, located at 30 km from the epicenter of the earthquake. The time series data was divided into month periods and then the periods were processed by the method of spectral analysis. The results showed that before the earthquake has ordered view spectrogram, whereas in other time intervals, both before and after the earthquake such orderliness in spectrograms is missing. An ordered view spectrograms for deformation monitoring data can be interpreted as a consequence of the self-organization of deformation process in the transition of seismically active fault into meta-unstable before the Kultuk earthquake.

Key words: seismically active fault; meta-instability; earthquake; strain monitoring; spectral analysis; synergism

RESEARCH ARTICLE

Recommended by K.Zh. Seminsky

Received: May 31, 2017
Revised: September 9, 2017
Accepted: September 14, 2017

For citation: *Bornyakov S.A., Ma J., Miroshnichenko A.I., Guo Y., Salko D.V., Zuev F.L.*, 2017. Diagnostics of meta-instable state of seismically active fault. *Geodynamics & Tectonophysics* 8 (4), 989–998. doi:10.5800/GT-2017-8-4-0328.

Диагностика метанестабильного состояния сейсмоактивного разлома

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Аннотация: На основе результатов лабораторного моделирования процесса сейсмической активизации разлома по механизму «stick-slip» [*Ma et al., 2012*] показано, что нагруженная система из двух блоков непосредственно перед реализацией импульсной подвижки проходит через метанестабильное динамическое состояние, со стадиями ранней и поздней метанестабильности. В первую стадию процесс смещения одного блока относительно другого начинается в квазикриповом стационарном режиме с медленной релаксацией накопленных на межблоковом контакте напряжений. Во вторую стадию «ускоренного синергизма» скорость смещения существенно возрастает и впоследствии через процесс самоорганизации и лавинообразного объединения многочисленных активизированных сегментов межблокового контакта переходит в динамическую импульсную подвижку. С учетом этих экспериментальных выводов анализируются результаты спектрального анализа данных деформационного мониторинга, проведенного в пределах южной оконечности оз. Байкал, где 27.08.2008 г. произошло Култукское землетрясение (M_s=6.1). Его эпицентр располагался в южном окончании зоны Главного Саянского разлома. Мониторинг деформаций горных пород проводился с апреля по ноябрь 2008 г. в штольне, расположенной в 30 км от эпицентра землетрясения. Временной ряд данных был разделен на тридцатидневные интервалы, которые обрабатывались методом спектрального анализа. Результаты расчетов показали, что перед землетрясением спектрограмма имеет упорядоченный вид, тогда как в другие временные интервалы, как до, так и после землетрясения такая упорядоченность в спектрограммах отсутствует. Такой упорядоченный вид спектрограммы для данных деформационного мониторинга может интерпретироваться как следствие самоорганизации деформационного процесса при переходе сейсмоактивного разлома в метанестабильное состояние перед Култукским землетрясением.

Ключевые слова: сейсмоактивный разлом; метанестабильное состояние; землетрясение; деформационный мониторинг; спектральный анализ; синергизм

1. Introduction

Tectonic earthquakes are produced mostly through two well-known mechanisms. One of them, described as the "snowball unstable crack origin model", assumes the fast connection of small short faults into the long one followed by seismogenic offset on it [*Myachkin et al., 1975*]. Another one, called the "stick-slip model", means episodic seismogenic offset on an existing fault [*Brace, Byerlee, 1966*]. It is assumed that in modern seismically-active zone of the lithosphere the last mechanism of earthquake generation occurred more often than the former.

There have been numerous attempts to simulate the "stick-slip model" by various kind of modeling in order to understand the physical regularities of impulse offsets on natural seismically active faults. Significant progress in the direction was provided by the development of synergetics [*Haken, 1977; Kondepudi, Prigozhin, 1998*]. In terms of synergistic interpretation, an earthquake was suggested to be "self-organized criticality" (SOC) [*Bak, Tang, 1989*] and a short-term self-organization of the deformation process just before seismic reactivation of a fault [*Feder, Feder, 1991; Ciliberto, Laroche, 1994; Olami et al., 1992; Sobolev, Ponomarev, 2003*].

The SOC model was developed in experiments of a seismic reactivation of faults by the "stick-slip" mechanism through a loaded system of two blocks [*Ma et al., 2012, 2014*]. The experimental results demonstrated a gradually developed deformation process in critical state before impulse offset. The first stage begins when the load deviates from the linearity and begins to fluctuate due to activation of individual fault segments. The second stage is associated with quasi-static instability of the initial meta-instability, when the quantity of

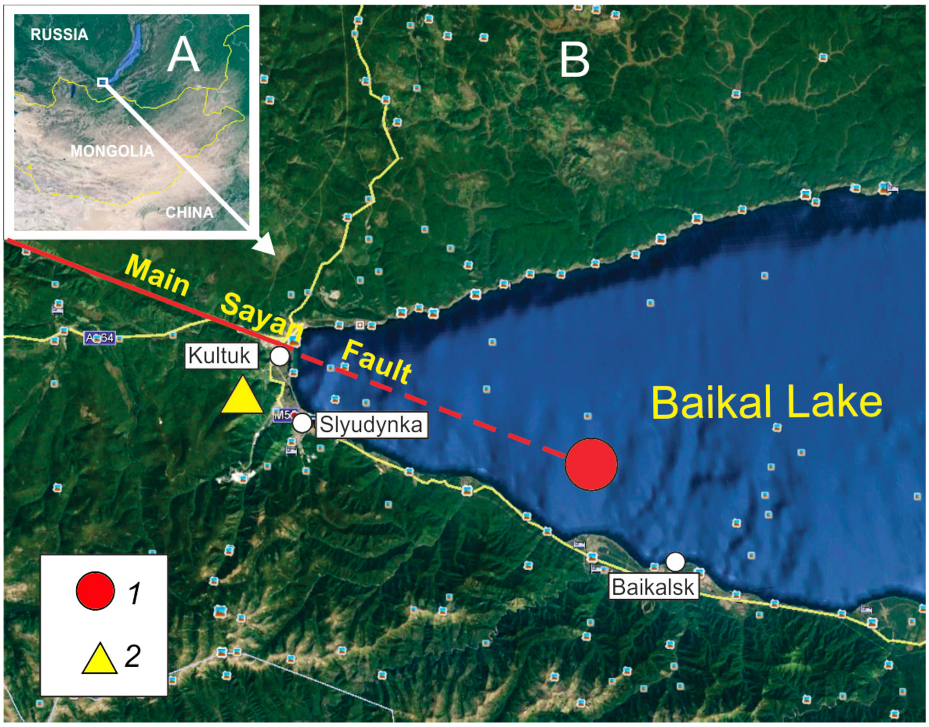

Fig. 1. Location of strain monitoring site in the south end of Lake Baikal (*A*) and its enlarged view (*B*). *1* – epicenter of Kultuk earthquake; *2* – Talaya seismic station.

Рис. 1. Схема с указанием положения пункта мониторинга в западной оконечности оз. Байкал (*А*) и ее увеличенное изображение (*B*). *1* – эпицентр Култукского землетрясения; *2* – сейсмостанция «Талая».

isolated strain-release foci increase. The third stage means the late meta-instability, i.e. quasi-dynamic instability when the strain release and accumulation is accelerated. The synergism is displayed, when a quasi-static state transforms into a quasi-dynamic one due to cooperative interaction between the reactivated fault segments. At this stage, the development of isolated fault segments is provided by linkage of the interacting segments and the fault reaches the critical state prior to an earthquake [*Ma et al., 2012, 2014*].

In this paper, we present data of rock strain monitoring before and after Kultuk earthquake and suggest interpretation using described above experimental results [*Ma et al., 2012, 2014*]. We identify the meta-instable stage of strain process in seismically active fault before the earthquake.

2. Locatin of strain monitoring, equipment, and method of data processing

The rock strain were monitored in the mine gallery located in the area of the Talaya seismic station since April to November 2008. At this period of time, the strong Kultuk earthquake (Ms=6.1) took place in a distance over 30 km eastwards in August 27, 2008 (Fig. 1).

Rock strain was measured by rod sensors installed in three orthogonal directions: NE 60°, SE 150°, and vertically (sensors 1, 2, and 3, respectively) (Fig. 2, *A*). The working elements were tensor-sensors manufactured by Scame (Fig. 2, *B*). The device «Shear» [*Ruzhich et al., 2009*] was used.

The accumulated deformations are demonstrated in Figure 3. Timing is given in minutes starting from the beginning of 2008.

The data of sensors 1 and 2 has gaps due to lack of observations are omitted. Only continuous records of sensor 3 are processed.

The spectral analysis is applied to processing of strain monitoring data. To analyze the data periodicity the Lomb-Scargle method was used (or least-squares spectral analysis, LSSA), which estimated a frequency spectrum based on a least squares fit of sinusoid [*Lomb, 1976; Scargle, 1982, 1989; Savransky, 2004; Press, 2007*]. It differs from the Schuster periodogram for unequally spaced data, which is a more traditional presentation of the capacity spectrum with the use of Fourier transformation.

Using values of time series $\mathbf{x_i}$ at time moment $\mathbf{t_i}$, i=1...N, we transform the equation is a way that an average value is zero, and a mean square deviation is one. For every analyzed frequency ω, the series is approximated by the following equation:

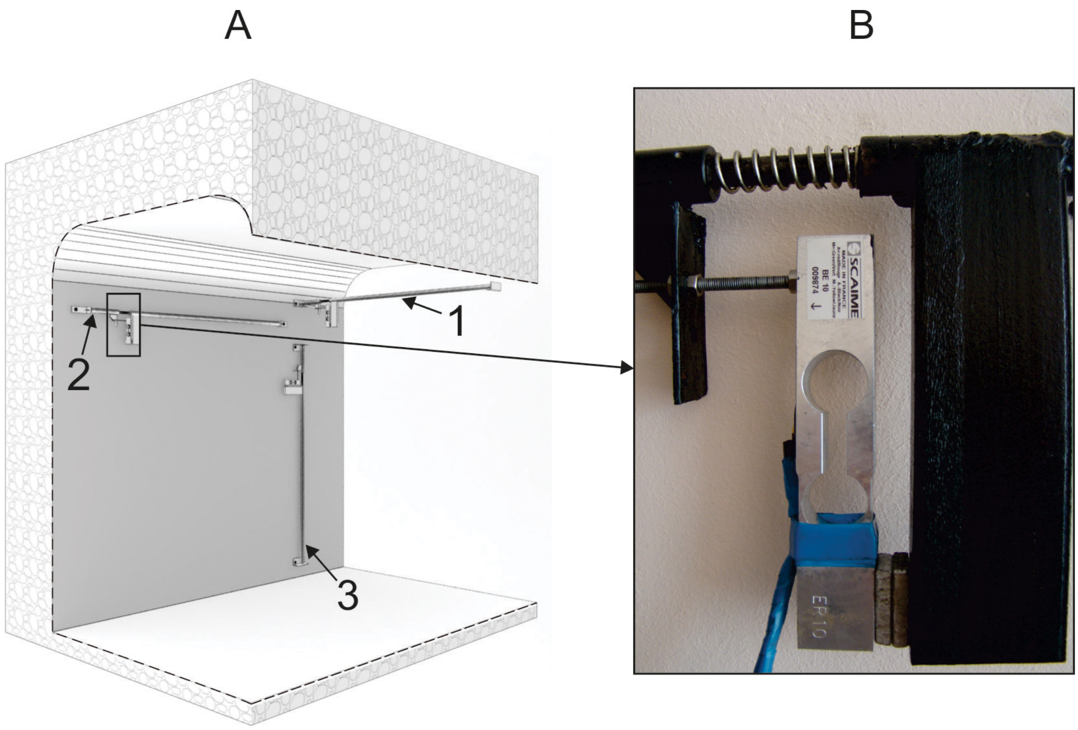

Fig. 2. Scheme of rod sensors locations in the mine gallery (*A*) and the tensor-sensor design (*B*).

Рис. 2. Схема расположения штанговых датчиков в штольне (*A*) и детали конструкции штангового датчика (*B*).

$$f_\omega(t) = a\,sin(\omega t + \tau) + b\,cos(\omega t + \tau)$$

at the best in terms of smaller square values:

$$\epsilon^2(\omega) = min_{a,b} \sum_{k=1}^{N} \big(x_k - f(t_k)\big)^2$$

where

$\left(\tau(\omega) = \frac{1}{2\omega} arctg\left(\sum_{k=1}^{N} sin\,2\omega\, t_k / \sum_{k=1}^{N} cos\,2\omega t_i\right)\right.$ is an auxiliary angle that is needed for more convenient statistical evaluations. The periodogram is represented by the following value:

$$LS(\omega) = \left(\sum_{k=1}^{N} x_i^2\right) - \epsilon^2(\omega).$$

The system of linear equations is solved for minimization, and the final equation is as follows:

$$LS(\omega) = \frac{1}{2}\left(\frac{\left[\sum_{i=1}^{N} x_i cos\omega(t_i-\tau)\right]^2}{\sum_{i=1}^{N} cos^2\omega(t_i-\tau)} + \frac{\left[\sum_{i=1}^{N} x_i sin\omega(t_i-\tau)\right]^2}{\sum_{i=1}^{N} sin^2\omega(t_i-\tau)}\right)$$

In case of the regular series, $t_i=t_0+i\Delta t$ and a set of fundamental frequencies, $\omega_j = \frac{2\pi}{N\Delta t} j$, the Lomb periodogram is equal to the Schuster periodogram (Fourier transformation) with the precision to the constant multiplier [*Vityazev, 2001*]. Unlike the Schuster periodogram, on the one side, the Lomb periodogram provides for the use of random or arbitrary sets of estimated time series and frequencies, including irregular ones. On the other side, unlike the Fourier transformations, the Lomb-Scargle periodogram is not factorization, i.e. it does not contain complete information of the form of the initial series, but shows only relative capacities of various frequencies.

3. Results

The preliminary processing rock strain monitoring data under discussion that was done using method of analysis of curvature of structural functions [*Vstovsky, Bornyakov, 2010*] showed SOC of the deformation process occurred 10–14 days before the Kultuk earthquake. In this paper, the last time interval is examined as the final stage of deformation development in the focal zone and the state of the lithosphere in the one is interpreted as pre-seismogenic. The entire time sequence is subdivided into monthly time intervals, except of the pre- and post-seismogenic periods since 10 May to 09 June, since 10 June to 09 July, since 10 July to 09 August, since 10 August to 26 August (pre-seismogenic period), since 28 August to 09 September, and since 10 September to 09 October (post-seismogenic period).

The data of sensor 3 were processed for all mentioned above periods Received spectral analysis results are shown in Fig. 4.

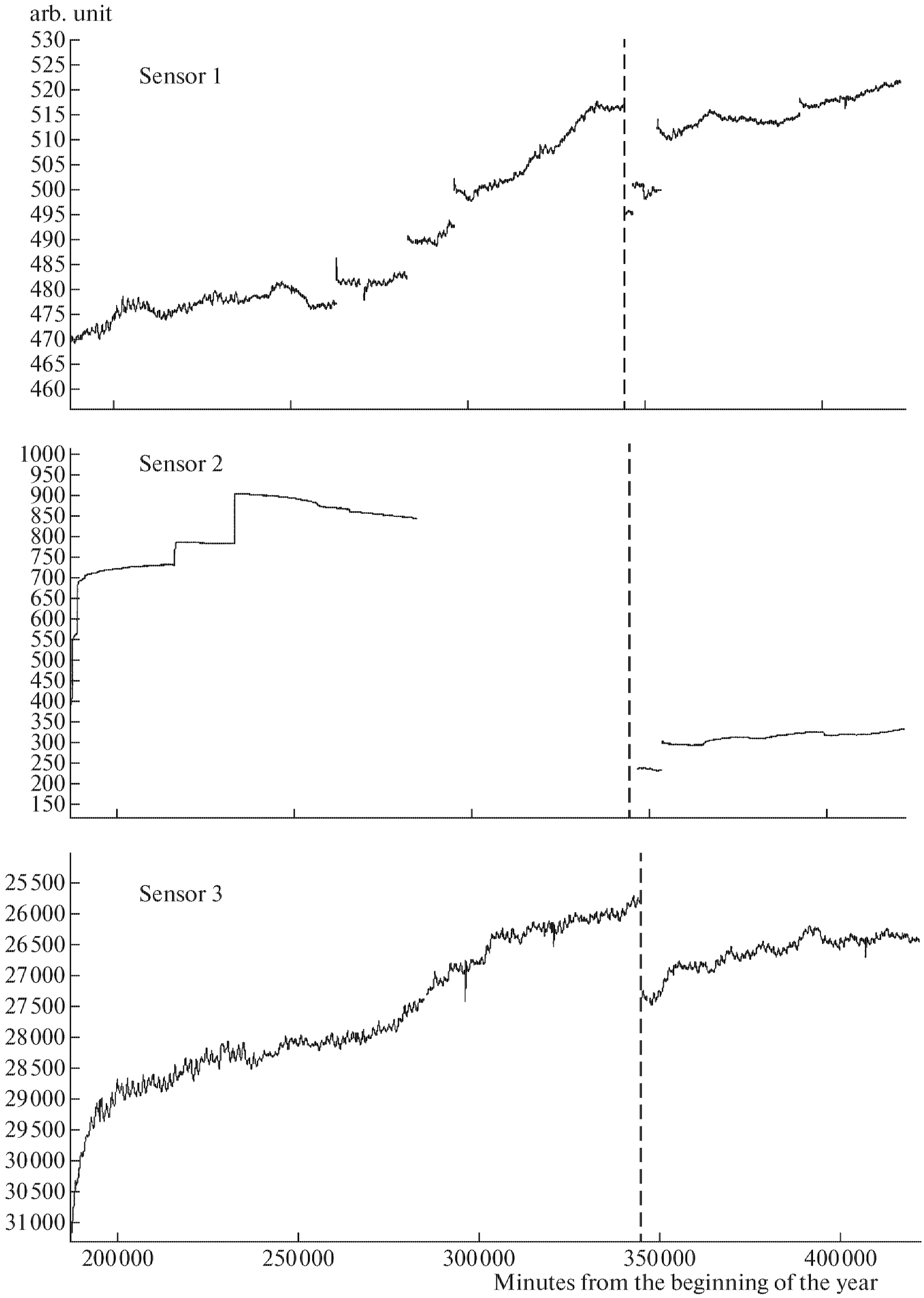

Fig. 3. Strain data of the rock in the mine gallery of Talaya seismic station from records of sensors 1, 2, and 3. The vertical dashed line indicates the moment of the Kultuk earthquake (344732 min).

Рис. 3. Деформации горных пород в штольне сейсмостанции «Талая», зарегистрированные датчиками 1, 2 и 3. Вертикальной штрихпунктирной линией отмечен момент реализации Култукского землетрясения (344732 мин).

Spectrograms show temporally variable structure and intensity of oscillations, especially in the large periods. In the spectrogram I, there are nine periods (Fig. 4, *A*). The "periodogram" parameter increases exponentially with increasing of the "period" values. This reflects a regular fractal structure of the spectrogram. In the spectrogram II, there are only six periods, their values are different, and the structure of the spectrum

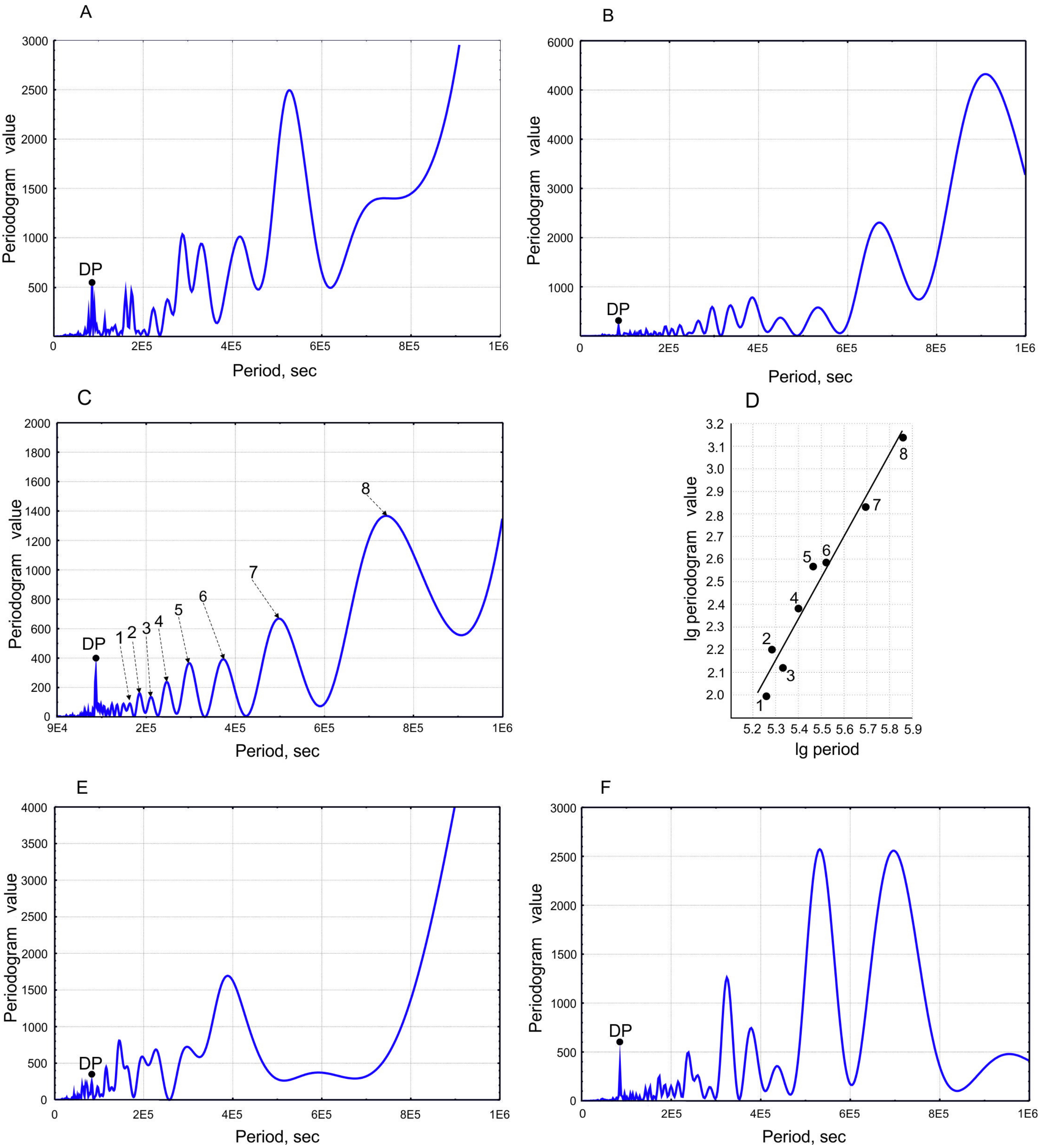

Fig. 4. Results of the spectral analysis of the rock deformation monitoring data obtained by sensor 3 in 2008 in the mine gallery near Talaya seismic station. Time intervals: 10 June – 09 July (*A*), 10 July – 09 August (*B*), 10–26 August (*C*), 28 August – 09 September (*E*), and 10 September – 09 October (*F*). Log-scale diagram for spectrogram *C* (*D*). DP – daily period.

Рис. 4. Результаты спектрального анализа данных деформационного мониторинга, полученных датчиком 3 в 2008 г. в штольне сейсмостанции «Талая». Временные интервалы: 10 июня – 09 июля (*A*), 10 июля – 09 августа (*B*), 10–26 августа (*C*), 28 августа – 09 сентября (*E*), 10 сентября – 09 октября (*F*). График «lg Periodogram – lg Period» для выделенных периодов 1–8 спектрограммы *C* (*D*). DP – суточный период.

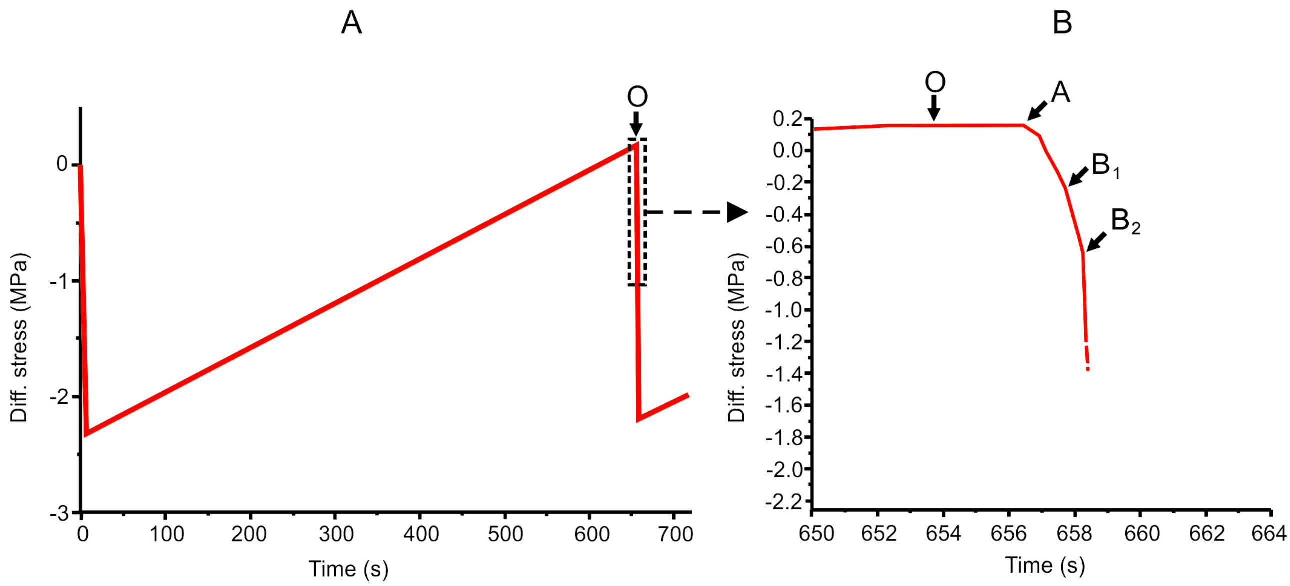

Fig. 5. Differential stress-time process of one stick-slip event (*A*) and time process of instability (*B*). Arrows indicate crucial moments of deformation (after [*Ma et al., 2012*] with changes).

Fig. 5. Изменение во времени дифференциального напряжения при подготовке и реализации одного импульсного смещения (*A*) и развитие нестабильности во времени (*B*). Стрелкой отмечен критический момент деформации (по [*Ma et al., 2012*] с изменениями).

is chaotic due to the irregular increase of the "periodogram" parameter for the different periods (Fig. 4, *A*). In the spectrogram III, the "periodogram" parameter reduces and the structure of the spectrogram shows regular elements. The spectrograms I and III demonstrate similarity in number and duration of the oscillation periods (Fig. 4, *A*). In the spectrogram IV (preseismogenic interval), the intensity of oscillations decreases, the number of periods reduces, and their values show the "log-periodic" sequence (Fig. 4, *B*, *C*).

The deformation regime significantly changes after August 27, when the Kultuk earthquake took place. The spectrogram shows chaotic deformation process, increasing values of the "periodogram" parameter, predominating oscillations with small and medium periods (from 0 to 4E5 sec.), and no large-period oscillations in the interval from 4E5 to 8E5 sec. (Fig. 4, *D*, spectrogram I). In the final time interval of observations, the deformation process returns to its initial regime. Spectrogram I on Figure 4, *A*, is similar to spectrogram II on Figure 4, *D*.

4. Discussion

The above-described results are discussed below on the basis of the synergy concept with reference to the "stick-slip" model. As shown by the experiments on a double-direction servo press machine, the impulse motion of one block relative to another one is preceded by two dynamic states. The metastable state with the auto-wave regime of load oscillations is followed by the meta-instable state, which passes the initial and final stages of meta-instability.

The temporal curve of differential stress illustrates several critical moments of deformation: O, A, B1, and B2 (Fig. 5). It is noteworthy that this curve is based on data from the press machine represents variations of all portions of the whole fault, while each site records strain processes of different portions. Below we analyze strain measurements of different sites at the critical moments on the curve of the average shear stress versus time. Measurements during laboratory tests on the press machine yield data on the average shear stress-time process of the fault (Fig. 5). An enlarged curve of its final stage is given in Fig. 5, *B*, to show details of the deformation development from the time 660s to 700s. The point O is stress peak. The segment OAB_1B_2 is the meta-instability stage of which OA is quasi-static release stage, B_1B_2 is quasi-dynamic release stage, and after point B2 the real instability is began.

At the initial stage, the displacement of one block relative to another one starts and develops in the quasi-creep stationary regime. Stress is gradually released in the inter-block contact zone. At the final stage (i.e. the stage of "accelerated synergism") [*Ma et al., 2012*], the displacement velocity increases, the self-organization process takes place. As a result, numerous reactivated segments of the inter-block contact zone are subjected to the avalanche-type joining accompanied by the dynamic slip. The experimentally established sequence of deformation assumes possibility of identification of the initial and final stages of meta-instability of seismogenic reactivation of a fault by the rate of stress release in the focal zone and the occurrence of indicators of self-organization during the deformation process development.

Now, taking into consideration the presented above experimental results, we can analyze the obtained monitoring data in terms of deformation development during the Kultuk earthquake preparation. Previous our study of deformation of the ice cover on Baikal Lake showed that then higher the stress in it, the higher the "periodogram value" parameter on spectrogram [*Bornyakov et.al., 2016*]. Following this the results of spectral analysis suggest that stress in the focal zone reached critical state in the first two estimated time intervals. The metastable state was achieved (Fig. 4, *A*). The two subsequent intervals should be interpreted as the initial and final stages of meta-instability, respectively. In the initial stage, stress in the focal zone decreased and the directional adjustment of oscillation periods took place (Fig. 4, *B*). During the final stage, the stress continued decreasing and indicators of self-organization of the lithosphere displayed, as it evidenced from the further decrease of the "spectrogram" parameter and the presence of the regular structure of the spectrogram with the a characteristic linear distribution of maximum periods in logarithmic scale (Fig. 4, *C*, *D*). This occurs usually due to the synchronization of fluctuations in different periods [*Chelidze et al., 2005; Lyubushin, 2012; Zhang et al., 1992*].

After the earthquake, the deformation process became chaotic and the stress gradually increase (Fig. 4, *E*, *F*). It is logical to expect that the stress should dramatically reduce due to seismogenic release, but the obtained results do not support this point. A possible explanation is that the earthquake could release only a small quantity of stress accumulated at the seismogenic fault.

5. Conclusion

From modeling results on the loaded system of two blocks [*Ma et al., 2012*], it was inferred that just before realization of displacement, the fault achieves a metastable state with an auto-wave mode of fluctuations of acting loading. The meta-stable state is followed by the meta-instable state, which is subdivided to stages of early and late meta-instability. In the initial stage, the displacement of one block relative to another one initiates and develops in the quasi-creep stationary regime, stress in the inter-block contact zone gradually releases. At the final stage (i.e. the stage of "accelerated synergism"), the displacement velocity increases, the self-organization process takes place, numerous activated segments of the inter-block contact zone quickly join to each other, and the dynamic slip occurs. Based on the experimentally established regularities, we suggested that the early and final stages of meta-instability in the seismogenic activation of a fault in nature can be recognized by the start of stress relaxation in the focal zone and the occurrence of indicators for self-organization in the deformation process.

The spectral analysis of the rock deformation monitoring data before and after the Kultuk earthquake is consistent with the estimated results and the experimentally established stages in the preparation of the displacement impulse. The proposed approach is promising for diagnostics of a meta-instable pre-seismogenic state of an active fault.

6. Acknowledgments

This study was partly supported by the Russian Foundation for Basic Research (Projects 16-55-44017-Mong-a), National Natural Science Foundation of China (Project No. 41572181) and Basic Research Funds from the Institute of Geology, China Earthquake Administration (Project IGCEA1203).

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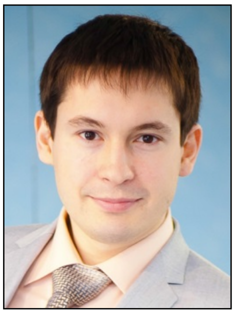

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