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The magnitude and creepex correlation parameter as an indicator of the environmental restructuring in preparation for the strongest earthquakes*

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Abstract. According to the data of the global and regional earthquake catalogs, the dynamics of the environment on the eve of strong ($M_S \geq 6.2$ for regions) and catastrophic ($M_S \geq 8$ for the whole world) earthquakes has been studied using the K_{COR} anomaly detection algorithm (the coefficient of paired correlation of the creepex Cr and the magnitude M_S). A pattern of long-term anomalies has been established within the boundaries of the far-reaching zone of influence on the seismic focus preparation, the radius R_F of which is calculated taking into account the stress distribution in elastoplastic environment. The seismic focus size is calculated from M_S using the RC-2016 formula. The results of different calculation methods of K_{COR} and creepex Cr are compared. On both a global and regional scale, in the R_F-vicinity, the scanning algorithm of the entire catalog revealed a pattern (in 100 % of cases) of significantly longer positive K_{COR} anomalies (from one and a half to nine years) before the strongest earthquakes of the catalogs when the classical creepex $\mathrm{Cr}_0 = M_S - m_b$ is used in comparison with other methods. This may indicate the establishment of a special elastic-plastic state of the environment in the preparation R_F-area of large earthquake foci.

Keywords: catalogs of earthquakes, parameters of the seismogeodynamic process, tectonic conditions, strong earthquakes, creepex

Introduction

It is known that the parameter of the classical creepex $\mathrm{Cr}_0 = M_S - m_b$ [1], calculated from the ratio of surface M_S and volume mb magnitudes, contains information about the state of the geophysical environment, and, possibly, not only in the earthquake focus (with a radius of R_0), but also in the zone of remote influence on the preparation of the source (up to a distance of R_F). On the other hand, it is known that, regardless of the selected catalog, the statistical distribution of all earthquakes by the coordinates Cr_0 and M_S shows a linear trend, i.e., the mutual dependence of these parameters. This forced many researchers to use various types of normalization of the creepex parameter [2, 3] in order to eliminate its dependence on magnitude. However, the growth of the creepex, synchronic with the increase in the

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earthquake magnitude, may be due to physical causes. For example, it can be associated with the rheological heterogeneity of the seismic focus environment (i.e., the lack of its uniform consolidation), since an increase in the focal size, linearly related to an increase in magnitude, naturally increases this heterogeneity [1]. In this paper, an attempt is made to find out whether this statistically pronounced dependence is a property of individual subsets of the earthquake catalog, and whether these sequences are related to a physically justified restructuring of the environment.

1. Methods and materials

The estimation of the seismic focus size according to the Richter formula [4]: $R_0 = 10^{M_S\cdot(0.433\div1.56)}$ is based on solving the task of elasticity theory. The formula of the rules code RC-2016 developed by the staff of the IFZ Institute of the Russian Academy of Sciences [5] is based on the final model of the Expecting Seismic Activity Places [6] (taking into account the magnitude, type of movement along the fault, the distance between the fracture surface and the observation point). According to this model, three earthquake impact zones are distinguished in [5]: focal R_0, near R_N and far R_F, where

$$R_0 = 10^{M_S\cdot(0.33\div1.51)}, \quad R_N = 10^{M_S\cdot(0.33\div0.61)}. \tag{1}$$

The table shows that the value of R_N is much closer to Richter's estimate of R_0 (for $M_S > 6$, exceeding Richter's estimates by 1–2 times, while R_0 of RC-2016 is lower by 4.7–7.5 times). That is, it is the R_N value in the RC-2016 model that reflects the area of influence of stress fields in polycrystalline elastic material (further decreasing exponentially) and can be taken as the boundary of the focus rigid inclusion. Beyond this boundary, the process of hydrostatic pressure transfer in a viscoelastic environment is apparently more active— the thrust action of a plastic substance filling existing cracks and fractures if the crystalline environment (for example, as a result of hydrothermal injection of deep material [7], when a pressure changes in local crystallic material can spread over hundreds to thousands kilometers).

The radii estimates of the focal, near and far zones depending on the earthquake magnitude

M_S	R_0 Richter	R_0 RC-2016	R_N RC-2016	R_F
4	1.49	0.65	5.13	10.33
5	4.03	1.38	10.96	30.60
6	10.91	2.95	23.44	90.60
7	29.58	6.31	50.12	268.27
8	80.17	13.49	107.15	794.33
9	217.27	28.84	229.09	2351.95

Thus, an estimate of the limiting size R_F of the influence zone on the seismic focus can be obtained based on solving the task of stress distribution in the vicinity of the inclusion (future focus) for the environment in an elastoplastic state (significantly different from the case of stress distribution in a purely elastic environment) [4]. A comparison of the rate of stress tendency until the initial values as one moves away from the inclusion in elastic and in elastoplastic environments gives estimates proportional to $1/R^2$ and $1/R^D$, respectively [4]. At the same time, the estimates of indicator D are different in six possible cases — for different types of inclusions (hard or soft) and for different geodynamic types of surrounding stress conditions (conditions of compression, stretching or shift). Excluding the case of soft inclusion in the horizontal stretching regime, which is rare in the nature of the strongest earthquakes, the minimum radius R_F corresponds to the maximum value $D = 1.4$ [4] (corresponding to the case of hard inclusion in the horizontal stretching environment and satisfying all other cases). Therefore, the minimum value of R_F is related to R_N as

$$R_F = R_N^{2/D} = R_N^{2/1.4}. \tag{2}$$

The table shows the estimates of the obtained using this formula radius R_F of the region, in which the parameter K_{COR} (the coefficient of paired correlation of the creepex and magnitude) is studied in this work on the eve of the strongest earthquakes.

It should be noted that earlier, in seismic-geodynamic studies of various scales [8–10], the normalized creepex $\mathrm{Cr}_0^{\mathrm{cat}}$ [8] (which represents the deviation of the classical creepex $\mathrm{Cr}_0 = M_S - m_b$ from the trend of $\mathrm{Cr}_0(M_S)$ dependence according to the selected catalog) was used. As a result of $\mathrm{Cr}_0^{\mathrm{cat}}$ application was found that on the eve of some of the strongest earthquakes, the accompanying its moderate seismicity in a certain local area is characterized by the establishment of a high correlation in time between the $\mathrm{Cr}_0^{\mathrm{cat}}$ and M_S parameters (i.e., synchronous or, conversely, antiphase dynamics). This correlation begins (with a value of $|K_{\mathrm{COR}}| \geq 0.7$) dozens of days before the main event and continues for dozens and hundreds of days after it. Moreover, direct correlation (synchronicity) is typical for most earthquakes in rift zones (geodynamic stretching regime), while reverse (antiphase dynamics) is typical for subduction zones (compression regime). Thus, the K_{COR} parameter empirically characterizes the dynamics of the ratio of plasticity and consolidation of the geophysical environment using the value of creepex deviation relative to the mathematical norm.

For a clearer physical justification of the revealed patterns on the eve of the strongest earthquakes, let us consider the behavior of the K_{COR}^0 parameter using the classical creepex Cr_0 [1] which reflects the physics of focal radiation absorption by the geophysical environment, the “ratio between slow and fast movement in the focus" and depends on "the strength type of rocks, the focal mechanism" [1] and other properties of the environment:

1. The growth of the creepex is influenced not only by the predominance of a quasi-plastic component in the focal movement (compared with brittle fracture), but also by lower tectonic stress of the environment [1], an increase in its temperature, as well as the phenomenon of dilatantion, causing absorption of high-frequency radiation;
2. The creepex growth, which is synchronous with the increase in the earthquake magnitude, is influenced by the rheological heterogeneity of the focal medium, which increases with the focal size [1], i.e., the absence of its solidity and consolidation.

Let us note that $\mathrm{Cr}_0^{\mathrm{cat}}$ and Cr_0 correlate with each other with a high coefficient of paired correlation with $K_{\mathrm{COR}} = 0.87$ (Figure 1).

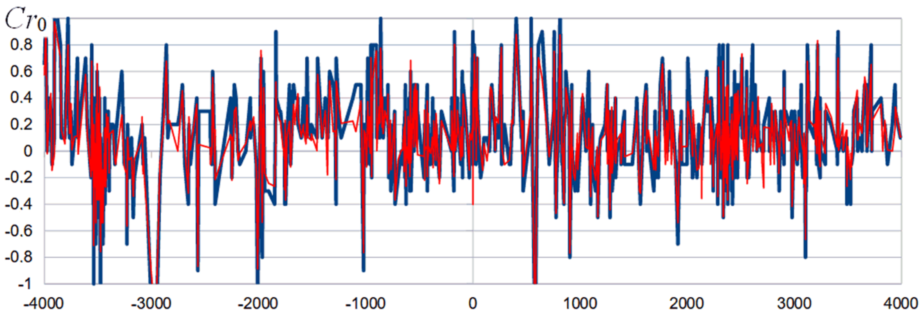

Figure 1. An example of a high pair correlation of the $\mathrm{Cr}_0^{\mathrm{cat}}(t)$ (red) and $\mathrm{Cr}_0(t)$ (blue) graphs for events in the Baikal Rift Zone regional catalog of the FRC UGS RAS [11]: $K_{\mathrm{COR}} = 0.8728$

The study is conducted by means of GIS-ENDDB geographic information system [8] based on catalogs: regional, compiled the data of the journals "Earthquakes of Northern Eurasia" [11] of the FRC UGS RAS, and global — of the English International seismological center ISC (with reference to IDC—International Data Center, Vienna International Center, Austria [12]). The characteristics of the catalogues of the FRC UGS RAS are given in [10] and other papers for 2025. The IDC catalog [12] contains 333080 records with paired definitions of M_S and m_b for 26.02.2000–09.05.2025.

In this paper, a new GIS-ENDDB scanning algorithm of the catalogs under consider is used, consisting of the following steps: 1) for each subsequent strongest event ($M_S \geq 6.2$ for the regional catalog and $M_S \geq 8$ for the global one) the choice of seismicity in a circular area of a R_F radius (calculated by formula (2)), and in the case of global catalogs (consisting of 87 % of subduction zones events) with a restriction on magnitude: $M_S \geq 4.5$ and depth: $H \geq 50$ km; 2) for the resulting sample, the calculation of the time graphs of the K^0_{COR} parameter using the calculation algorithm "with the right edge of the sliding window fixed at the point of the main event"; 3) the output of earthquake sequences up to the main event with K^0_{COR} above an input value (here $|K^0_{\mathrm{COR}}| \geq 0.7$) during time not less the input T (here $T \geq 20$ days).

2. Results

It was previously shown [10] that the K_{COR} parameter sometimes gives different results in terms of the sign and duration of the anomaly at different scale levels. For example, for the Kultuk earthquake of 08.27.2008, $M_S = 7.2$, corresponding to the case of a hard inclusion in the horizontal stretching mode (Figure 2), a negative anomaly is observed in the local circular region of $R_F = 320$ km nine months before the event, while by the entire seismicity of the regional catalog of Baikal branch of the FRC UGS RAS, there is a positive anomaly K_{COR} 30 days before the main event (Figure 3). If the negative anomaly reflects the process of consolidation of the environment

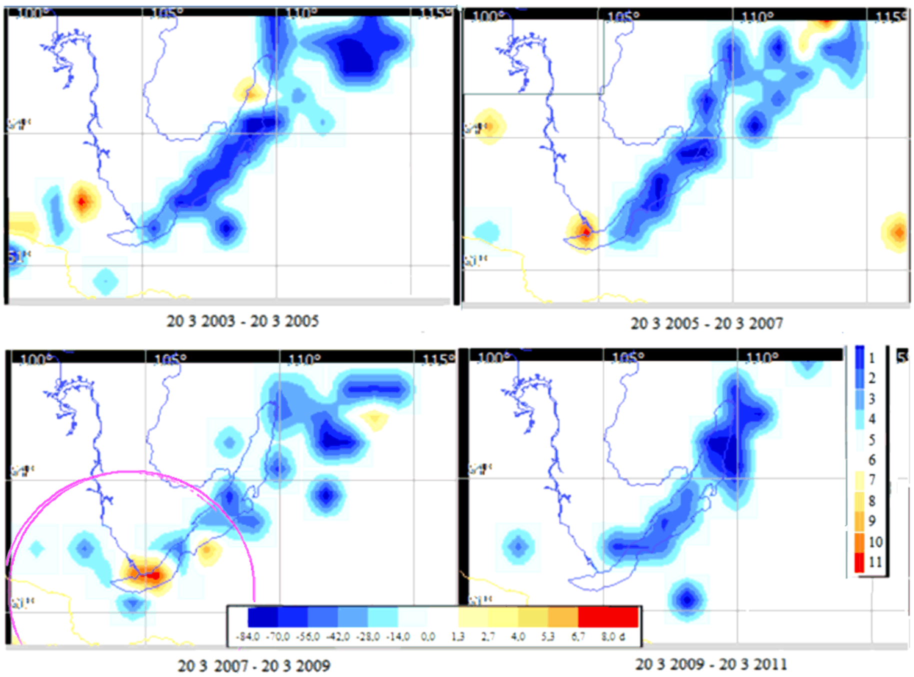

Figure 2. Lateral distribution of the total slip vector in the Baikal rift zone from 2003 to 2011 over consecutive 2-year time intervals according to the sample of [8] with $M_S \geq 2.8$ (the R_F-vicinity of the Kultuk earthquake on 08.27.2008 is indicated by a lilac circle): blue areas represent stretching, red ones are compression (obtained in GIS-ENDDB, the FRC UGS RAS catalog of mechanisms)

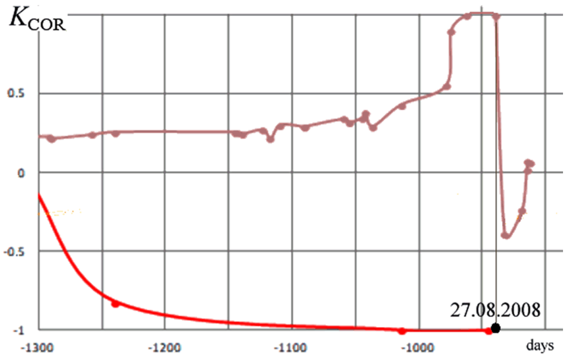

Figure 3. $K_{\rm COR}$(t) in R_F-vicinity of the Kultuk earthquake (red) and in the entire Baikal region (brown)

during the preparation of the seismic event, sometimes very long in the local area, then on a regional scale in the last month, the stretching mode could be activated, manifested by a positive anomaly.

Indeed, in other geodynamic settings, for example, in the case of a hard inclusion in the horizontal compression regime, which corresponds to the events of the Altai and Yakutian regions, the value of R_F, according to [4], is 2.8 orders of value greater than the minimum value assumed by us (see the table). Thus, in the R_F-area of the Altai earthquake of 09.27.2003, $M_S = 8.1$, the negative $K_{\rm COR}$ anomaly (32 days before the event) is identical to the anomaly for seismicity of the entire Altai-Sayan region [10]. The same pattern is observed for the earthquake of 11.12.2005, $M_S = 6.5$ — the anomaly 32 days before the event in the R_F-area with a radius of 157 km is identical to the anomaly for all events in the Yakut catalog [10]. Let us note that since the earthquake class K is presented as an energy characteristic in the regional catalogs of the FRC UGS RAS, we calculate the magnitude M_S (used in calculating R_N) according to the formula recommended by the FRC UGS RAS for earthquakes with $K \geq 14$: $K = 8 + 1.1M_S$.

Despite the high correlation of the $\mathrm{Cr}_0^{\rm cat}$ and Cr_0 parameters (see Figure 1), when switching to the $K^0_{\rm COR}$ calculation, the results turn out to be different. In the R_F-areas of the above-mentioned strongest earthquakes in the Altai, Yakutian and Baikal regional catalogs, the $K^0_{\rm COR}$ anomaly always becomes positive and is an order of during longer. Instead of 1.1–9.5 months before the event for $K_{\rm COR}$, it is 1.4–9.2 years for $K^0_{\rm COR}$. In addition, a full scan of the regional catalogs showed a greater repeatability of this regularity, unlike the first method ($K_{\rm COR}$). For example, for the Altai and Yakutian catalogs, this anomaly was detected on the eve of 80 % of all earthquakes with $M_S \geq 6.2$ (for the first method — only 50 %). Given the small number (from 4 to 6) of strong earthquakes with $M_S \geq 6.2$ in the continental regions under consideration, it is interesting to consider the occurrence of this anomaly for catastrophic events of $M_S \geq 8$ in the global catalogues, the number of which is 2 or more times greater (depending on the selected catalog).

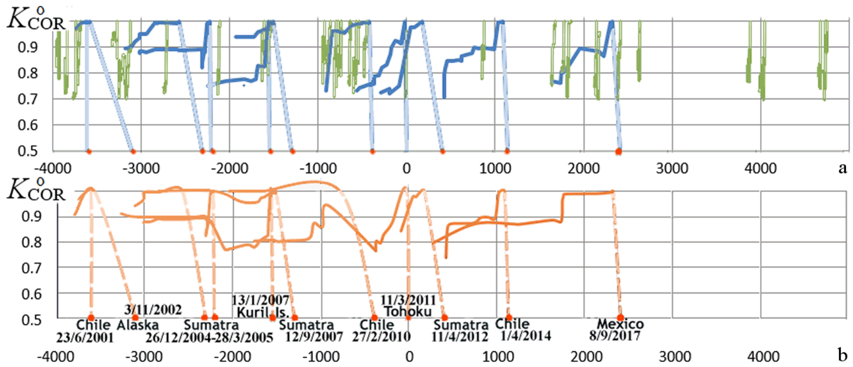

Figure 4. Anomalies $|K^0_{\mathrm{COR}}| \geq 0.7$ before catastrophic earthquakes $M_S \geq 8$ of the IDC catalog in the far region of the influence of their future foci (at the bottom—for R_F according to the table, at the top—for R_F increased by 1.8 times). Red dots on the time axis mark the moments of events with $M_S \geq 8$

For example, scanning the IDC global catalog in the R_F-vicinity of all its catastrophic earthquakes with $M_S \geq 8$ (11 events) reveals the preceding them positive anomalies K^0_{COR} which are significantly longer in time (from 0.4 to 5.5 years, Figure 4b) compared with K_{COR}. Let us note that increasing the radii of the circles by 1.8 times reduces the anomalies duration by 2 times or more (0.4–2.3 years, Figure 4a), which indicates the optimality of our chosen method of R_F calculating (2). Interestingly, there are no negative anomalies, regardless of the type of foci and their geodynamic environment. The total number of earthquakes included in the chains of high correlation (together with the main events of $M_S \geq 8$) is not large, accounting for $\sim$5 % of the total number of catalog events (2433 entries with $M_S \geq 4.5$) and $H \geq 50$ km with paired definitions of M_S and m_b). However, there were also identified independent of the strongest events, 198 earthquake chains with $|K^0_{\mathrm{COR}}| \geq 0.7$ in the R_F-areas of the last earthquake of the chain and with the chain duration of more than 20 days. These chains have a duration of 20 days to 4 months, consist of 4–52 events in a chain, and the total number of events in them is 1752, i.e., covers 73 % of all catalog events. This suggests that the preparation processes of the 8 % moderate ($M_S \geq 4.5$) earthquakes in the catalog (198 out of 2433) are similar to the preparation of the strongest events.

For comparison, let us check the correlation of catalog events, without limiting the chronological chains by R_F-areas. Scanning the catalog reveals 41 such chains lasting from 0.5 to 4 months (the green color of the graph in Figure 4). Moreover, only three of this 41 K^0_{COR} anomalies are negative (they characterize the possible consolidation of the environment), the rest are positive. Less than a third (12 out of 41) of the chains are geographically and chronologically associated with areas of preparation for catastrophic earthquakes (see Figure 4a), the rest (accounting for ~ 14 % of the catalog by the total number of events in them is 335) are correlated, independent of the preparation of certain earthquakes. Perhaps their presence is due to external (regional or planetary) stretching/compression processes.

The positive sign of the K^0_{COR} anomalies and their duration in R_F-preparation areas of the eleven strongest and 198 moderate earthquakes (in the near and far zones of their foci) can be explained by plastic processes, for example, by the hydrostatic pressure of a viscoelastic medium when filling existing faults with additional material. The source of the introduction of plastic matter may be deep areas of rocks partial melting [13, 14]. The increase in rheological and density heterogeneity of the environment is consistent with the establishment of a proportional dependence of the creepex on the focal size [1] in the areas of earthquake preparation.

Conclusion

Scanning the parameters of seismic events in both the regional (FRC UGS RAS) and global (IDC) catalogs shows a pattern of K^0_{COR} anomalies (the coefficient of paired correlation of the creepex and magnitude of the earthquake) with $|K^0_{\mathrm{COR}}| \geq 0.7$ lasting from 0.4 to 9.2 years in R_F-area of the preparation influence on the future focus of the strongest catalogs earthquakes. Unlike the normalized modifications of the creepex, the K^0_{COR} parameter based on the classical creepex $\mathrm{Cr}_0 = M_S - m_b$ shows the presence of anomalies in 100 % of cases of catastrophic events with $M_S \geq 8$ (with paired definitions of M_S and m_b) in the IDC world catalog. At the same time, abnormal K^0_{COR} chains of events in the R_F-areas of moderate ($M_S \geq 4.5$) IDC earthquakes do not exceed four months in duration, but they are widespread in terms of the coverage of chains events (72 % of all catalog events). That is, the property of the dependence of the classical creepex on magnitude, which is statistically manifested throughout the catalog, is actually concentrated in local chains of seismicity that precede less than a tenth of the catalog events in their preparation areas. The positive sign and the duration of the described anomalies may indicate plastic processes in the preparation of the future seismic focus, which are very long (multi-years) in time and large-scale (up to thousands of km) in distance.

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