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# The Creepex-analysis of processes in large earthquakes focal zones by the GIS-ENDDB tools on the Tohoku example

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**Abstract.** The paper explores the possibility of modifying the creepex (creep and explosion) parameter, an increase in its informativeness and applicability of using public catalogs by the GIS-ENDDB geoinformation system. Instead of the canonical form of the creepex ($\mathrm{Cr} = M_S - km_b - l$), the introduced normalized estimate of this parameter is investigated: $\mathrm{Cr}_N = 4(M_S - m_b)/(M_S + m_b)$, which has a less pronounced systematic dependence of the difference $(M_S - m_b)$ on the earthquakes magnitude $M_S$ and its significantly lower variance. The catalogs NEIC and ISC are analyzed. An example of this study is carried out on a sample (Jcreepex catalog: 1,458 records) from the ISC Integrated Catalog for the focal zone of the Great East Japanese Earthquake (Tohoku), for 2010–2012, with the ISC own definitions of $m_b$ and $M_S$. Based on a complex analysis of the distribution of the creepex-colored earthquake focal zones, patterns of changes in this parameter in space, revealing its connection with the tectonic environment, and in time, revealing patterns of seismogenesis before and after a strong event under consideration, are established. On an example of the crust Tohoku earthquake (March 11, 2011, $M_S = 8.7$) the informativeness of the normalized creepex is confirmed, and it is shown that the source relaxation process partially occurs, by periodic focal chains, with the value of the creepex demonstrating the process alternation of a quasi-plastic flow and a brittle fracture.

**Keywords:** Catalogs and databases of earthquakes, seismic and geodynamic process, tectonic environments.

## 1. Introduction

The formally constructed parameter creepex (creep & explosion), determined by a residual in the orthogonal regression of the magnitudes $M_S$ and $m_b$: $\mathrm{Cr} = M_S - km_b - l$ [1], provides information on the relation between low- and high-frequency radiation components in the earthquake source and can reflect various aspects of the seismic-geodynamic process: the inter-relationship between seismogenesis and tectonic environment, the dynamics of the preparation processes of a strong event; the help in selecting explosions and earthquakes, the determination of the viscous slip fractions during the formation of a seismogenic crack, etc. [1–3]. In particular, in [2] it was shown that since a tectonic motion shows the property of "aseismic creep" in spreading zones, their seismic sources must have a considerably higher creep value than that in the subduction zones characterized by the "cold" brittle fracture.

From the mathematical point of view, the creepex parameter is the difference between values of the same dimension, but with a different physical content, in fact, it is the normalized logarithm of the ratio of earthquake energy estimates. Each estimate is a reflection of a complex set of information: about the source of an earthquake; the geophysical environment containing the source; the medium in the volumes covered with seismic wave propagation paths, etc. The magnitudes $M_S$ and $m_b$ for the same event are determined by different types of waves with different generation mechanisms in mismatched frequency ranges (low frequency for $M_S$: usually, with a period of 20 s; and high frequency for $m_b$: usually with a period of 1 s), recorded by different types of equipment, not provided with a unified metrological certification [4]. Moreover, these magnitudes contained in various catalogs are determined by various services and agencies using individual algorithmic, apparatus-methodological and model approaches. This creates difficulties in identifying non-random variations in the Cr parameter associated, for example, exclusively with the structure of a medium in the focus area.

Nevertheless, since the spatio-temporal changes in the parameter will generally be "caused by variations in conditions in the source zone for the emission of compression and shift waves", with a purposefully strict determination of $M_S$ and $m_b$ and with empirically correct coefficients $k$ and $l$, the ratio of Cr can serve "a measure of the specificity of a focal zone" [3].

Thus, the creepex parameter can and must be used for seismic-geodynamic studies if taking into account its dependence on many related parameters (the coordinates of hypocenter, the quality of data recording and processing, the anomalies in the state of the surrounding geophysical environment, etc.), the analytical relationship between which is not yet possible to establish. The authors, using the modern expert information and computing system GIS-ENDDB [5], try to identify the influence of accompanying factors based on the analysis of data in open catalogs and to determine the most informative samples on which it is possible to calculate and visualize the distribution of the creepex parameter and to trace its retrospective dynamics.

## 2. Characteristics of the data used

The discrepancies between the magnitudes $M_S$ and $m_b$ provided by different agencies can be of significance. Thus, a comparison of the definitions of $m_b$ in the ISC [6] and NEIC [7] catalogs over a circular area centered in the Pamir-Hindu Kush seismic focal zone of radius 500 km (7093 records for 1963–2017 years) gives a residual up to 35 % relative to the value $m_b$ according to NEIC, limiting by values up to 7 % only for $m_b \geq 5.5$ (Figure 1).

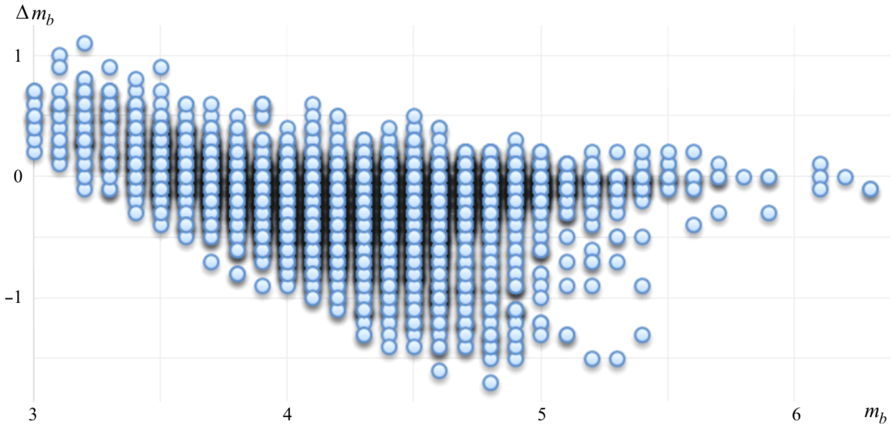


**Figure 1.** Distribution of the residual $\Delta m_b = m_b^{\mathrm{ISC}} - m_b^{\mathrm{NEIC}}$ of synchronous events in the ISC and NEIC catalogs (a sample within a radius of 500 km around the Pamir-Hindu Kush seismic focal zone for 1963–2017, 7,093 records) relative to the value $m_b$ according to NEIC

In addition, there is a problem of event synchronization when comparing different catalogs. According to the values $m_b$ from the ISC catalog (where the definitions of this magnitude are collected with references to various sources, but the problem of the event synchronization has been already solved), the distribution of the residuals is slightly better: $\Delta m_b = m_b^{\mathrm{ISC}} - m_b^{\mathrm{NEIC}}$ (the difference in the definitions of $m_b$ with references to ISC and NEIC) for the largest events reaches acceptable values of 10 % relative to $m_b^{\mathrm{ISC}}$ already for $m_b^{\mathrm{ISC}} \geq 5$. Let us note that a separate consideration of 288 deep events (recorded below the Moho boundary) shows an increase in the dispersion of the residual $m_b$ to 45.2 % of $m_b^{\mathrm{ISC}}$ for the deepest events.

In the above comparison of the two catalogs, we used pairs of synchronous events with a time difference of up to 2.6 s. But even more stringent conditions for the selection of synchronous events: with a difference in the occurrence time of no more than 1 s (which reduced the number of events up to 3,689) do not provide a stricter equivalence of other recording parameters: the difference in the determination of the hypocenter coordinates and epicenter depths can reach 10 km. The errors in the depth determination given in the NEIC catalog make it possible to estimate a relative number of events with an unreliable depth: 1,072 versus 4,682 (i.e., almost 1/4 of the number of events with a reliable depth); however, the influence of this parameter on the distribution of residuals by magnitudes has not been revealed yet.

Thus, the analysis of the correspondence between the parameters provided by different catalogs shows that the use of mixed definitions from different agencies is not desirable due to an essential scatter of values determined by a wide variety of definition errors. If we assume that these errors have a less diverse character within each catalog, then it is better to analyze the distribution of earthquake characteristics within the framework of a single catalog.

In this study, the unified catalog ISC was selected, because it contains the most complete information about various magnitudes — both their own definitions of $M_S$ and $m_b$, and the definitions of $M_S$ of various agencies. This catalog contains records combined from many sources, and it is obvious that the data quality of these source catalogs is not always controlled. In addition, the ISC own definitions of magnitude pairs ($M_S$ and $m_b$) may not be independent.

For example, for a two-year period before and after the Great East Japan Earthquake (Tohoku), both in the near and far zones of this mega-event, regular patterns were revealed in the $(M_S - m_b)$ versus $m_b$ plot (Figure 2a). The same graph for the sample expanded to the global scale for the same period of time (8,827 determinations) has a similar appearance. However, this dependence is far from being typical and, possibly, is associated with the peculiarity of the data processing under conditions of an anomalously high seismic activity (in terms of energy, frequency and the number of earthquakes) during the Tohoku mega-earthquake. In other samples, for example, in the area around the Pamir–Hindu Kush seismic focal zone, such dependencies were not revealed (Figure 2b).

These facts indicate to the fact that the creepex analysis results for pairs of the ISC own definitions of $M_S$ and $m_b$ are not always more reliable than for more independent definitions of $M_S$ and $m_b$ from various agencies collected in the ISC Catalog, or for synchronous events of different catalogs.

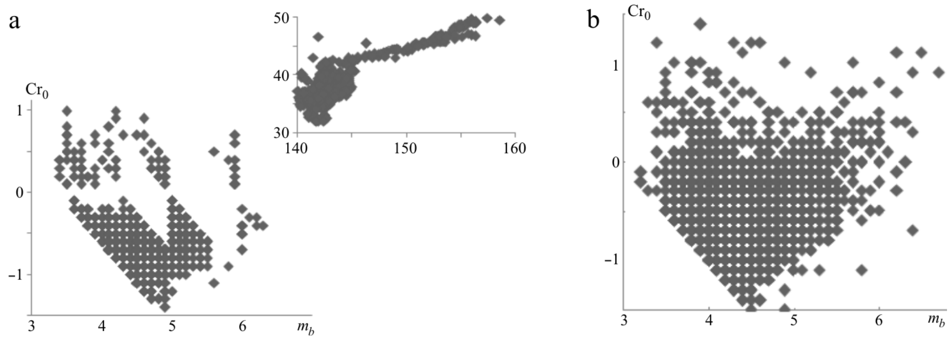


**Figure 2.** Dependence of the creepex $\mathrm{Cr}_0 = M_S - m_b$ on the magnitude $m_b$ according to the ISC agency own definitions of the magnitudes $M_S$ and $m_b$: a) the 1,458 paired determinations a year before and a year after (03/11/2010–03/11/2012) the Great East Japan Earthquake (Tohoku) in the far zone along the seismic lineament: 30–50°N; 140–160°E (see insert picture); b) the 1,925 measurements within a radius of 500 km around the Pamir-Hindu Kush seismic focal zone

However, when using definitions of magnitudes from different agencies, one should take into account systematic discrepancies between them. For example, the magnitude $m_b$ from the Seismological Bulletin of the Federal Research Center of the UGS RAS, cited in the ISC Catalog with the "MOS" index, systematically exceeds (by an average of 0.4–0.6 M units) the ISC own definition of $m_b$. This difference is comparable with the variations in the $\mathrm{Cr}_N$ parameter, which will associated with the tectonic features of the source zones and the preparation of strong earthquakes.

Despite an insufficient quality of the data in the ISC Catalog, in particular, due to the lack of independence in determining the magnitudes during the periods of preparation and aftershock activity after the Tohoku earthquake, at the initial stage of the study described in this study, a sample of the ISC Catalog with its own definitions of $M_S$ and $m_b$ is used, which is compiled with the Jcreepex Catalog (1,458 events).

## 3. Examples of the method application

Instead of the canonical representation of the creepex $\mathrm{Cr} = M_S - km_b - l$ [1], in analyzing a subsystem of the GIS-ENDDB program [5], a normalized estimate of this parameter is proposed and implemented: $\mathrm{Cr}_N = 4(M_S - m_b)/(M_S + m_b)$. The advantages of normalization are the suppression of the observed systematic dependence of the difference $(M_S - m_b)$ on the magnitude $M_S$ of earthquakes according to a linearly increasing law and a significant decrease in the scatter (Figure 3).

Despite an insufficient quality of the initial data (which was mentioned above), the application of the method described for calculating $\mathrm{Cr}_N$ in the Jcreepex Catalog generated by the authors has provided results that do not contradict the general interpretation [2]. The visualization of the spatial distribution of earthquake foci colored by a creepex magnitude shows (Fig-

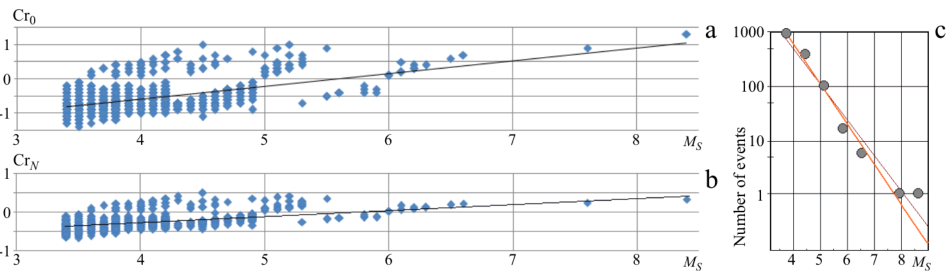


**Figure 3.** Dependence of the parameters $\mathrm{Cr}_0 = M_S - m_b$ (a) and $\mathrm{Cr}_N = 4(M_S - m_b)/(M_S + m_b)$ (b) on the magnitude $M_S$ for events in the vicinity of Tohoku (Jcreepex Catalog, 1,458 events) and the representativeness of the used catalog (c) in terms of the repeatability graph on $M_S$ and $m_b$ (the graph shown in red is one on $M_S$ without taking into account the main shock, in blue is one on $m_b$)

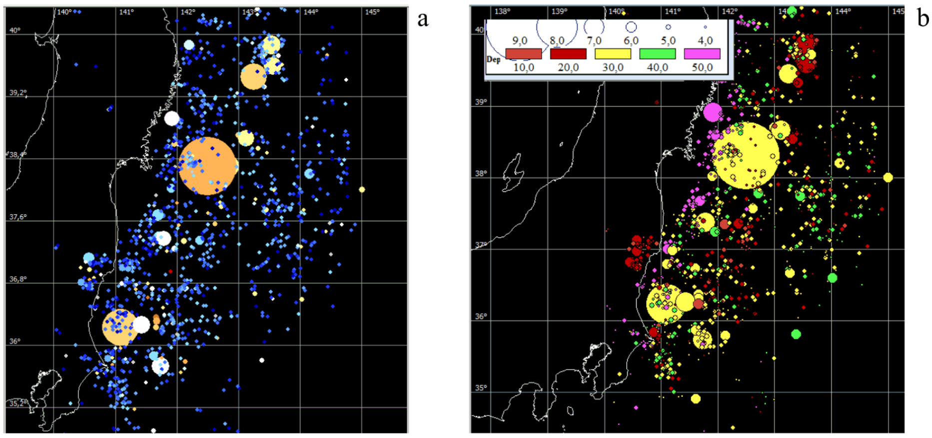


**Figure 4.** In the map, distribution of the earthquakes with $M_S \geq 3$ in the source zone of the Tohoku earthquake a year before and a year after the earthquake according to the Jcreepex Catalog (1,292 events): a) the size of the circles is set by the earthquake foci size estimated by $M_S$ [8] (see the legend in Figure 6); b) the size and color of the circles is determined by the magnitude and depth. The figures were obtained using the GIS-ENDDB system

ure 4a) predominantly negative values (shades of blue) for weak earthquakes associated with brittle destruction of a medium, and positive values (shades of yellow to red) for large events, apparently associated with quasi-plastic processes. A comparison with the map of earthquakes colored with respect to a depth shows that a brittle fracture characterizes not only the shallow-focus events of the oceanic crust, but also the deep events ($H \geq 40$ km) of the submerged slab zone (lilac circles in Figure 4b). Speaking of quasi-plastic processes, we mean both the translational motion of a plastic matter from depths and a change in the viscosity of rocks forming the rheological heterogeneity of the medium under the influence of an energy released by earthquakes.

Let us note that the connection of the largest seismic events not only with strong elastic stresses in crystalline rocks, but also with the processes of the quasi-plastic "creep" of matter is evidenced by many indirect facts, when the characteristics of seismic events do not agree with the general tectonic setting or the seismic geodynamic regime, in general. First, these are the cases of the following one after another (with an interval of several weeks or less) of the strongest shocks with a magnitude of $M_S \sim 8$ (as it was in the cases of Khangai, July 9–23, 1905 or Nepal, April 25–28, 2015 multi-earthquakes), which, according to the earthquakes recurrence law, must be separated in time by centuries. Second, according to the results of studies of paleoseismic dislocations, it was revealed that the largest earthquakes occur in the same places [9, 10], i.e., they are probably associated with deep crustal and mantle inhomogeneities [11, 12]. And, finally, third, these are eyewitness reports about an unusual course of seismic dislocations development during disastrous earthquakes that have occurred in the areas accessible for direct observations. For example, during the Muya earthquake (06/27/1957, $M_S = 7.8$), the vertical rotational movements of large granite blocks and the formation of torsion folds in wide valleys between faults were observed. Rotational clockwise deformations were also observed during the Middle Baikal shock (August 29, 1959, $M_S = 6.8$). During the Gobi-Altai earthquake (December 4, 1957), in addition to rotational (counterclockwise), the wave reciprocating movements of ridges and blocks (recorded, including those recorded in the slip mirrors) were observed. At the same time, in the epicentral earthquake zone, within a few minutes, discontinuous deformations opposite in genetic types were formed: faults in the vicinity of uplifts, strike-slip faults with thrusts, etc. [13]. In Iceland, according to V.G. Trifonovs observation, during a series of weak earthquakes, the growth of cracks in the Earth's crust was noted, and, higyly likely, this growth is associated with the rise of basalt magma [14]. All these observations do not count in favor of a typical mechanism of unloading elastic stresses and make us assume an additional component of the tectonic motion associated with deep quasi-plastic processes.

The function of displaying the distribution of earthquakes on the time axis, implemented in the GIS-ENDDB analysis subsystem, can reveal the patterns of the seismogenesis development with respect to time, in particular, before and after the strong event in question in the entire source zone or in its near epicentral zone. For example, for the Great East Japan Earthquake (Tohoku) (03/11/2011, $M_S^{\rm ISC} = 8.4$), the relaxation process of the focus in the first days after the main shock is clearly manifested in the time graph in the form of en-echelon chains of events with a periodicity of 1.5 days with a decreasing trend changes in the $\mathrm{Cr}_N$ creepex (Figures 5b, 5c). The alternating behavior of $\mathrm{Cr}_N$ with a decreasing trend of values after each maximum in the chain can indicate (according to the interpretation [2]) a frequent alternation of the quasi-plastic flow and the brittle fracture events with a gradual increase in the brittle fracture contribution. Note that before the Tohoku mega-earthquake, the trend of the $\mathrm{Cr}_N$ creepex change during a year was generally increasing (Figures 5a), which apparently indicates to the growing influence of subcrustal quasi-plastic processes in the preparation of the mega-earthquake. A sharp change in the annual trend to a negative one after a mega-shock (Figure 5a, 5b) may indicate, accordingly, to an increasing contribution (at a scale of the whole year) of the processes of subsequent brittle deformations of the upper layers of the crystal shell. Let us note that a comparison of changes in the values of the modified (normalized) and classical creepex variants ($\mathrm{Cr}_N$ and $\mathrm{Cr}_0$) shows (Figure 5b) a relatively large variability of $\mathrm{Cr}_N$, as well as a higher intensity of its periodic maxima, close

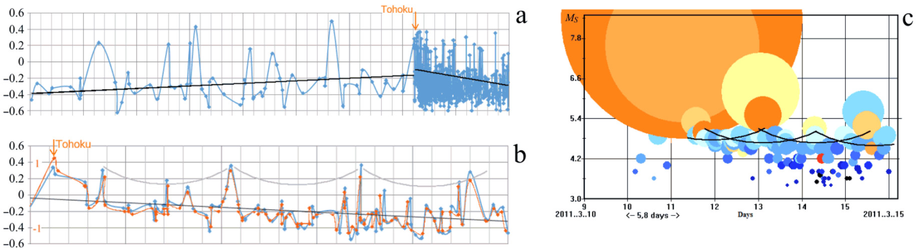


**Figure 5.** A change in the $\mathrm{Cr}_N$ creepex value and the distribution of earthquakes over time in the area of Figure 4a: a) a change in the creepex (in days) one year before and three months after the Tohoku earthquake (823 records); b) and c) within five days after the earthquake (107 records) — b) a change in the creepex $\mathrm{Cr}_N$ (blue) in comparison with $\mathrm{Cr}_0$ (red); c) the distribution of earthquakes, the size of the circles is set by the source size estimated by $M_S$, the color is set by the creepex value (see the legend in Figure 6). The picture was obtained by the GIS-ENDDB analysis system

in value to the maximum of the main shock and even sometimes exceeding it.

In particular, when considering the time distribution of the creepex value of the strongest (in terms of the released energy) aftershocks of the epicentral zone of Tohoku ($M_S \geq 5$) within two months after the main shock, a generally horizontal trend of the positive creepex values is observed (Figure 6a), periodically (every $\sim$ 20 days) interrupted by abrupt negative emissions, presumably marking a large destruction of rigid blocks. The energy of these events $M_S \geq 5.8$ (Figure 6b) significantly exceeds the energy of dislocations characterized by the positive creepex: $5.0 \leq M_S \leq 5.4$ (Figure 6b).

The $\mathrm{Cr}_N$ creepex calculation can be used in other types of analysis as well. So, to study the features of the development of the foreshock and

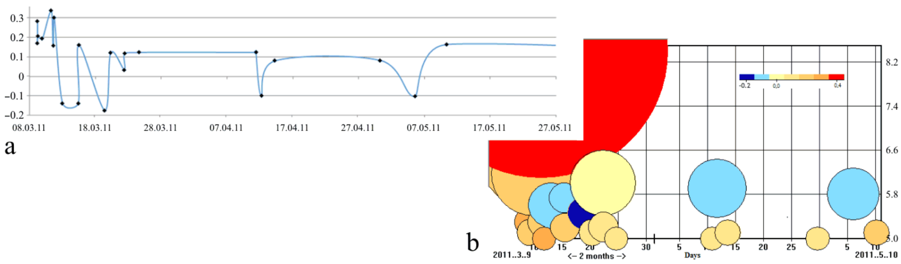


**Figure 6.** Development of the seismic-geodynamic process in terms of time in the near zone of the Tohoku earthquake (in the area 36.5–39°N, 140–145°E) by large aftershocks ($M_S \geq 5$) within two months after the main shock (26 events): a) a change in the $\mathrm{Cr}_N$ value; b) the distribution of the foci of events colored according to the creepex value

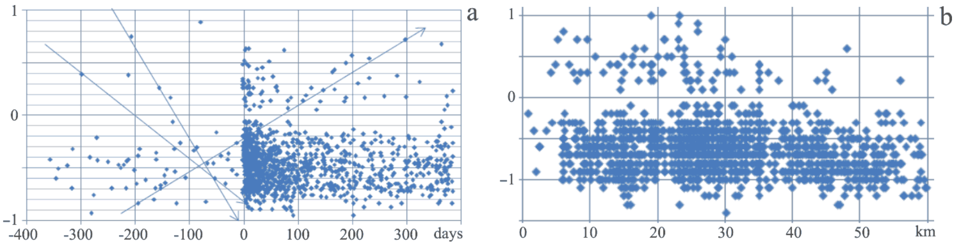


**Figure 7.** The dependence of the creepex in the source zone of the Tohoku earthquake on time (in days) and on depth (in km): a) $\mathrm{Cr}_N$ for foreshocks and aftershocks in the year before and the year after the shock (ISC), straight lines show examples of a decreasing and an increasing creepex of the chains of foreshocks and aftershocks; b) $\mathrm{Cr}_N$ for aftershocks only (ISC: 1,284 determinations of the pairs $M_S$ and $m_b$ for 386 days after the event)

aftershock processes of the Tohoku earthquake, the dependence of $\mathrm{Cr}_N$ not only on time, but also on the depth of events was considered. The first graph (Figure 7a) made it possible to trace the time chains of foreshocks, which are responsible for the maturation processes of the focus, its development, as well as aftershocks, which are responsible for the relaxation and discharge processes, i.e., transitions from a positive to a negative creepex and vice versa.

The second graph (Figure 7b) shows a generally homogeneous distribution of the creepex parameter values for the aftershock process over the depth $H$ from 0 to 60 km, of which only 6.1 % of definitions have a positive creepex value. Let us note that the graph for 172 paired foreshocks definitions shows a similar distribution configuration and the same ratio of positive and negative creepex values. This allows us to assume that before and after the main shock in the Tohoku source (in the tectonic setting of "cold" lithosphere subduction), the processes of "aseismic creep" of matter are manifested only in a small number of events, which are mainly concentrated at depths of $H = 14$–$35$ km.

## 4. Conclusion

The method for calculating the normalized $\mathrm{Cr}_N$ creepex implemented in the GIS-ENDDB geographic information system makes it possible to carry out a complex analysis of its changes in space and time, revealing the connection between seismic events and the tectonic setting (according to the distribution of $\mathrm{Cr}_N$ in space), as well as the regularities of seismogenesis processes before and after the considered strong event (by a change in $\mathrm{Cr}_N$ over time).

Thus, using as an example of the Great East Japan Earthquake (11.03.2011, $M_S = 8.7$), it was confirmed that the relaxation process of the focus occurs in part, by periodic chains of sources, demonstrating the transition from a quasi-plastic flow to a brittle fracture in terms of the creepex value. An example of the creepex study of foreshocks and aftershocks in the focal zone of the Tohoku earthquake suggests that in the first year before and after the main shock, in the total number of seismic events, the processes of "aseismic creep" of matter, are mainly concentrated at depths of $H = 14$–$35$ km.

The GIS-ENDDB analysis subsystem makes it possible to assess the degree of reliability of the results obtained, based on the analysis of the data quality of the catalogs used and of their separate samples. A set of analysis functions makes it possible to assess the advisability of extending this type of seismic-geodynamic research to a combination of other types of magnitudes. We believe this will increase the reliability and variety of the results obtained.

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