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# The dynamics of parameters of individual earthquake swarm sequences in different geotectonic settings*

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**Abstract.** To study the swarm sequences of earthquakes in the areas of plate convergence and divergence, the parameters: surface wave magnitude $M_S$ and depth $H$ are used, as well as one of the characteristics of the seismic regime — creepex $\mathrm{Cr}_N^{\mathrm{cat}}$, included in the complex of the GIS-ENDDB program and characterizing the ratio of the contributions of the "hard" and "soft" components to the earthquake displacement. The factual material of this study is various samples of catalogs with their own definitions $M_S$, $H$ and body wave magnitudes $m_b$ — of the England seismological center ISC and of the more representative Chinese Catalog CSN. The regularities of a change in time of the three considered parameters in the individual swarm sequences for the areas with different geotectonic settings — in the Frisa Strait, near the island of Honshu, in the Avacha Bay (Kamchatka), under the Iceland and in the Pamir–Hindu Kush seismic focal zone, have been established. These patterns indicate to the presence of an organized state of the environment, which is expressed in the following: 1) synchronous dynamics of the parameters $M_S$, $H$ and $\mathrm{Cr}_N^{\mathrm{cat}}$ (with direct or inverse phase correlation), which characterizes the echo of earthquakes at two or more depth levels; 2) mutual dependence of $M_S$, $H$ and $\mathrm{Cr}_N^{\mathrm{cat}}$, determining the type of predominant physical processes in a seismic focal zone: a dilatancy and a fracture healing under the tectonic pressure influence or a plastic flow under the temperature influence.

**Keywords:** catalogs and databases of the earthquakes, seismic-geodynamic process parameters, physical processes type in the seismic focal zone: a plastic flow or a brittle fracture.

## Introduction

The creepex (creep and explosion) parameter, determined by the ratio of the magnitudes $M_S$ and $m_b$, has been modified several times over 47 years of its existence [1–4] in order to increase its information content for identifying the plastic flow components in the focal mechanism, i.e. the creep, and brittle destruction, i.e. an explosion. However, the creepex value is a reflection of a complex set of processes in the earthquake focal zone and therefore does not only characterize the ratio of the contributions of the "hard" and "soft" components to the movement of an earthquake, but also carries some information about the geophysical environment both in an earthquake focal zone

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and in the volume covered with the seismic wave propagation routes. The magnitudes $M_S$ (or $m_B$) and $m_b$ formative the creepex for the same event are determined by different types of waves in different frequency ranges: $M_S$ — by the interference surface waves with a period of 20 s at distances of 20–160°; $m_b$ — by the volumetric longitudinal waves with a period in the range of 0.3–3 s at distances of 15–100°; $m_B$ — by the volumetric longitudinal and transverse waves with a period of up to 5 s, where $m_B$ is defined instead of $M_S$ for most deep events. This is known [3] about the statistically significant effect:

- on the creepex reduce: a high level of tectonic stresses in a seismic focal zone and the upthrust-downthrow component of the slip;
- on the creepex increase: a low level of tectonic stresses, predominance of a shift component of the slip, the high spreading rate, a large focal zone size and a relatively high temperature of a material.

In this study, in the environment of the GIS-ENDDB program [5], the data are prepared for studying seismic swarms: selection of the most informative catalogs (by the assessment of their completeness and representativeness), selection of tectonic regions and depth range, identification of seismic swarms in a seismicity map (if necessary, the statistical methods are used to identify the events grouping in time and distance [5]) and the calculation of the modified creepex parameter $\mathrm{Cr}_N^{\mathrm{cat}}$ [4] for the resulting earthquakes set. After that, the data for each swarm are studied according to the graphs of $\mathrm{Cr}_N^{\mathrm{cat}}(t)$ changes versus the $M_S(t)$ and $H(t)$ changes; the patterns of their joint dynamics are traced at different stages of the seismic source development, new factors are revealed that affect the creepex change. Among the patterns of change in $\mathrm{Cr}_N^{\mathrm{cat}}(t)$, $M_S(t)$, and $H(t)$ is the synchronicity of these graphs observed in a number of cases, i.e. a coincidence of the frequencies of their oscillations, both in-phase and anti-phase. Thus, dozens of swarms were investigated in the areas with different geotectonic settings, from which those were selected in which the described regularities of changes

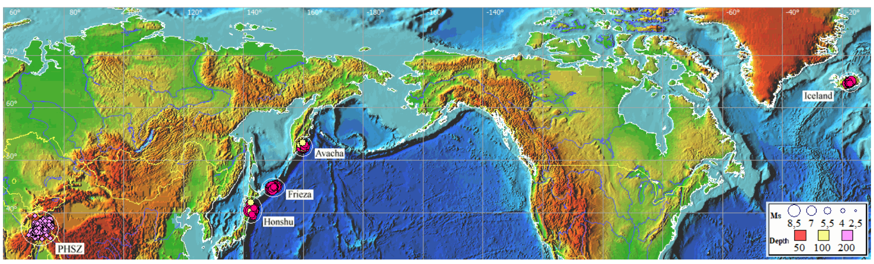


**Figure 1.** The location of the earthquakes swarms selected for the research in the GIS-ENDDB map

in the considered parameters are traced: in the Freeze Strait, near the island of Honshu, in the Avacha Bay of Kamchatka, under the Iceland island and in the Pamir-Hindu Kush seismic focal zone (Figure 1).

## 1. The characteristic of the data used

It is more efficient to analyze the distribution of earthquake characteristics within the framework of a single catalog [6], but sometimes the results obtained must be confirmed using data from other catalogs. Therefore, in this study, catalogs from several sources were used. First of all, this is the combined ISC global catalog [7], which contains the most complete information about various magnitudes: both their own definitions $M_S$ and $m_b$, and the definitions $M_S$ of various other agencies. But, for example, for the deep earthquakes of the Pamir–Hindu Kush seismic focal zone (PHSZ) with $H \geq 100$ km the ISC does not give its own $M_S$ definitions, and when investigating deep swarms, we use the ISC links to data on $M_S$ and $m_b$ of the agency IDC (The International Data Centre, Vienna International Centre, Austria), and for even deeper earthquakes with $H \geq 200$ km of the agencies GCMT (The Global CMT Project, Institute de Physique du Globe de Paris), MOS (Geophysical Survey of Russian Academy of Sciences) and IPGP (Institute de Physique du Globe de Paris). The sample obtained in this way is 1661 records for the period of 17.03.2000–27.05.2019.

In addition, a more representative CSN Catalog of the Chinese seismological network was used [8], which has its own $M_S$ and $m_b$ definitions for crustal earthquakes, and own $m_b$ and $m_B$ definitions for deep events ($H \geq 100$ km). For example, a sample of crustal events in the West Pacific subduction zone (−15–80°N; 140–180°E) is 542 records for the period of 01.01.1994–01.01.1996, and for deep events in the PHSZ area is the 984 records for the period of 05.01.2000–25.08.2017.

The use of different sources of catalogs and magnitudes is explained by the different representativeness of samples with paired magnitudes, which affects the reliability of the estimation of the creepex parameter. The calculation of errors according to the method described in [5] has shown, based on the samples used in this study, that for creepex estimate of large crustal earthquakes with $M_S \geq 7$ according to ISC, the statistical error $\delta \sim 1/\sqrt{n}$ (where $n$ is the number of events in the sample) exceeds 40 % (therefore, in this paper, the ISC catalog was not used to study crustal earthquakes), and according to CSN — $\delta \sim 28\,\%$ (moreover, $\delta = 6.7\,\%$ for $6 \leq M_S \leq 6.9$ and $\delta = 2.2\,\%$ for $5 \leq M_S \leq 5.9$). According to the samples of deep earthquakes of the PHSZ, where only one event occurred with $M_S \geq 7$, the statistical reliability of the ISC data is not high already since $M_S \geq 5$ and the error is according to IDC — 30% (moreover, $\delta = 7.4\,\%$ for $4 \leq M_S \leq 4.9$ and $\delta = 3\,\%$ for $3 \leq M_S \leq 3.9$), while according to CSN (for $m_B \geq 5$) — 9.6 %. In other catalogs, we use only single determinations of the magnitude $M_S$. Thus, the most reliable information on the destruction nature in the area of earthquake swarms (with a satisfactory error of quantitative estimates: $\leq 10\,\%$) can be obtained from the time behavior of the creepex of the crustal events with $M_S \leq 6.9$ according to the CSN catalog and deep-seated with $M_S \leq 5.6$ according to the IDC catalog, those belonging to the magnitude ranges with a statistically sufficient sample size (one hundred or more events).

## 2. Regularities of parameters changing for earthquake swarms

In the papers [6, 9], the regularities of changes in the parameters of magnitude, depth, and creepex in aftershock sequences caused by the largest earthquakes in the areas of plate convergence were revealed. The temporal distribution of the aftershocks $M_S(t)$ clearly manifests the process of relaxation of the seismic source in the first hours after the main shock by partial, periodic chains of events. The behavior of $\mathrm{Cr}_N^{\mathrm{cat}}(t)$ in the overwhelming majority of examples, at the moment of the main shock demonstrates a positive jump of creepex (less often — zero, i.e., the background value of creepex), which can characterize a greater contribution of quasi-plastic motion to the mechanism of the main shock (and sometimes of several subsequent shocks). After that the first hours (sometimes the first days) there is a dynamics of a creepex within the values of 0–0.3 or sign-alternating dynamics with a positive trend (presumably, partial dilatancy), then a gradual or sign-alternating decline with a negative trend (from several days to several months), characterizing the transition of the environment to brittle destruction.

It is interesting that a comparison of the graphs $\mathrm{Cr}_N^{\mathrm{cat}}(t)$ and $H(t)$ for the aftershock swarms of large earthquakes shows that often, positive jumps of a creepex among aftershocks (or the moment of the main shock, regardless of the magnitude of its creepex) correspond to depth jumps or are associated with an increase in the depths of the preceding shocks. Physically, this can be explained by the effect on these shocks or on the process of their preparation from the deep thermodynamic processes that increase the temperature of the environment $T$ with depth and in this case affect the type of influence on the seismic source and on the final value of the creepex due to the $T$-factor.

An explanation for the cases of a positive jump of the creepex at the moment of the main shock in the absence of its connection with depth can be the process of dilatancy [10, 11], i.e., the destruction of rocks in the focal zone and their transformation to a finely dispersed (free-flowing) state with a high absorption of high-frequency seismic waves, as a result of which seismic radiation at the exit from the focal zone is depleted in the high-frequency component. The same model (but in the form of destruction of individual brittle partialities of the focal zone and their transfer to a finely dispersed state, consolidating adjacent rock areas [11]) well explains the sign-alternating behavior and positive trend of creepex in the beginning of the aftershock swarm. Subsequently, the geophysical environment can heal, due to the fluids, the pressure $P$ and the temperature (for example, calcium, magnesium and iron chlorides cement free-flowing silicates several days until the monolithic state of the rock [12]). Healing will be accompanied by the emergence of the new internal stresses (for example, due to the crystallization pressure), and a smooth negative trend in the creepex value will be observed in the seismic source for several days or months [6].

The listed patterns refer to the aftershock sequences, which have their own specifics: the largest earthquake is the first one (before it, weak events in the future focal zone are either absent or are separated in time by weeks, sometimes by months) and has the most significant effect on the environment. In this paper, we study swarms that are organized in another way: large shocks occur among many weak events in a certain local zone of the Earth's crust and may not have a pronounced main event of the senior energy class. In such swarms, on the background of an increased frequency of events, there is no decay of the event energy in time, which is characteristic of the aftershock sequences [13]. We will consider the properties of earthquake swarms, both shallow (in the zones of plate divergence and spreading) and deep-focus (by the example of PHSZ).

The swarm near the Freeze Strait 03.12.1995 is located in the divergence zone of the oceanic and continental plates and is unique in that after its largest earthquake (of $M_S = 7.5$) within 22 minutes, six larger earthquakes occur, four of which of $M_S = 7.0$–$7.2$. A specific of this fragment is its relatively large depth: 29–40 km, as well as the clear phase correlation of periodically varying magnitudes and depths (which indicates to the state of an earthquake roll-call) and their inverse correlation with the creepex

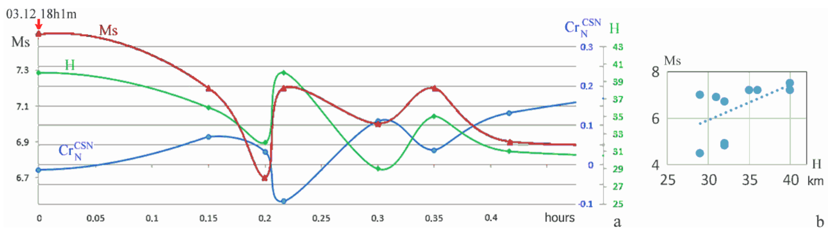


**Figure 2.** a) The dynamics of the parameters $H$, $M_S$ and $\mathrm{Cr}_N^{\mathrm{CSN}}$ of a half-hour fragment of the seismogeodynamic process in the focal zone of the earthquake swarm near the Fries Strait (03.12.1995, $M_S = 7.5$, 6.7–7.2): black color is $M_S(t)$, green is $H(t)$, blue is $\mathrm{Cr}_N^{\mathrm{CSN}}(t)$. Zero time-point shows the strongest event of the swarm 03.12.1995, 18h 1m, $M_S = 7.5$. b) The dependence $M_S(H)$ of the events over the interval from $-3.6$ hours to 0.77 hours

**Table 1.** The earthquakes parameters $H$, $M_S$ and $\mathrm{Cr}_N^{\mathrm{CSN}}$ of a swarm fragment near the Fries Strait until the strongest shock 03.12.1995 18:01 ($M_S = 7.5$)

| Date, h:min | Hours | $\mathrm{Cr}_N^{\mathrm{CSN}}$ | $M_S$ | $H$, km |
|---|---|---|---|---|
| 02.12, 22:00 | −19.4 | 0.01440 | 4.4 | 31 |
| 02.12, 23:00 | −19.0 | −0.05631 | 5.1 | 32 |
| 02.12, 24:00 | −17.7 | 0.09119 | 4.7 | 31 |
| 03.12, 01:00 | −16.9 | −0.00066 | 4.6 | 33 |
| 03.12, 09.00 | −8.5 | 0.02306 | 4.8 | 32 |
| 03.12, 12.00 | −5.4 | 0.03477 | 4.9 | 32 |
| 03.12, 14.00 | −3.6 | 0.02672 | 4.5 | 29 |
| 03.12, 18:01 | 0 | −0.01318 | 7.5 | 40 |
| 03.12, 18:10 | 0.15 | 0.07104 | 7.2 | 36 |

(Figure 2a). The inverse correlation between the dynamics of the creepex and depth can be explained by the predominant influence on the value of the creepex of the above-described (for aftershock swarms) effect of dilatancy, which decreases with depth due to the tectonic pressure of the overlying rocks ($P$-factor).

Let us note that the correlation of the graphs $M_S(t)$ and $H(t)$ (Table 1) starts 8.5 hours before the strongest event of the swarm ($M_S = 7.5$), and the inverse correlation of the graph $\mathrm{Cr}_N^{\mathrm{CSN}}(t)$ with them is 3.6 hours before this event, and these patterns ends at a point of 0.77 hours after it, which may indicate to the preceding strongest shock state of the weak earthquakes roll-call (of $M_S = 4.5$–$4.9$) at depth levels of 29–32 km, which has caused a shock of $M_S = 7.5$ at a greater depth ($H = 40$ km) and then a roll-call of stronger swarm earthquakes at depths of 29–40 km. Figure 2b shows a directly proportional relationship $M_S(H)$ for synchronous events of the interval from $-3.6$ hours to 0.77 hours, which are grouped at three depth levels: $30 \pm 2$, $35 \pm 1$, and 40 km.

In general in swarms, in contrast to aftershock sequences, such a uniform periodicity of the parameters $M_S$, $H$ and $\mathrm{Cr}_N^{\mathrm{cat}}$ change in time is not often observed (in this swarm, it is also traced only in a short-term cluster of events, characterized by the increased frequency and energy), but for alternating-periodic oscillations similar to the shown here inverse correlation in phase of the graphs $H(t)$ and $\mathrm{Cr}_N^{\mathrm{cat}}(t)$ is often observed, demonstrating the establishment of an organized state of the environment with a strictly deterministic effect of depth parameters on a creepex.

For example, for a swarm of earthquakes near the island of Honshu (08.04–31.12.1994), the inverse correlation of $H(t)$ and $\mathrm{Cr}_N^{\mathrm{cat}}(t)$ traced throughout the whole swarm (except for individual events), starting from the second event after the first shock of the swarm (08.04.1994, $M_S = 6.8$) (Table 2), continuing on very rare events for 268 days at depths of 31–53 km

**Table 2.** The earthquakes parameters $H$, $M_S$ and $\mathrm{Cr}_N^{\mathrm{CSN}}$ of a swarm fragment near Honshu Island (08.04–28.12.1994) until the strongest shock 28.12.1994 12:00, $M_S = 7.9$

| Date, h | Hours | $\mathrm{Cr}_N^{\mathrm{CSN}}$ | $M_S$ | $H$, km |
|---|---|---|---|---|
| 08.04, 01 | −268.5 | −0.02185 | 6.8 | 13 |
| 08.04, 14 | −267.9 | 0.07436 | 4.9 | 36 |
| 23.04, 19 | −252.7 | 0.00185 | 4.3 | 49 |
| 30.07, 21 | −152.6 | 0.00185 | 4.3 | 53 |
| 14.08, 09 | −138.1 | −0.03504 | 5.6 | 44 |
| 18.09, 16 | −102.8 | 0.09119 | 4.7 | 31 |
| 10.12, 09 | −18.1 | −0.07730 | 4.6 | 47 |
| 28.12, 12 | 0 | −0.01326 | 7.3 | 25 |

until the strongest shock 28.12.1994 ($M_S = 7.9$, $H = 25$ km) and ending 4.5 days after it. The dynamics correlation of the parameters $H(t)$ and $M_S(t)$ is inverse here (Figure 3) and lasts 268 days, including the strongest shock. Then, from the next event after the strongest shock, a short fragment of the direct correlation of the graphs $M_S(t)$ and $H(t)$ appears with the continuing inverse correlation of the depth with the creepex, which is completely similar to the previous example, and continues for 0.35 days after it (i.e. $\sim 8$ hours), ending 1 hour 40 minutes before the next large shock happened at a much shallower depth ($M_S = 6.6$, $H = 10$ km). This indicates that, under conditions $P$-factor, the phase correlation between the oscillations $H(t)$ and $M_S(t)$, associated with the earthquakes depth roll-call, can be both direct and reverse. On the example of the swarm near Honshu Island, we observe both types of the correlation, i.e. two modes of the earthquake roll-call.

The type of the correlation of the graphs $H(t)$ and $M_S(t)$ is determined by the circumstance at which the depth level the strongest earthquake of the roll-call occurs: at the upper or at the lower one. In addition to the example of a swarm near the island of Honshu, the inverse correlation of the graphs $H(t)$ and $M_S(t)$ can be traced, for example, on the first day of

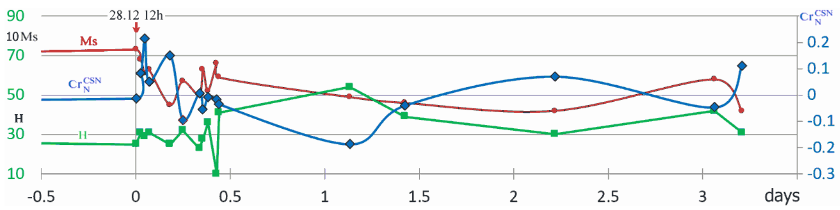


**Figure 3.** The dynamics of the parameters $H$, $M_S$ and $\mathrm{Cr}_N^{\mathrm{CSN}}$ of a 3.2-days fragment of an earthquake swarm near Honshu Island (28–31.12.1994). The scale for $H$ and $10M_S$ is on the left and the scale for $\mathrm{Cr}_N^{\mathrm{CSN}}$ is on the right. Zero timepoint shows the strongest event of the swarm 28.12.1994 ($M_S = 7.9$)

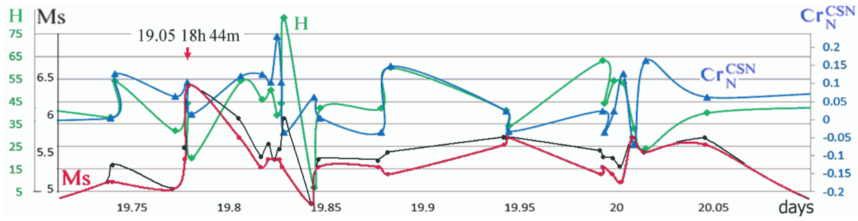


**Figure 4.** The dynamics of the parameters $H$, $M_S$ and $\mathrm{Cr}_N^{\mathrm{CSN}}$ of 6-hour fragment of the earthquake swarm 19–22.05.2013 in the Avacha Bay of Kamchatka Peninsula. The scale for $H$ and $M_S$ is on the left and the scale for $\mathrm{Cr}_N^{\mathrm{CSN}}$ is on the right. The gray line is the dynamics of $M_S$ after introducing corrections for depth. Zero time-point shows the strongest event of the swarm 19.05.2013 18:44, $M_S = 6.4$

the swarm on May 19–22, 2013 in Avacha Bay on the Kamchatka Peninsula (Figure 4). Since the first strong event of the Avacha swarm occurred at the upper level of the depths (in contrast to the swarm of the Freeze Strait, where it occurred at the lower, deeper level, see Figure 2), the dependence $M_S(H)$ in the Kamchatka swarm is inversely proportional. In addition to the pronounced roll-call of its earthquakes, the Kamchatka swarm demonstrates the establishment of an organized state of the environment, characterized by the interrelation of the depth and the creepex, but with the other relationship between their dynamics (see Figure 4). The short-term (0.25 days from 17:44 19.05 to 0:05 20.05) direct correlation of $H(t)$ with $\mathrm{Cr}_N^{\mathrm{cat}}(t)$ (with the exception of one $H$-transition to the level of 83 km and three weak events before and after it), probably, indicates to the predominant influence of temperatures increasing with depth on the increase in the creepex, i.e. of the $T$-factor (see Figure 4). In the same fragment, the inverse correlation $H(t)$ with magnitude characterizing the roll-call is observed (except for the above-noted events of $H$-transition). After this fragment, throughout the 4-day Avacha swarm and after it, a similar type of correlation between the parameters $H$, $M_S$ and $\mathrm{Cr}_N^{\mathrm{cat}}$ are observed in this focal zone only occasionally, for a small number of events (for example, for six rare events that occurred from May 24 to 28, 2013, $H = 17$–$39$ km). It is interesting that according to the first three events of the Avacha swarm ($M_S = 5$–$5.4$), happened an hour before its strongest event (19.05.2013 18:44, $M_S = 6.4$, $H = 20$ km), there is a direct correlation of all the three parameters: $H$, $M_S$ and $\mathrm{Cr}_N^{\mathrm{cat}}$, which suggests that this shock (and the entire subsequent swarm) is preceded by a roll-call of deep seismically activity (at depth levels $H = 32$–$54$ km), activated a stronger response with $M_S = 6.4$ in the upper layers of the Earth's crust ($H = 20$ km). This correlation is especially noticeable after the introduction into the value $M_S$ of the corrections for the depth according to [14]. A synchronous with $H$ and $M_S$ change in the creepex may indicate to the predominant influence on the physics of these events of the $T$-factor as well.

It can be assumed that the phase-synchronous periodicity of the parameters $H$, $M_S$ and $\mathrm{Cr}_N^{\mathrm{cat}}$ before the largest events of earthquake swarms is a characteristic sign of such type of the environment organized state (a roll-call of stronger and deeper earthquakes with weaker and shallow ones, the $T$-factor of the depth effect on the creepex), which is a condition conducive to the occurrence of stronger earthquakes in the swarm.

Unfortunately, such a synchronicity is not often observed in seismicity related to the Earth's crust in divergence zones of the oceanic and continental plates. It was noted only in the seismic swarm activity, and has not been yet identified before large individual seismic shocks accompanied by an aftershock sequence. Let us consider whether such a synchronicity is observed in deep seismic focal zones in the divergence areas of the continental plates, as well as in spreading zones.

In general, the swarm seismicity in the "hot" spreading zones, in contrast to the convergence zones, is characterized by a positive creepex trend over long time intervals (up to several months). So, the vast majority of the earthquakes swarm of 2.10.2014–13.01.2015 on the island of Iceland ($M_S = 4.6$–$5.6$) according to the CSN data is characterized by positive creepex values, and its dynamics correlates with the dynamics of the earthquake magnitude (except for some of the most abrupt $H$-transitions). At the same time, the dynamics of the creepex has a positive trend (Figure 5a), and the depth changes in a very small range ($H = 3$–$11$ km) in contrast to the examples considered above in the areas of convergence, where the events of each focal zone are characterized by a large scatter of magnitudes and depths. The Icelandic swarm shows a direct proportional dependence of the creepex on magnitude $\mathrm{Cr}_N^{\mathrm{CSN}}(M_S)$ (Figure 5b, on the top) and inversely proportional one on depth $\mathrm{Cr}_N^{\mathrm{CSN}}(H)$ (Figure 5b, on the bottom). The dependence of the magnitude on the depth has not been established. The direct proportional relationship of the creepex with magnitude (and positive trends in the creepex and magnitude changes for the swarm) can be explained by the growing heterogeneity of the medium simultaneously with an increase in the size of a focal zone of stronger shocks, which is apparently a characteristic of the seismicity in the spreading zone caused by the arrival of a new deep material and non-uniformity of its component phase transitions. An increase in the creepex with a decrease in depth (and a negative trend in the swarm depths dynamics) can be explained by the transition of seismic activity to the upper layers of the crust, characterized by an increase in the effect of dilatancy (weakened with depth due to an instant restoration of the rock strength: $P$-factor), which is similar to the explanation given above for an increase in the creepex for earthquakes of the upper level of depths in the Freeze Strait (i.e. in the plate convergence zone), which indicates to the fundamental similarity of the processes in a seismic source, independent of the focal mechanism and the type of tectonic setting. This physical model

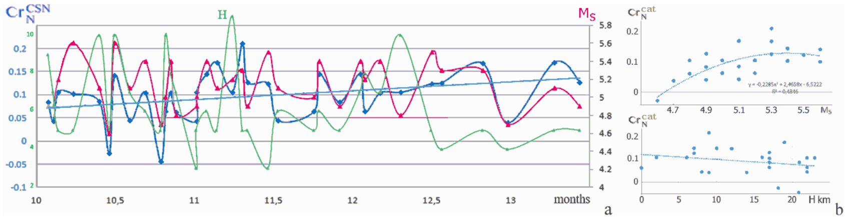

**Figure 5.** The dynamics of the parameters $H$, $M_S$ and $\mathrm{Cr}_N^{\mathrm{CSN}}$ of 3.5-month swarm of earthquakes on 2.10.2014–13.01.2015. The scale for $\mathrm{Cr}_N^{\mathrm{CSN}}$ and $H$ is on the left and the scale of $M_S$ is on the right. $M_S = 4.6$–$5.6$ and $H = 3$–$11$ km under the Iceland (a), as well as $\mathrm{Cr}_N^{\mathrm{cat}}(M_S)$ and $\mathrm{Cr}_N^{\mathrm{cat}}(H)$ dependence trends (b)

indicates to an increase in the contribution to the earthquake at a greater depth of a rigid fracture of a larger scale due to a more strength state of the medium.

Another important feature of the Icelandic swarm is a 1-month direct correlation of all the three parameters: $H$, $M_S$ and $\mathrm{Cr}_N^{\mathrm{cat}}$ at the end of the swarm (see Figure 5a), which we explain by the predominant influence on the creepex of the $T$-factor associated with the transition of the seismic process to the upper depth level of 4–5 km, characterized by a large temperature gradient with a colder brittle fracture at shallower depths. Thus, by the end of the swarm activity, the properties of the medium change, and the resulting synchronization of all the three of its parameters at a small depth range leads to the cessation of the seismic swarm activity. Let us note that the same synchronization of a change in the values of the three parameters (but with a wide spread of depths of 5–10 km) is present in Figure 5a before the second strongest earthquake of the swarm (located at 10.48 months): 15.10.2014 ($M_S = 5.6$, $H = 10$ km) within 14 hours before it, which like in the conditions of the plate divergence (for the Avacha swarm, see Figure 4) acts as a similar prognostic sign for a strong shock under conditions of spreading.

In conclusion, let us consider whether the synchronous behavior of the parameters of interest to us $H$, $M_S$ and $\mathrm{Cr}_N^{\mathrm{cat}}$ is typical before the largest earthquakes in deep swarms localized in narrow seismic focal zones.

When calculating the $\mathrm{Cr}_N^{\mathrm{cat}}$ on a sample of events with $H \geq 100$ km of the ISC Catalog (with reference to the IDC) for a 500-kilometer circular neighborhood of the Pamir–Hindu Kush seismic focal zone (PHSZ), attention is drawn to the branching of the $\mathrm{Cr}_N(M_S)$ graph, which, apparently, characterizes the presence of two different processes that cause deep earthquakes of the PHSZ (Figure 6a). This branching can be seen in the $\mathrm{Cr}_N(m_B)$ dependence graph according to a more representative Chinese Catalog CSN (red dots in Figure 6a). Since the polygonal trend of this distribution should be used to find the $\mathrm{Cr}_N^{\mathrm{cat}}$ [4], and the largest earthquake of PHSZ: 26.10.15

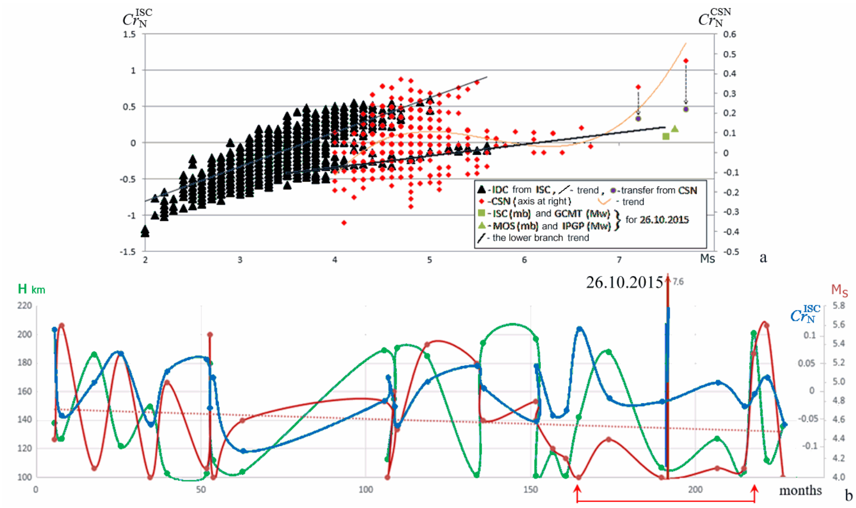


**Figure 6.** Distribution of the parameters of deep earthquakes at $H \geq 100$ km for 2000–2018 in the Pamir–Hindu Kush seismic focal zone: a) a comparison of the dependencies $\mathrm{Cr}_N(M_S)$ on a sample of the IDC Catalog (ISC) and $\mathrm{Cr}_N(m_B)$ on a sample of the CSN Catalog with adding the event of 26.10.2015, $M_S = 7.6$, $H = 206$ km; b) the dynamics of the parameters $H$, $M_S$ and $\mathrm{Cr}_N^{\mathrm{ISC}}$ of events of the lower "branch" of the previous graph. The arrows mark the interval of the parameters the graphs synchronization

($M_S = 7.5$, $H = 207$ km) lies on the lower branch of the graph (green dots in Figure 6a), then the events of the lower branch were selected from the whole set to plot its separate trend.

In [15], general properties of the parameters dynamics of deep earthquakes with $H \geq 100$ km in subduction zones of the South Asian region are noted: mainly the negative values of the creepex; the time stretching of the dynamics of parameters $H$, $M_S$ and $\mathrm{Cr}_N^{\mathrm{cat}}$, similar to the ones of the crustal earthquakes, in particular, for relaxation processes in the seismic source (if for the crustal events are days, then for the deep ones are months; if for the crustal events are months, then for the deep ones are years). In addition to these general properties of deep-seated processes, we present Figure 6b, which reveals the features for the events of the PHSZ belonging to the lower branch of Feagure 6a, i.e. having underestimated creepex values, like as for the deep earthquakes of subduction zones:

1. Very rare events (occurring with an interval of 1 to 43 months);
2. The graphs $M_S(t)$ and $H(t)$ are asynchronous with respect to each other except for the interval from 26 months before the strongest event (26.10.15) up to 28 months after it;

3. The graph $\mathrm{Cr}_N^{\mathrm{IDC}}(t)$ becomes synchronous with respect to the graphs $M_S(t)$ and $H(t)$ 11 days before the main shock and then during 29 months with the negative creepex of a greater fragility of shallower and weaker earthquakes.

Unlike the subduction zones, there are few strong events in the PHSZ, and for an accurate assessment of $\mathrm{Cr}_N^{\mathrm{cat}}$ of the strongest PHSZ event (26.10.15), as is shown above, there are statistically insufficient events in the IDC primary source Catalog with $M_S \geq 5$. However, a change in time of the creepex of events with $M_S \leq 4.9$, it is this magnitude range in which the events of the synchronous part in Figure 6b belong to: $M_S = 4$–$4.4$ thus became providing a sufficiently reliable information with an error $\leq 8\,\%$.

Thus, in the deep seismic focal zones, we observe the same synchronous oscillatory dynamics of the parameters $H$, $M_S$ and $\mathrm{Cr}_N^{\mathrm{cat}}$, but more extended in time, which is probably associated with the earthquakes roll-call by depth levels, and characterizes (as in the crustal swarm seismicity) the state of the medium favorable for the preparation of a strong earthquake.

## Conclusion

The method for calculating the normalized creepex $\mathrm{Cr}_N$ implemented in the GIS-ENDDB geographic information system and its statistical modification $\mathrm{Cr}_N^{\mathrm{cat}}$ allows us to use the latter in a complex geodynamic analysis, identifying by change of the $\mathrm{Cr}_N^{\mathrm{cat}}$ in time the physically substantiated regularities of seismogenesis processes in the seismic focal zones characterized by swarm sequences. At the same time, a value of a creepex is determined by the development of the thermoactivation mechanism for overcoming the ultimate strength of a medium in different-scale structural units of the focus: a negative creepex when covering all the scales of a brittle fracture; a positive creepex predominantly multiple small-scale breaking bonds in a solid.

Examples of this mechanism used in the geodynamic studies of specific focal zones, given in the paper, suggest that most swarm processes are the brittle destructions, overcoming the ultimate strength as a result of the action of physical conditions that change in time and lead to different ratios of the contribution of viscous-plastic and rigid slidings to the destruction mechanism. In particular, these can be conditions of a strictly deterministic influence of depth parameters on a creepex, expressed in the proportional ratio of creepex and depth or in the correlation of $H(t)$ and $\mathrm{Cr}_N^{\mathrm{cat}}(t)$ graphs. Depending on the type of correlation (direct or inverse), these can be the effects of factors also related to depth: the temperature $T$ or the pressure $P$.

It has also been shown that the seismic activity in a focal zone is often predetermined by the correlation of the graphs of changes in time for all the three parameters: magnitude, depth, and creepex ($M_S$, $H$, $\mathrm{Cr}_N^{\mathrm{cat}}$). Such an analytical connectivity, apparently, is a consequence of the establishment of an organized state of the medium in an earthquake source. In particular, such an organized state of the medium may be evidenced by the earthquakes roll-call observed in the swarm sequences at two or more depth levels. This organization is expressed in synchronous (with direct or inverse phase correlation) dynamics of the parameters $M_S$ and $H$, as well as in their direct or inverse correlation with $\mathrm{Cr}_N^{\mathrm{cat}}$, which characterizes the type of predominant physical processes in a focal zone. For example, it is possible that the directly proportional synchronicity of a change in the parameters $H$, $M_S$ and $\mathrm{Cr}_N^{\mathrm{cat}}$ characterizes the state of a medium favorable for the completion of the strong earthquake preparation in the seismically active focal zone.

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