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On the possible relationship between remote seismic activations and strong earthquakes in southeast regions of Eurasia and adjacent seismic focal zones*

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Abstract. Using the example of the 14 largest earthquakes ($M_S \geq 7.9$) in area: -30–$50°N$, 78–$180°E$, the possible geodynamic interconnectedness of the processes of focus preparation with a preliminary moderate seismic activation in the subduction or collision zones crossing the areas of a future earthquake preparation remote from the focus is considered. Using the methods of the GIS-ENDDB software system (the selection of the circular area of influence of the seismic source preparation zone, the clustering of the event sample, the calculation of the normalized creepex and of the coefficient of its pair correlation with magnitude), the largest events of the Chinese global catalog CSN for 1999–2017 in areas under consideration were studied. Signs of such interconnectedness have been detected, what can serve as strong evidence in favor of the concept of the environment plasticity exhaustion in the preparation zone as a sign of transition to fragile destruction in the future focus.

Keywords: catalogs of earthquakes, parameters of the seismic geodynamic process, tectonic conditions, seismic activation systems, strong earthquakes, creepex

1. Introduction

In accordance with the "planetary-regional model" [1] of tectonic earthquake preparation, the cases of remote foreshock activation observed in nature may indicate a single geodynamic process on a regional scale preceding a major earthquake" [1, 2] and "preparatory deformation processes may occur at a distance of tens and hundreds of kilometers from the future seismic focus" [3]. Well-known models of seismic generation associate the deformation processes of the lithosphere with the dynamics of multi-scale faults: those that are forming ("avalanche unstable fracture formation" model AUF [4]) or those that already exist (model "stick-slip" [5]). At the same time, within the framework of seismic prognostic studies, much attention is paid to the migration of seismic activity in the areas of dynamic influence of these faults, as well as to the trigger mechanisms of seismicity [5].

For example, "there are cases when aftershocks occur far enough from the rupture plane of the main earthquake" [6], which by analogy suggests

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the possibility of a triggering effect on the preparation of a strong shock from remote regional or global deep faults. From the point of view of crack theory, such an influence can be explained by the localization of anomalies of increased stresses caused by the activity of a global rupture, not only near the vertices of the crack, but also "on each side of the crack at a distance of the order of its size" [6].

Estimates of the diameter of the zone of influence on the focus preparation area, based on solving the tasks of elasticity theory [7], give the value l_0, which is an about one and a half order larger than the size of the focal zone l (in the elastic-plastic deformation model [8] this influence extends over much longer distances).

In this paper, using the example of the largest $M_S \geq 7.9$ earthquakes in area: -30–$50°N$, 78–$180°E$, covering the southeast regions of Eurasia and adjacent seismic focal zones, let us consider how common are the cases of their pre-occurrence by moderate seismic activation along convergent deep faults (and cracks of lesser rank crossing them), remote to a distance of l_0 from a future earthquake. The size l of the events focus of energy classes $K = 16.7$–17.8 (corresponding to the considered magnitudes $M_S = 7.9$–8.9) is estimated as 79–185 km according to the formula [6, p. 55]:

$$l\ (\mathrm{km}) = 10^{\frac{\lg E\,(\mathrm{Joul})-11}{3}} = 10^{\frac{K-11}{3}}.$$

Consequently, one and a half orders larger area of influence of the focus preparation zone l_0 will be equal to 708–2512 km for them, respectively.

In continuation of the work started in [9], studies of moderate seismicity in remote fault zones (which are anomalous, foreign inclusions in the extended (of radius l_0) area of influence on the strong earthquake preparation) are being conducted as a preparatory process of the gradual exhaustion of plasticity, anticipating brittle fracture in the focus [9, 10].

2. Methods and materials

The study was conducted by means of the GIS-ENDDB [11] geographic information system using data from the CSN regional catalog [12] containing the parameters of 58931 earthquakes worldwide for the period from 26.07.1999 to 31.08.2017 with magnitudes M_S and m_b. The ratio of these magnitudes is used to estimate the creepex parameter, which shows the relative contribution of "soft" and "hard" movements (plastic or brittle component) to the process of focal radiation. The algorithm used in GIS-ENDDB for calculating the normalized creepex Cr_0^{cat} is described in detail, for example, in [13]. As a result of the use of the $\mathrm{Cr}_0^{\mathrm{cat}}$ parameter in seismic and geodynamic studies of various regions [14, 15], it was empirically established that 30 % of the world's strongest ($M_S \geq 8$) earthquakes are characterized by a high correlation in time of the $\mathrm{Cr}_0^{\mathrm{cat}}$ and M_S parameters (i.e., by their synchronous or antiphrasis dynamics) of accompanying moderate seismicity lasting a month or more before and after the main event. Moreover, direct correlation (synchronicity) is characteristic of rift zones (geodynamic stretching mode), and reverse (antiphase dynamics) is characteristic of subduction zones (compression mode), i.e., the stress-strain state of the geophysical environment of the studied seismic geodynamic regions can be estimated by the sign of the correlation of the creepex and magnitude. On the other hand, according to [16], a statistically significant influence on the creepex value of the general tectonic situation was established: the predominance of the plastic component of the movements in conditions of spreading and brittle fracture — in conditions of high tectonic stresses in the environment. Thus, according to the value of the coefficient of paired correlation of magnitude and creepex K_{cor}, estimated from N chronologically consecutive events (in a sliding time window), we can talk about the average medium plasticity of the period of seismicity covered by them. It is proposed to identify periods of increased plasticity according to the following scale: periods of weak plasticity — at $0 \le K_{\text{cor}} < 0.2$, moderate — $0.2 \le K_{\text{cor}} < 0.4$, high — $0.4 \le K_{\text{cor}} < 0.8$ and maximum — $K_{\text{cor}} \ge 0.8$.

In this work, the following number of GIS-ENDDB methods are used [11]: 1) selection on the map of a circular area with a diameter of $2 \cdot l_0$ km around the strongest ($M_S \ge 7.9$) earthquakes in the region under consideration in 1999–2017, 2) calculation in the circular area of each strongest earthquake of the time distribution graph of the creepex-magnitude correlation $K_{\text{cor}}(t)$ (the K_{cor} calculation method is used "with a fixed sliding time window size" equal to N points [14]) of moderate seismicity $M_S \ge 4 \sim 2$ months before the main shock and identification on the graph of periods of increased plasticity of the medium, 3) the method of clusters calculating [17] to display on the map the chronological sequences of events connected in pairs by directional segments in accordance with the specified parameters dT and dS (maximum time and distance differences in each pair of events; here $dT = 60$ days and $dS = 5000$ km).

3. Results

Of the five strongest ones ($M_S \ge 7.9$) studied in [9] earthquakes of the region under consideration in 2011–2017, the Great East Japanese earthquake (Tohoku) 11.3.2011, $M_S = 8.7$ was the first described. When examining a sample of moderate seismicity preceding it in a circular area (181 events with $M_S \ge 4$ in 2 months at a distance of up to $l_0 = 1927$ km from it), the stages of the preparation process for this mega-earthquake are clearly manifested (Figure 1a):

- in the period 11.2.2011–27.2.2011, the regime of partial, periodic earthquake chains is observed with spatial grouping (white connecting lines), centrally oriented to the local area 26–27.5°N, 143–144.5°E in ∼ 1200 km south of the Tohoku focus and the longest (up to 3000 km) “rays” of the NW and NE direction;

- in the period 28.2.2011–8.3.2011, the dynamics of earthquake distribution changes sharply: their frequency drops by 1.5 times, the creepex increases, and the spatial distribution, despite the large spread (up to 2500 km), becomes symmetrical (yellow lines in Figure 1a) relative to the future focus (marked on the map by the area of lines concentration of a pink color);
- in the 3-day period of the foreshock activity of the Tohoku focus: 9.3.2011–11.3.2011, firstly, the frequency of earthquakes is sharply increasing (on March 9 and 10 — by 16 times, starting with its largest foreshock: 9.3.2011, $M_S = 7.6$, and on 11 March — by 80 times), secondly, the localization of events is limited to the 400-kilometer neighborhood of the northern part of Honshu Island (pink lines) with only one 1300-kilometer “outburst” towards the central part of the Kuril Ridge — to the earthquake of 11.3.2011, $M_S = 4.5$, an hour before the Tohoku event (Figure 1a).

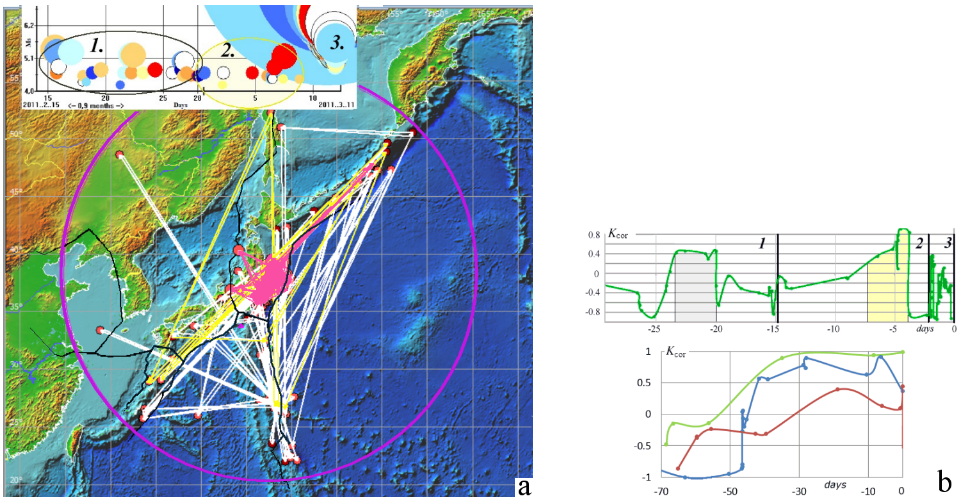

Figure 1. A map of the distribution of moderate seismicity events in the l_0-neighborhood (shown by a lilac circle) of the Tohoku earthquake (a), the inset at the top is the graph $M_S(t)$, the boundaries of microplates are shown in black; graphs $K_{\text{cor}}(t)$ (sliding calculation window of $N = 5$ points) of seismicity (b) in the l_0-neighborhood of the Tohoku earthquakes, a total of 161 points on the graph , 123 of them in periods 1 and 2 (above) and of the earthquakes near Solomon Islands (below): 1.04.2007, $M_S = 7.9$: 22 points (blue), 7.10.2009, $M_S = 7.9$: 11 points (red), and 12.04.2014, $M_S = 7.9$: 6 points (green)

It should be noted that the Tohoku earthquake focus is not located on the interplate fault (it occupies the entire area of the southern protrusion of the Okhotsk microplate), unlike the center of grouping of events preceding it (1st stage). At the same time, within the 1st and 2nd stages, periods of positive anomalies are highlighted on the $K_{\text{cor}}(t)$ graph (filled in gray and yellow in Figure 1) corresponding to the high and maximum plasticity regime at intervals of 4–7 days and 20–23 days before the Tohoku event. The maximum of the Graph falls on 5 events on 6.03.2011 in the same grouping center (1st stage). In general, the seismicity of plasticity periods belongs to: within the 1st stage — the local swarm south of Tohoku and the interplate boundary along Japan and the Kuril Islands, and within the 2nd stage — the same local swarm and the most far southern and northern events of the stage (yellow sequence in Figure 2a), i.e., it is structured along the nearest interplate faults. This example demonstrates that the process of exhaustion of plasticity, preceding a major earthquake, results in the organized state of the environment is established, completing by an abrupt increase in its consolidation (a sharp drop in the values of the $K_{\text{cor}}(t)$ graph at the end of 2nd stage) and then destroying by a major earthquake (or, in this case, by its foreshock of 9.3.2011) with the transition to “chaoticization of the seismic radiation regime” [6, p. 112] (instability of the graph at 3rd stage).

According to the following strongest CSN catalog events considered in [9] (see summary Table 1), the $K_{\text{cor}}(t)$ graphs of seismicity of their l_0-neighborhoods show periods of moderate and maximum plasticity beginning: for 11.4.2012 ($M_S = 8.6$, near the Sunda thrust off Sumatra Island) $\sim$ 6 days before the event, for 12.04.2014 ($M_S = 7.9$, near the Solomon Islands) $\sim$ 35 days (Figure 1b) and 25.04.2015 ($M_S = 8.2$, in the Himalayan collision zone) $\sim$ 18 days before the event (Figure 3b). In the vicinity of $l_0 = 708$ km there are only two events preceding the earthquake 2.03.2016 ($M_S = 7.9$, near Sumatra Island): 13.01.2016 ($M_S = 4.6$) and 16.01.2016 ($M_S = 4.5$, $H = 54$ km), however, only the first of them manifests itself by a high plasticity degree ($K_{\text{cor}} = 0.93$) together with the preceding event 5.01.2016 ($M_S = 4.1$, $H = 64$ km, $K_{\text{cor}} = 0.92$). And in the extended 2000-km neighborhood of this earthquake [9], moderate preliminary seismicity (32 events with $M_S \geq 4$), revealed the property of high plasticity in the period 60–49 days before the event.

Let us consider the behavior of the K_{cor} graphs for the remaining nine strongest earthquakes ($M_S \geq 7.9$) of CSN catalog in the region under consideration, which occurred from 1999 to 2010.

The first two are 4.06.2000 ($M_S = 7.9$) and 18.06.2000 ($M_S = 8$) occurred at a distance of $\sim$ 1100 km from each other (see Figure 2a). On the eve of the first of them, only two events have a positive K_{cor} value (see Figure 2c): 12.04.2000 ($M_S = 4.6$, $K_{\text{cor}} = 0.12$) and 8.05.2000 ($M_S = 5.3$, $K_{\text{cor}} = 0.15$), localized (the sequence is white in Figure 2a) symmetrically

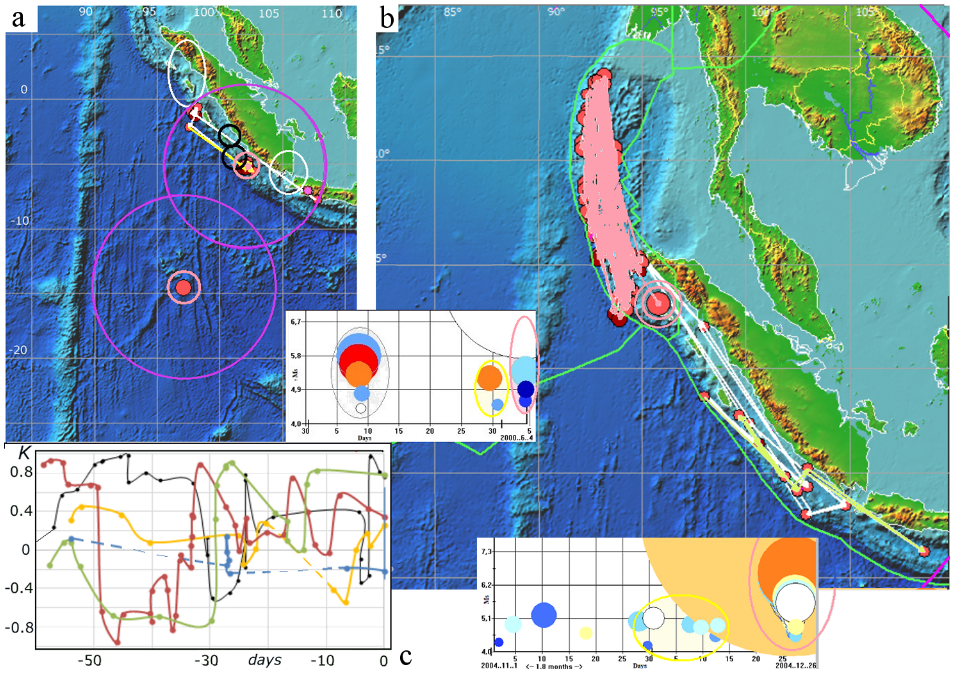

Figure 2. Maps of the distribution of moderate seismicity events in the l_0-vicinity of earthquakes: 4.06.2000 and 18.06.2000 (a); 26.12.2004 (b) (in their inset pictures — graphs $M_S(t)$); graph $K_{\rm cor}(t)$ (sliding calculation window of $N = 5$ points) of seismicity in the l_0-vicinity of these and close to them earthquakes (c): 4.06.2000: a total of 8 points (blue color), 26.12.2004: 21 points (green), 28.03.2005: 40 points (red), 6.04.2010: 14 points (yellow) and 12.09.2007: 32 points (black), the dotted line indicates the absence of earthquakes in a long interval

relative to the main event $\sim$ 700 km to the SWW and NE of it (the latter belongs to the swarm marked in the inset picture of Figure 2a in gray). All three events are located along the subduction arc of the Sunda thrust (see Figure 2a). The second earthquake of the considered pair (18.06.2000) is located $\sim$ 1100 km south of this arc and there are no events preceding it in its l_0-neighborhood (794 km) (see Figure 2a). However, given the high probability of its trigger nature, it is possible to consider seismicity 2 weeks before it in the vicinity of the 4.06.2000 quake. In this case, according to the positive values of $K_{\rm cor}$ the period of exhaustion of plasticity by earthquakes of the aftershock swarm of the latter is revealed: 1) during the first day of the swarm 4–5.06.2000 ($K_{\rm cor} = 0.36$–0.8), as well as the earthquake of 5.06.2000 450 km SWW of the swarm ($K_{\rm cor} = 0.88$, in Figure 2a is highlighted with a purple circle), and 2) at the interval of a sharp increase in $K_{\rm cor}$ — 3–6 days before the main shock (18.06.2000 in the same aftershock swarm (when aftershock events cluster, again forming a "time structure of seismic radiation" [6, p. 112]).

The parameters of the $K_{\text{cor}}(t)$ graphs before the strongest earthquakes, considered in [9]

Date	M_S	Localization	Periods of plasticity (days)
11.03.2011	8.7	Honshu Island	23–20 and 6–4
11.04.2012	8.6	Sumatra Island	6–0
12.04.2014	7.9	Solomon Islands	35–0
25.04.2015	8.2	Himalayas	18–0
2.03.2016	7.9	Sumatra Island	58–50 (60–49)

The largest Sumatran earthquake on 26.12.2004 ($M_S = 8.9$), which occurred a thousand km northwest of the earthquake on 4.06.2000, has a 1.5 thousand km elongated focus over almost the entire area of the Burma microplate outlining the Sunda convergent fault (the aftershock swarm sequence shown in pink in Figure 2b to the north of the main shock). The moderate seismicity preceding this event is located on the same fault, but south-southeast of the main event, splitting into 2 sequences: 1) started a month before the event (shown by yellow in Figure 2 and in the inset picture at the bottom) and 2) two months before the event (white cluster color). High positive values of the $K_{\text{cor}}(t)$ graph (shown in green in Figure 2c) characterize the plasticity of the first sequence practically throughout its entire length.

The next strong earthquake was on 28.03.2005 ($M_S = 8.6$) localized on the same convergent fault only 170 km SE of the Sumatran strongest shock and therefore can hardly be considered independent. By selecting events that do not belong to the Sumatran earthquake focus from the large volume of seismicity preceding it, we obtain the $K_{\text{cor}}(t)$ graph, indicating two periods of plasticity (the red graph in Figure 2c) — 50–60 days before the event and 0-33 days before it. All of them are located on the edge of the Sunda plate.

The event 6.04.2010 ($M_S = 7.9$) is located at almost the same coordinates as on 28.03.2005. The moderate seismicity preceding it is also located along the interplate fault (in the NW and SE directions from the shock) and exhibits the property of moderate and weak plasticity (positive values of the K_{cor} coefficient) with the exception of pairs of events at intervals of 23–25 and 5–9 days before the event (yellow graph in Figure 2c).

Another large earthquake at Island of Sumatra near the event discussed above on 4.06.2000 occurred on 12.09.2007: two tremors with an interval of 12 hours $M_S = 8.6$ and 8.2 (marked with black circles in Figure 2a). It was also preceded by two active seismic swarms of nesting localization at the same distance to the NW and SE of it (the location of the swarms is indicated by white ovals in Figure 2a). Plasticity exhaustion according to the $K_{\text{cor}}(t)$ schedule was carried out in the first swarm in the interval of 56–33 days before the event and in the second — the last three days (black graph in Figure 2c).

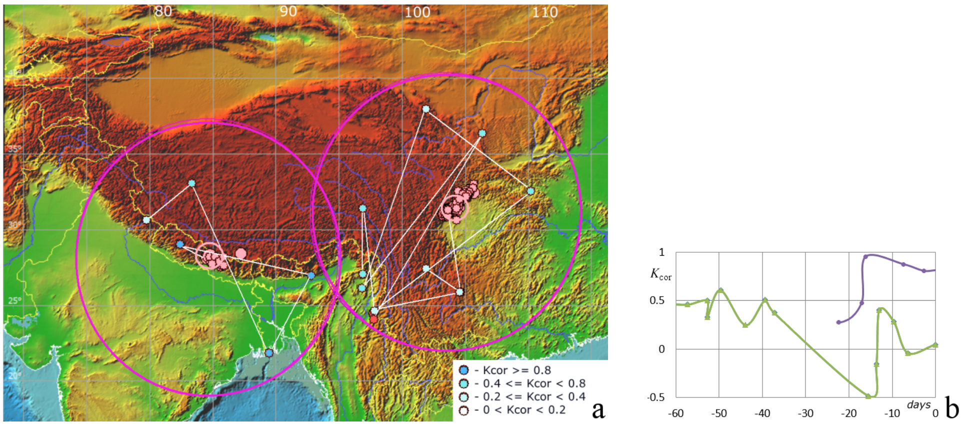

Figure 3. Distribution map of moderate seismicity events in the l_0-vicinity of earthquakes in the Tibet-Himalayan collision zone (a): Sichuan 12.5.2008, $M_S = 8.2$ (on the right) and in Nepal 25.4.2015, $M_S = 8.2$ (left); $K_{\text{cor}}(t)$ graphs (sliding calculation window of $N = 5$ points) seismicity in the l_0-vicinity of this earthquakes (b): 12.5.2008: a total of 14 points (green) and 25.4.2015: 5 points (blue)

The remaining ones are strong ($M_S \geq 7.9$) earthquakes in the region under consideration are the Sichuan 12.05.2008 ($M_S = 8.2$) in Tibet and two near the Solomon Islands: 1.04.2007 and 7.10.2009 (both with $M_S = 7.9$). The $K_{\text{cor}}(t)$ graph of the Sichuan earthquake being similar to the graph of the Himalayan event discussed above: 25.4.2015 shows (Figure 3b) a positive jump in plasticity ~ 13 days before the main shock, followed, however, by a sharp drop already 7 days before the shock. Moderate plasticity is also observed in the interval of 60–38 days before the shock (green graph in Figure 3b). Interestingly, the spatial distribution of the moderate seismicity preceding these earthquakes demonstrates axisymmetric structures (Figure 3a), and events characterized by plasticity: from high to weak (shown in Figure 3a in shades of blue, respectively) are evenly distributed around the future event.

For two earthquakes near the Solomon Islands, the $K_{\text{cor}}(t)$ graphs are shown together with the above-mentioned event in the same area of 12.04.2014. Attention is drawn to the similarity of these three curves (see Figure 1b) in the monotonous growth of their values, showing an increase in the plasticity of the preceding seismicity in the last 30 or more days before the main shock. The identity of the graphs may be due to the spatial connectivity of these events. Thus, the nest structures of seismicity preceding the earthquake of 12.04.2014, are localized in the area of the 1.04.2007 focus on the edge of the Solomon microplate — in the last two days before the main shock (14 events with $M_S = 4.7$–6.7) and in the area of the 7.10.2009 at the edge of the Fiji microplate — 60–55 days before the shock (3 events with $M_S = 4.8$–5.5).

Conclusion

In accordance with the “planetary-regional model” [1] for the preparation of tectonic earthquakes, which assumes the connectivity of earthquakes at distances of hundreds and thousands of kilometers, for the vast majority of the strongest earthquakes with $M_S \geq 7.9$ in southeast regions of Eurasia and adjacent seismic focal zones, signs of a relationship with the moderate seismicity of the areas of regional faults closest to the focus and of their finer structural components have been revealed.

The time distribution of the creepex-magnitude correlation parameter K_{cor} shows the presence of periods of increased K_{cor} values (characterizing the large contribution of quasi-plastic movement in foci) of the seismic activation preceding the strongest earthquakes (in an area of a half orders of size greater compared to the focal area size). The spatial distribution of the preliminary seismicity shows: 1) in most cases, axisymmetric structures of their distribution relative to the future shock, 2) the presence of nesting or linear local clusters of seismicity on deep faults crossing the area of preparation of the main shock, a month or less before it, 3) in the case of a multitude of deep faults surrounding the focus - the uniform distribution of events (characterizing the plasticity of the environment) around the future shock.

These patterns support the concept of exhaustion of plasticity by moderate earthquakes of average distance from the future main shock (within the geodynamically related area of its preparation), as a sign of the transition to brittle destruction in its focus.

Thus, some patterns of changes in the elastic-plastic state of the environment in the preparation of the largest earthquakes in the region under consideration have been identified, showing the gradual process of exhaustion of the plasticity of the medium by moderate earthquakes of medium distance from the future focus within the geodynamical related its preparation zones.

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