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On the correlation of creepex and magnitude in intermediate-depth swarm seismicity before and after large crustal earthquakes*

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Abstract. A study was continued to identify the spatial-temporal relationship between strong crustal earthquakes and moderate intermediate-depth seismicity preceding them. In the field of preparation of these shocks, a pattern of direct correlation of graphs $M_S(t)$ and $\mathrm{Cr}(t)$ has been revealed, testifying creation the conditions for strictly deterministic influence of a focal zone size on the creepex parameter during the main seismic source preparation. It is possible that the proportional dependence of the creepex on the size of focal zones is associated with increased heterogeneity of the medium within the focal area, when the brittle destruction processes of the subducting crust blocks are adjacent to the receipt processes of the deep mantle material. This neighborhood ensures heterogeneity of the environment properties in the large earthquakes preparation in the South Asian subduction zones. The vertical movement of these processes is indicated by the fact that the direct correlation of the graphs is preserved in the case of vertical displacements in the seismic source of main shock (upthrust or downthrow), which, unlike horizontal moves (shift), does not violate the state of large-block medium heterogeneity in the focal zone.

Keywords: intermediate-depth seismicity, focal mechanism, creepex, correlation of various seismicity parameters change

Introduction

By applying the algorithm for the creepex-parameter calculation available among the geodynamic analysis methods from the GIS-ENDDB geoinformation system, it is possible to identify the signs for preparation of a strong earthquake through the time evolution of the creepex ratio along with other parameters of intermediate-depth seismicity.

The identification of a temporal relationship between the crustal shocks and the moderate seismicity preceding them at relatively large depths [1, 2] allows expectation the following aspects: the presence of large earthquakes prognostic signs expressed as the Cr-parameters of intermediate-depth shocks; the possibility of assessing the environment state before and after destructive events. In order to check it on a specific example of the South Asian

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earthquakes with parameters $M_S \geq 7.5$ and $H < 50$ km, the time behavior of the graph $\mathrm{Cr}(t)$ is calculated for earthquakes with $H \geq 50$ km within the main event neighborhood and its correlation with the graph $M_S(t)$ was found for a year or more before the main event and during the aftershocks process.

1. Research methods and database

The study was carried out in the GIS-ENDDB geoinformation system [3] using the calculation method of the classical creepex (creep & explosion) parameter reduced to the trend $\mathrm{Cr}_0^{\mathrm{CSN}}$ [4,5], according to the regional catalog CSN [6], containing 58931 records worldwide for the interval of 26.07.1999–31.08.2017 with the pairs of magnitude determination: M_S and m_B for crustal earthquakes, or mB and m_B for intermediate-depth events ($H \geq$ 50 km). The trend line for the event creepex distribution of this CSN catalog sample has a linear formula: $\mathrm{Cr}_0(M_S) = 0.429M_S - 2.1041$.

To identify temporal anomalies of the creepex parameter in a focus area of the strongest events in the region, the selection of area is performed according to the focus configuration. The later is determined by the method of aftershocks separation implemented in GIS-ENDDB. The parameters of method are the following: magnitude of the main event $M_S \geq 7.5$, minimum magnitude of the aftershock $M_S = 1.5$, noise level 5, rectangular grid cell for preliminary search of aftershocks 0.5° while using the elliptical method of "equal probability" [7]. Then the upper limit of the deep extent of the swarm is established: $H = 50$ km (at the time after the main event, only aftershocks are considered). The obtained sets are investigated by the time variation of parameters $\mathrm{Cr}(t)$, $M_S(t)$ and $H(t)$, and in their mutual correlation calculated in pairs.

2. Distribution of the deep seismicity creepex in the South Asian region

The 22 largest events with parameters $M_S \geq 7.5$ and $H < 50$ km (some of them were paired or multiple) count for the period 2000–2016 are shown in Figure 1.

Previously researched graphs $\mathrm{Cr}_N^{\mathrm{CSN}}(t)$ and $M_S(t)$ according to deep seismicity for 8 zones of preparation of the largest events for 2000–2008 [1], containing 10 crustal events of the region with $M_S \geq 7.5$ (including the multiple earthquakes) showed their synchronous correlation from several months up to six months before each event (and for the upthrust or downthrow type of displacement after it too) (Figure 2). At the same time, synchronicity with these graphs among the depth change graph $H(t)$ is not always observed, but only on its individual fragments, where, obviously, there is a differen-

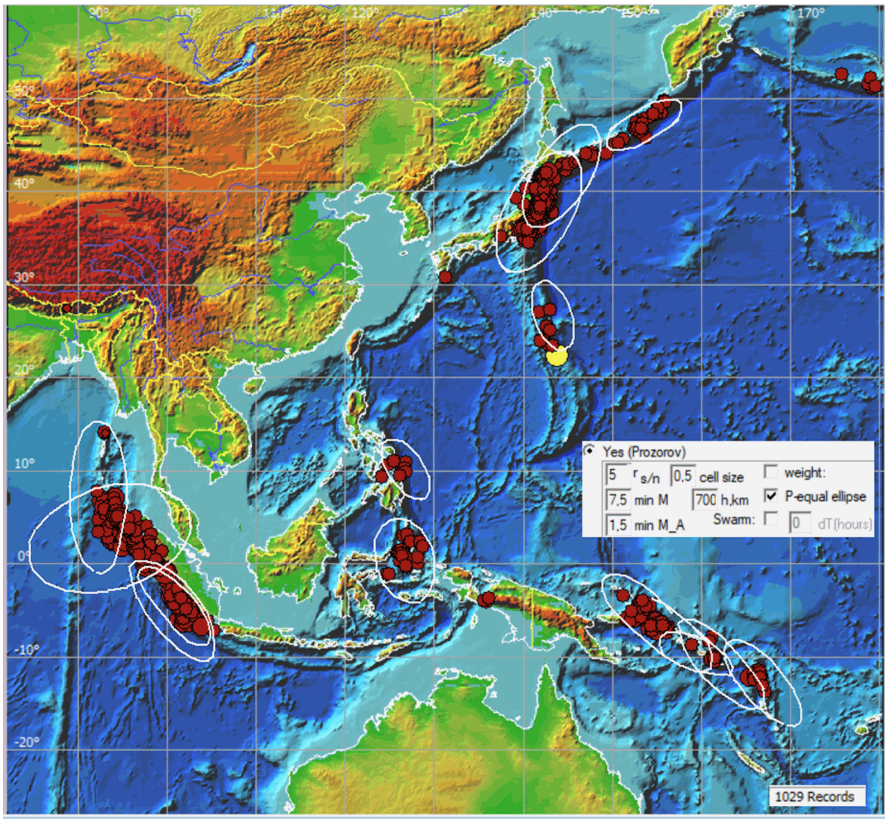

Figure 1. The intermediate-depth events ($H \geq 50$ km), caught in the swarms of the largest crustal events aftershocks identified by the GIS-ENDDB program ($M_S \geq 7.5$ and $H < 50$ km). The modified Prozorov elliptic method (i.e., the method of equal probability ellipses) was applied [7]

tiation in depth for some parameter affecting the value of the creepex (for example, temperature). The absence of a total correlation with the depth can be explained by a lower differentiation in depth and greater mobility of the rheological properties of the medium in the upper mantle compared to the crustal layers. Further studies of the preparation zones of the 12 largest events during 2009–2017 also showed that the graphs $\mathrm{Cr}_0^{\mathrm{CSN}}(t)$ and $M_S(t)$ according to the intermediate-depth seismicity, a synchronous correlation was demonstrated from several months to one and a half years (for shifts—to three years) before the event [2] (Figure 3). But after the major crustal shock, synchronicity of $\mathrm{Cr}_N^{\mathrm{CSN}}(t)$ and $M_S(t)$ either is completely broken, or is replaced by an inverse correlation (i.e. synchronicity in the opposite phase), or does not change at all (the latter occurs more often for vertical displacements: upthrust, downthrow or upthrust-downthrow) or changes occur (recovers) not immediately after the shock, but gradually. This suggests

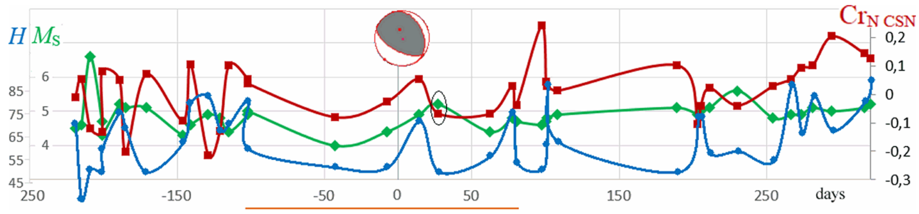

Figure 2. The distribution of parameters $M_S(t)$, $H(t)$ and $\mathrm{Cr}_N^{\mathrm{CSN}}(t)$ of the intermediate-depth seismicity (with $H \geq 50$ km) surrounding the double crustal earthquake dated 01.04.2007, $M_S = 7.7$–7.9, $H = 10$ km (the Papua) marked with the zero time value. The time interval marked as orange line shows a direct synchronous correlation for three graphs $M_S(t)$, $H(t)$ and $\mathrm{Cr}_N^{\mathrm{CSN}}(t)$ for 102 days before the main shock and for 80 days after it: correlation coefficient of graphs $M_S(t)$ and $\mathrm{Cr}_0^{\mathrm{CSN}}(t)$ is $K = 0.902$ (without the point marked with an oval symbol — an underestimated value of the creepex due to the relatively small depth of the event), whereas for the whole swarm $K = 0.1791$; correlation coefficient of graphs $H(t)$ and $\mathrm{Cr}_0^{\mathrm{CSN}}(t)$ is $K = 0.841$, whereas for the whole swarm $K = 0.062$

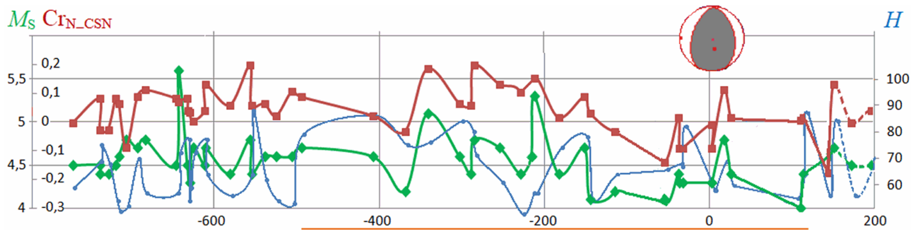

Figure 3. The distribution of parameters $M_S(t)$, $H(t)$ and $Cr_0^{\mathrm{CSN}}(t)$ of the intermediate-depth seismicity (with $H \geq 50$ km) surrounding the crustal earthquake with 31.8.2012, $M_S = 7.5$, $H = 31$ km (the Philippines) marked with the zero time value. The time interval underlined by the orange line shows a direct synchronous correlation of the graphs $M_S(t)$ and $\mathrm{Cr}_0^{\mathrm{CSN}}(t)$ starting 495 days before the main shock: correlation $K = 0.7208$ before the main event and $K = 0.644$ after it, whereas for the whole swarm $K = 0.4$. The dotted line shows a swarm sequence that is not related to the aftershocks

that not only the state of the environment affects the preparation of a major earthquake, but the shock itself changes this state, which is reflected in the interdependencies of the focal parameters. For more unambiguous conclusions about the change in focus parameters after the main shock, only the aftershock sequences of listed earthquakes were studied in this work. Let us describe these results in more detail.

The exact values of the correlation intervals before the main event are given in [2] in the form of a table. It should be noted that at some intervals, the sequences of events selected by the program in the 1000-kilometer window around the future event were adjusted (random points eliminated), and in the presence of foreshocks, by removing their aftershocks (associated with foreshock events). The reason for the random hit of individual points in a sample may be that, unlike the aftershock sequence, the seismicity preceding a major earthquake does not fit into the elliptical geometry of the distribution. This creates certain difficulties in clarifying the selection window shape of the earthquakes forming the focus.

The sequences obtained after this correction up to the main event moment are characterized mainly by a positive correlation coefficient of the Cr and M_S, parameters, and only some of them have a negative correlation (i.e., inverse correlation). The latter refers either to the repeated shocks in the focus environment modified by the previous largest shocks, or to the shocks characterized by a direct correlation of the Cr and H parameters at the same intervals.

Since for the events of 2009–2017, the regularity established for the events of previous years (2000–2008) in maintaining the synchronic nature after the main shock in the case of a vertical movement (upthrust or downthrow) is often not fulfilled [1]. Therefore, in the time interval after the main shock, not all earthquakes in its vicinity were considered, but only the sequence of aftershocks selected by the modified Prozorov method [8] and shortened by depth $H \geq 50$ km (see Figure 1). With this methodic, the indicated synchronicity at vertical movement in the focus of the main shock either remains, despite the major event occurred, or resumes after a certain break. For example:

- 10.8.2009 (downthrow, $M_S = 7.7$, the Andaman) — the synchronicity of the Cr and M_S graphs is maintained for 18 days after the main event ($K = 0.509$);
- 7.10.2009 (upthrust, $M_S = 7.8$–7.9, the Vanuatu) — the synchronicity is maintained and lasts from 7 to 83 days after the main event ($K = 0.534$);
- 12.6.2010 (upthrust, $M_S = 7.6$, the Sumatra) — there are no deep aftershocks, but according to the deep events swarm in the vicinity of the main event, synchronicity remains for 111 days after it ($K = -0.896$);
- 25.10.2010 (downthrow, $M_S = 7.7$, the Sumatra), belongs to a earthquake series 30.09.2009–11.04.2012 [2] — the reverse synchronicity is maintained from 21 to 90 days ($K = -0.746$);
- 21.12.2010 (downthrow-shift, $M_S = 7.6$, Mariana Islands)—the reverse synchronicity is maintained for 101 days after the main event ($K = -0.758$);
- A series of major events at the Honshu Island 9.3.2011 (upthrust-downthrow, $M_S = 7.6$) and 11.3.2011 (upthrust-downthrows, $M_S =$

8.6, 7.7, 7.7) — the synchronicity is maintained from 41 to 129 days ($K = 0.624$), and also 07.12.2012 (downthrow, $M_S = 7.6$) — the synchronicity is maintained from 8 to 30 days ($K = 0.536$);

- 11.4.2012 (shift, $M_S = 8.2$, the Sumatra), belongs to a earthquake series 30.09.2009–11.04.2012 [2] — the synchronicity stops after the main event ($K = -0.206$),
- 31.8.2012 (upthrust, $M_S = 7.5$, the Philippines) — the synchronicity is maintained for 114 days after the main event ($K = 0.644$) (see Figure 3);
- 19.4.2014 (upthrust, $M_S = 7.6$, the Vanuatu), belongs to a earthquake series 12–19.04.2014 [2] — the synchronicity after the main event is maintained for 45 days ($K = 0.763$);
- Double event 25.4.2015–12.5.2015 (upthrust-downthrows, $M_S = 8.2$–7.7, the Tibet) has no deep aftershocks, but according to a very rare swarm of deep events in the main event vicinity, the synchronicity is maintained for 333 days after it ($K = 0.769$).

For the three crustal earthquakes remaining outside this list, no aftershocks were detected at a depth of more than 50 km. These are the shift earthquakes: 24.03.2011 ($M_S = 7.6$, the Indochina), 13.11.2015 ($M_S = 7.5$, the Philippine Sea), and 02.03.2016 ($M_S = 7.9$, the Sumatra).

Conclusion

In this paper, the creepex-parameter is used to verify the thesis about the influence on large crustal earthquakes of intermediate-depth processes associated with the transformation and movement of matter in the upper mantle, and, conversely, about the following influence of displacements in these shocks on the change in the intermediate-depth processes.

In the preparation area of a strong crustal earthquake (1–3 years before it and for the upthrust and downthrow type of displacements after it), a rule of direct correlation between graphs $M_S(t)$ and $\mathrm{Cr}(t)$ has been revealed, evidencing the conditions creation for a strictly deterministic effect of the focal zone size on the creepex during the focus preparation. This is expressed in the proportional ratio of the creepex and magnitude. The value and dynamics of this proportionality have not yet been investigated, except for the correlation coefficient. This dependence, apparently, is a consequence of the environment organized state in the focal area during large crustal earthquakes preparation accompanying by processes in the upper mantle within the intermediate-depth layers. This dependence also indicates large-block heterogeneity of the medium in the shock preparation area, where the blocks of brittle fracture (for example, in the subducting crust) are adjacent to the areas of deep mantle material arrivals. The vertical type of displacements (upthrusts, downthrows and upthrust-downthrows) does not change this environment state, or it recovers after a few days, being disturbed only during the most active aftershocks period causing the spontaneous destruction in the focal zone.

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