Types of strong earthquake precursor behavior obtained from world and regional catalogs of earthquakes

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Abstract. Typical features of seismicity inherent to the period prior to the strong earthquake occurrence are examined using the regional and world-wide earthquake catalogs by the method of construction of the Generalized vicinity of a large earthquake (GVLE). These features are foreshock power-law cascade, the weak long-term background increase in seismic activity, and the definite clustering of the main events. Worth to note, that all these features appear to indicate the loss of a stability of a system, without any reference to the physical mechanism of development of the instability. Thus, these features are expected to occur in connection with the bifurcation points in systems of other physical nature, examples of such behavior are given. Besides, a tendency of a decrease in earthquakes depth in the close GVLE vicinity was found. This precursor feature has a specific character and evidences in favor of a fluid involvement in the mechanism of earthquake occurrence.

1. Introduction

However, even the mostly supplied with statistical data case of large earthquake occurrence is far from the whole understanding and the possibility of strong event forecasting. The study of strong earthquake precursor behavior meets serious difficulties because of a very strong turbulent random component in the seismic process, that results in a great diversity in regimes of foreshock and aftershock sequences of individual strong earthquakes. One meets essential difficulties if tries to identify typical features of the foreshock and aftershock behavior upon the background of a large random component of the seismic regime. The variations that are observed in different fore- and aftershock sequences are so great that the very existence of common regularities in foreshocks and aftershock behavior such as the power-law foreshock cascade and the occurrence of the aftershock process following the Omori law have been questioned [17; et al.]. And although the existence of such patterns had been confirmed [2; et al.], the details of foreshocks' behavior remain unclear.

The existence of a set of typical common features in the foreshock–aftershock process was confirmed, and some details of these processes were revealed or verified by the method of construction and analysis of the generalized vicinity of a large earthquake (GVLE) [10–13]. The idea...
of this method is to carry out a scaled aggregation of data from a large number of individual foreshock and aftershock sequences into a generalized foreshock–aftershock sequence. The method of data combination for a large number of events, which is usually referred to as the method of epoch superposition, is not new. As an example, [9] made use of this method to perform the statistically rigorous identification of the tendency of a decrease in b-values before large earthquakes. The approach used in the present study differs from those of the other authors in the use of larger (up to 1000) number of individual foreshock and aftershock sequences and in scaling of the spatial vicinity by the size of the main shock.

Application of the GVLE method to the regional data [14, 15] had met an inevitable decrease in data volume, but it gave a possibility to reveal some new features of the precursor regime in seismicity. This way a noticeable clustering of the strong and main events (after aftershocks removing) was found. The brief discussion of the regularities in the precursor seismic behavior revealed by GVLE method is given below.

2. Complex of precursors found in GVLE

In the procedure of the GVLE construction the events that occurred near the N strongest events of the used catalog are selected (below, when using the world GCMT and ISC catalogs, the vicinities of 500 strongest events are summed up). Each event in the GVLE, in addition to its parameters, is characterized by the time interval of its occurrence before (or after) the corresponding large earthquake, and by the distance from the hypocenter of the corresponding large event normalized to the source size of the corresponding large event.

The source size R (in kilometers) is calculated here as a function of the magnitude M of the corresponding large event following the relation [18]:

$$R = 10^{0.5M - 1.9}. \tag{1}$$

Further, the events are sorted by time before (or after) the moment of the corresponding large event. As the result of this procedure, the number of foreshocks and aftershocks in the GVLE increases sharply, and the influence of random variations of the seismic regime decreases. The experience of the GVLE construction shows, the details of the procedure, such as the specific form of relation (1), are not so essential.

The GVLE that displays several important regularities in precursor behavior is shown in figure 1 (earthquakes with depth $H < 70$ km and $M_{W} \geq 5.4$ from the global GCMT catalog are used). First of all, the power-law sequence of growth in foreshock number can be seen clearly. Besides, at distances up to a couple of source size of the main event, the weak long-term increase in seismic activity can be seen; this growth in earthquake number begins up to several (maybe up to 5–10) years before the moment of the generalized large earthquake (GLE) event. In figure 1 it can also be seen that the source area of a large event is surrounded by a zone of a decreased seismicity. This decrease in seismic activity occurs at a distance of about 4–6 source sizes around the GLE event and is seen during one to several days (see figure 1).

Besides the change in foreshocks and aftershocks number the set of anomalies of a few different characteristics of the seismic regime (such as b-value, mean earthquake magnitude value, mean earthquakes' depth and some others) were found in GVLE. All these anomalies increase in their amplitude $A$ approaching the GLE time moment as minus logarithm of time $\Delta t$ before (or after) the GLE time moment

$$A = a + b \log(\Delta t), \tag{2}$$

where $a$, $b$ – coefficients, $b < 0$. 


Figure. 1. Spatiotemporal density of number of events N in vicinity of generalized large earthquake. The spatial distance is normed by the source size of the corresponding main earthquake. X-axis – time before and after the GLE moment, Δt=0, days, earthquakes with $M_w \geq 5.4$, $H \leq 70$ km are used.

As an example, figure 2 shows the plots for the current mean magnitude $M_w$ in the GVLE. It can be seen that mean $M_w$ value increases in foreshock sequence approaching the GLE event time moment according relation (1).

Figure 2 shows a linear increase in foreshocks' mean magnitude with $\Delta t$ decrease (and increase in $|\log (dt)|$) and a power-law increase in the average energy of foreshocks with the approach of the moment of the generalized main earthquake, respectively. We emphasize that this precursor anomaly can be interpreted almost as a tautology – "a sign of an increase in the probability of a strong earthquake is an increase in the average amplitude of current earthquakes."

Applying the GVLE method to regional data allows new results to be obtained. In this case, growth of foreshock activity as a rule became to be complicated by a number of strong bursts of seismicity arising near the moment of a generalized strong earthquake (GLE event). Figure 3 shows the
distributions of time intervals $dt$ between events for real main events and for a virtual random in time catalog with the same number of events. ISC catalog is used. The program by V.B.Smirnov of aftershock removing by Molchan-Dmitrieva algorithm [8] is applied. It can be seen that for both regions, the subduction zone of South America and the Mid-Atlantic Ridge zone, the probability of observed small time intervals between events is significantly higher than would be expected for a sequence of independent events. Note that this anomaly will not be so prominent with a linear scale along the y axis. Note also, that the anomaly is more pronounced for the subduction zone than for the mid-ocean ridge zone, an area of rock submelting. This tendency also appears to be valid for other similar seismogenic zones (for example, it has been identified for the Kuril-Kamchatka zone [14]). We suggest that when analyzing global seismicity, this clustering effect has been masked by overlapping data from different seismogenic zones.

![Figure. 3. Distribution of time intervals $dt$ between successive main events for the subduction zone of South America (a) and for the region of the Mid-Atlantic Ridge (b). Plots for real main events (red line) and for 500 random realizations for the same number of events and the same time intervals (blue lines); $N$ – number of intervals between events ordered by $dt$ value.](image)

Should be emphasized, that all the above precursor anomalies – signs of an increase in the probability of occurrence of a strong earthquake – are nonspecific. They can be expected to arise in development of bifurcations in systems of very different physical nature.

An anomaly specific for the case of earthquakes is shown in figure 4. This is an anomaly of a decrease in the average depth of earthquakes as the moment of the generalized main event approaches ($H < 70$ km). This anomaly can be explained by the breakthroughs of the low-density deep fluid into the overlying horizons of the lithosphere because of growth of fracturing in the large earthquake focal zone. The development of such an anomaly testifies in favor of the widely spread model of existence of fluid in the source zones of many earthquakes [3, 16; and many others].

![Figure. 4. Change in the mean depth of focus in the GVLE, ISC world catalog [13].](image)
3. Conclusion
A complex of precursor anomalies has been identified by the GVLE method using data of world and regional earthquake catalogs. The list of identified anomalies includes a weak background increase in seismic activity, the development of a foreshock power-law cascade, increasing in the average magnitude of earthquakes, the "shadow" of precursor seismic activity, clustering of strong (and main) earthquakes and some other anomalies [10–13]. The clustering was examined in more detail for this region (Sakhalin and Kuril Islands); the presence of the clustering effect was shown both for the strongest earthquakes [14] and for a larger set of main events after the removal of aftershocks [15].

The majority of the precursor anomalies are nonspecific; their development can be expected in systems of very different nature. Indeed, based on a similar approach in [4, 5], a change in the administration of the White House (USA) was predicted. An analogue of clustering of strong (and main) earthquakes can be seen in the events of the Arab Spring 2010–2011.

Besides nonspecific predictive anomalies, a specific predictor of a decrease in the average depth of earthquakes was revealed by GVLE method. This effect is associated with the existence of the deep fluid in the source areas of earthquakes and with the breakthrough of this low-density fluid into the upper horizons of the lithosphere in connection with growth of fracturing during the preparation and realization of strong earthquakes.

The complex of nonspecific and specific precursor anomalies identified in the GVLE can be used as a basis for the development of earthquake prediction algorithms. With regard to the earthquake prediction problem in this region (Sakhalin and the Kuril Islands), this approach can be used in the future as an addition or alternative to the used earthquake prediction methods based among other methods on the method of calculating self-developing processes [5, 6] and the load/unload response ratio method [20]. The effect of developing of the self-developing process appears to be very similar with the foreshock cascade, the precursor anomaly concerned with the change in load/unload response ratio can be added into the list of precursor anomalies found in the GVLE and described briefly above.

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