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Seismicity Localization Before Large Kamchatkan Earthquakes

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Gradual restriction of fracturing toward the plane of the future main rupture and its subsequent localization near this plane are qualitatively described by the avalanche unstable-fracturing model of earthquake precursors. Localization of fracturing was recorded in the laboratory during tests of rock specimens. A study of this effect during the precursory seismicity of large earthquakes occurring in the Kamchatka seismic region is reported. The examined parameters were the distance R from the center of mass of the hypocenter points to the first nodal plane of the relevant earthquake and the distribution of seismogenic rupture density P_s for their behavior in time and space. These quantities were combined into a single parameter, $S = RP_c$, which shows the closeness of seismic events to the nodal plane of a large earthquake and the degree of cracking in the medium. The results suggest that seismicity tends to be localized near the nodal plane of a future main rupture, the localization volume probably specifying the location of the future high-magnitude earthquake hypocenter (the place of rupture nucleation). The main event is followed by aftershocks occurring in a region of lower values of P_c close to the mainshock hypocenter, thus terminating the failure process.

INTRODUCTION

Analysis of the time-space behavior of the seismic process in the source zones of large earthquakes based on the avalanche unstable-fracturing model [6] suggests that, when many earthquake ruptures take place, they tend toward the future main rupture plane. A good corroboration of this theory is furnished by laboratory experiments of K. Mogi and C. Scholz [13], [15] where rock specimens were subjected to increasing loading. A sequence of experiments to investigate the behavior of cylindrical Westerley granite specimens under uniaxial loads in an environment of constant confining compression also led to the localization of sources of acoustic pulses [10]. That the number of cracks increases toward the main rupture is known from geological evidence [7]. There are comparatively few papers on the time-space distribution of seismicity during the precursory period of a large earthquake, which reported the tendency of earthquake epicenters to occur in a narrow zone of the same direction as the future main rupture [3], [4], [9], [14]. Sobolev and Zavyalov [11] put forward a simple algorithm and a computer program for calculating parameters that characterize this seismicity localization and investigated the localization process before the December 15, 1971, magnitude 7.9 Ust-Kamchatsk earthquake.

In this paper we report the results of our work conducted with a view to detecting the above effect during the precursory periods of large ($K \geq 14.0$) earthquakes occurring in the middle of the Kamchatka seismic region, using a formalized approach.

SEISMICITY DATA SET AND DATA PROCESSING TECHNIQUE

Computation algorithms. Let a "cloud" of N points (earthquake hypocenters) with coordinates (x_i, y_i, z_i) be distributed in some restricted volume (Fig. 1). The magnitude of each point (earthquake) is specified by giving a weight parameter in the form $m_i = l_i^{\alpha}$, where l_i is rupture length for the i-th earthquake, α being an exponent. The length l_i is found from the formula [8]

$$\lg l_i = 0.244\,\mathrm{K}_i - 2.266, \tag{1}$$

where K_i is the earthquake energy class.

Suppose there is a plane (one of the nodal planes of the future large earthquake) specified as $Ax+By+Cz+D = 0$. The distance from the point (x_i, y_i, z_i) to the plane can be found from

$$r_i = \left| \frac{Ax_i + By_i + Cz_i + D}{(A^2 + B^2 + C^2)^{1/2}} \right|.$$

The weighted mean distance R between the center of the mass of the hypocenters and the nodal plane of the future large event will then be

$$R = \left[\sum_{i=1}^{N} m_i r_i \right] \Big/ \left[\sum_{i=1}^{N} m_i \right].$$

The weight of an earthquake m_i was calculated with the power exponent varied in the range $\alpha = 0$–3. When $\alpha = 0$, all earthquakes make equal contributions into the value of R. When $\alpha = 3$, the contribution is proportional to the energy released by the respective earthquake. In the latter case the result is controlled by several relatively larger events, the contribution due to smaller earthquakes being negligible. All results will be quoted for $\alpha = 1$ in what follows. The contribution of an earthquake into the result is proportional to its rupture length.

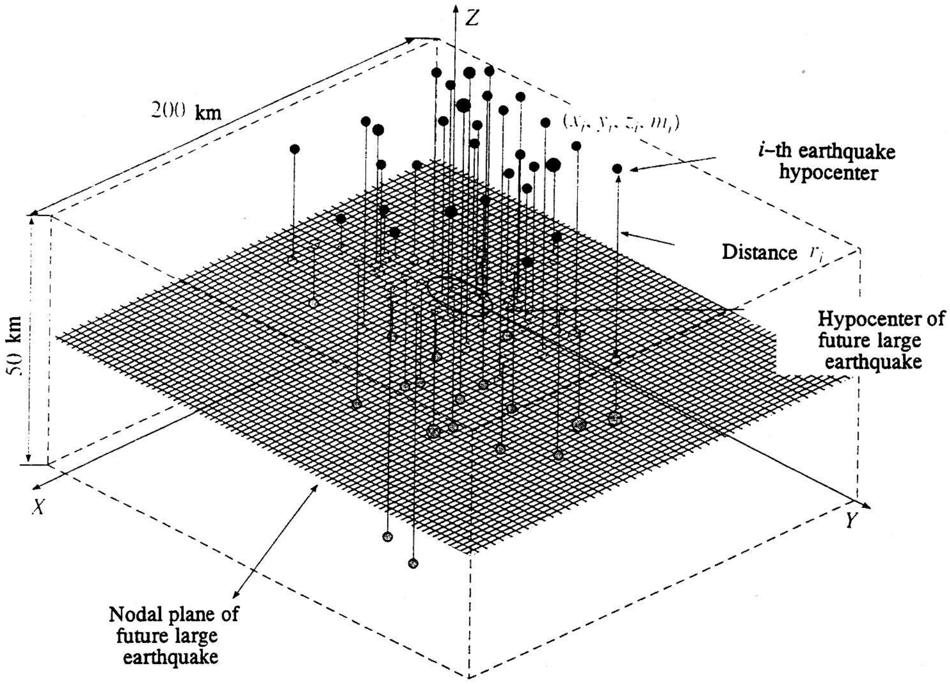

Figure 1 Model to study seismicity localization.

The parameter R as a function of time for a large earthquake was investigated by first selecting a sphere centered at the hypocenter of the large earthquake. The radius of the sphere was 50 km, which is comparable with the future rupture length as estimated from (1) for earthquakes of $K \geq 14$. Values of R were calculated in this sphere in a moving time window of 2 years spaced at intervals of 2 months.

To investigate the parameter R in space we used a 200×200-km earthquake-generating layer extending along the nodal plane of the large earthquake (Fig. 1), the layer thickness across the nodal plane being 50 km. The layer was divided along the plane into 20×20-km elementary areas that overlapped by halves, and values of R were calculated for each elementary area. Also for each area, we calculated values of the concentration of earthquake ruptures P_c, which is the ratio of the mean interrupture length to mean rupture length [1]:

$$P_c = N_*^{-1/3} / l_{avr},$$

where $N_* = n/V$ is rupture concentration, V the earthquake-generating volume, and $l_{avr} = \frac{1}{n}\sum_{i=1}^{n} l_i$. It has been shown [1], [2], [5], [12], [16], [17] that high-magnitude ruptures generally occur in zones of low P_c values.

We examined the time-space distributions of $S = RP_c$. We found them to be more expressive than those of R and P_c. The parameter S is a measure of both how close are seismic events to the nodal plane of a large quake and the degree of cracking present in the earth. The closer the seismicity in an elementary area to the nodal plane of the large earthquake and the greater the degree of cracking in that area, the smaller is the value of S. Treated in this sense, the parameter S characterizes the contribution of each element of volume into the precursory process of a future large earthquake.

DATA SET

This study was based on the seismicity data contained in the catalog of the Kamchatka seismic region for the period 1962–1996. The cutoff energy class of complete reporting for the entire period of observation is K $\geq$ 10.5. However, since most of the events under consideration fall in the area of complete reporting for K $\geq$ 8.5 earthquakes, we used a subcatalog with K $\geq$ 8.5, in all about 30 000 events in the depth range of $H \leq$ 100 km.

The area of study was chosen to be a 600×600-km square whose center was in the Gulf of Kronotskii (Fig. 2), one side of the square being along the axis of the Benioff zone. Thirteen K $\geq$ 14.0 earthquakes occurred in the area during the observation period (see Table 1). Among these were three events with K $\geq$ 15.0: Petropavlovsk event (November 24, 1971, K = 15.9), Ust-Kamchatsk event (December 15, 1971, K = 15.4), and an earthquake of August 17, 1983, with K = 15.4. Because event 1 (see Table 1) had occurred 1.5 years after the starting date of the catalog, it was discarded. Events 9 and 11 can be regarded as interrelated, since they are close in time and space, and their nodal planes are nearly parallel. For this reason we considered the first of the two events only. Event 12 was discarded as well, because it had been caused by the outbreak of an eruption on Karymsky Volcano and seems to have involved a precursory process peculiar to itself.

Figure 3 shows R as a function of time for four of the ten remaining quakes. The value of R at each point was calculated for a time window whose rightmost end was at the point.

Figure 4 shows distributions of S along the nodal plane for the same events. This calculation was for the four-year intervals preceding the main shocks.

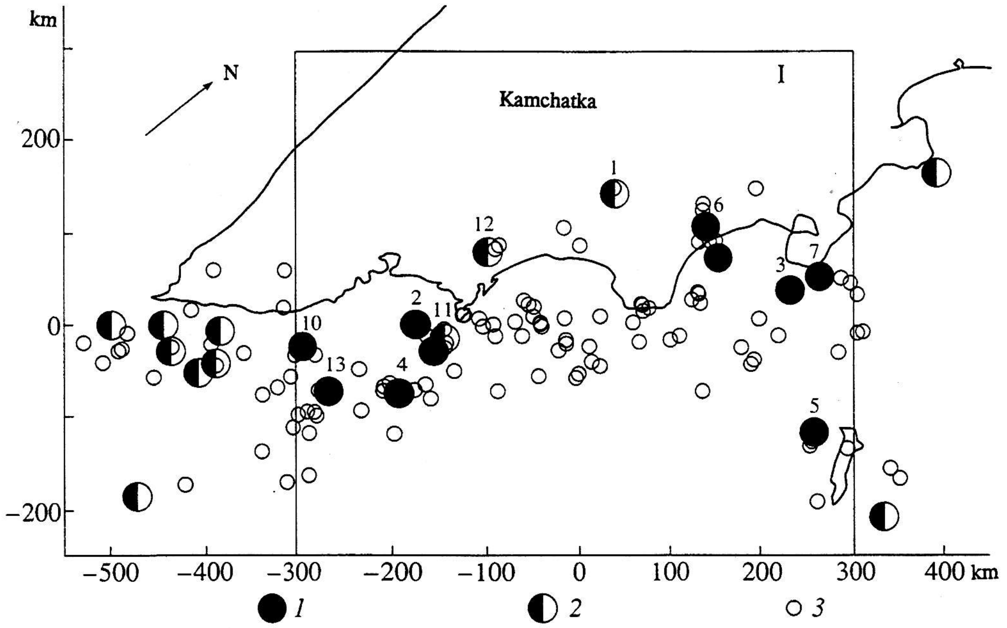

Figure 2 Distribution of moderate and large earthquakes for all of Kamchatka: *1* - epicenters of K ≥ 14 earthquakes used in analysis (see Table 1); *2* - epicenters of K ≥ 14 earthquakes discarded; *3* - epicenters of moderate (13 ≤ K < 14) earthquakes. The coordinates are Cartesian; I - area of study. Numerals at symbols refer to earthquakes as numbered in Table 1.

RESULTS AND A DISCUSSION

Seismicity localization as a function of time. The parameter R is seen in Figs 3, *b*, *c*, and *d* to decrease during long (5- to 15- year) intervals of time. It has the lowest value 2–4 years before a large earthquake. The minimum is followed by a slight increase, probably to be interpreted as a relative local seismicity quiescence, and then a large event occurs.

A different R behavior was recorded before the December 15, 1971, Ust-Kamchatsk earthquake (Fig. 3, *a*) [11]. A significant swarm of earthquakes occurred around the nodal plane in 1969. It was followed by an appreciable R increase (a local quiescence) culminating in a large earthquake.

Some less pronounced lows in R were detected before the other large Kamchatkan earthquakes (see Table 1).

Table 1 Large Kamchatkan earthquakes.

Event no.	Date	Coordinates, deg		Cartesian coordinates, km			Energy class, K	Attitude of nodal plane, deg			
		N	E	*X*	*Y*	Z^{***}		str1	dp1	str2	dp2
1^*	26.05.1963	55.13	160.05	40.0	144.3	0	14.4	-	-	-	-
2	24.11.1971	52.77	159.66	-174.8	1.5	100	15.9	40	89	305	15
3^{**}	15.12.1971	55.84	163.35	231.7	39.4	25	15.4	51	88	326	25
4	23.01.1980	52.22	160.39	-190.4	-73.5	14	14.1	192	21	47	72
5	31.05.1982	55.06	165.47	257.4	-115.1	40	14.0	308	53	211	81
6^{**}	17.08.1983	55.63	161.52	140.4	109.3	98	15.4	216	41	73	65
7	28.12.1984	56.16	163.50	263.9	55.8	19	14.0	260	61	259	74
8^{**}	04.10.1987	55.52	162.08	153.8	75.02	72	14.0	214	44	76	54
9	02.03.1992	52.75	160.19	-154.5	-26.8	20	14.6	346	51	216	51
10^{**}	13.11.1993	51.79	158.83	-292.0	-22.0	40	14.6	206	31	34	59
11^*	07.05.1994	52.90	160.14	-144.0	-14.0	39	14.0	203	31	43	61
12^*	01.01.1996	53.77	159.47	-98.1	79.4	9	14.2	-	-	-	-
13	21.06.1996	51.70	159.67	-264.4	-72.0	2	14.4	211	25	38	66

Note. 11^* aftershock, 12^* volcanic earthquake.

* Earthquakes excluded from analysis.

** Earthquakes shown in figures.

*** Depth.

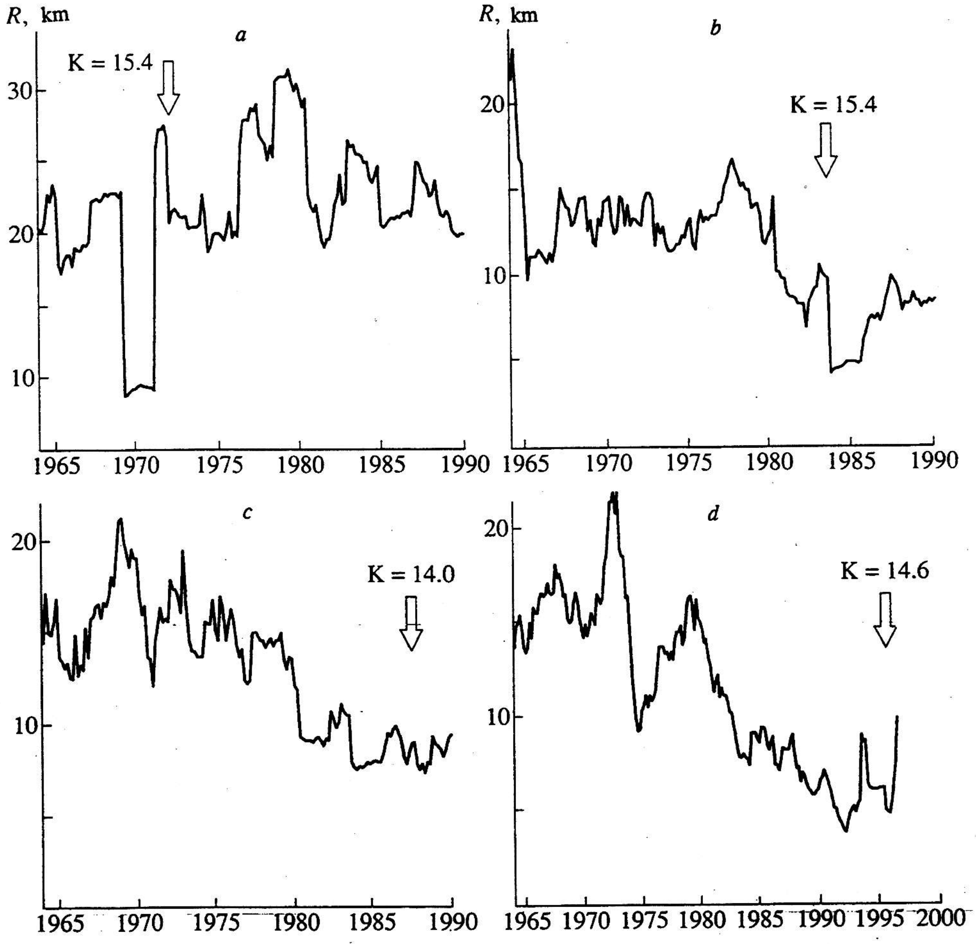

Figure 3 Time variations of parameter *R* before large earthquakes: *a* - Dec 15, 1971; *b* - Aug 17, 1983; *c* - Oct 4, 1987; *d* - Nov 13, 1993. Arrows mark times of respective large quakes.

To sum up, most of the events considered here had been preceded by diminished values of *R*. This shows that seismicity before a large quake tends to be localized toward its future nodal plane, i.e., more events occur near the plane (in the future rupture region) than far from it. This fracturing throughout the future main rupture volume is well known from laboratory experiments in rock loading [15].

Seismicity localization in space. The spatial distributions of the parameter *S* displayed in Fig. 4 demonstrate that the hypocenters of all large earthquakes concerned lie in the regions of the lowest *S* values. Consequently, the seismicity is localized near the nodal plane of a future main rupture, and the region of its localization indicates the location of a future large earthquake hypocenter.

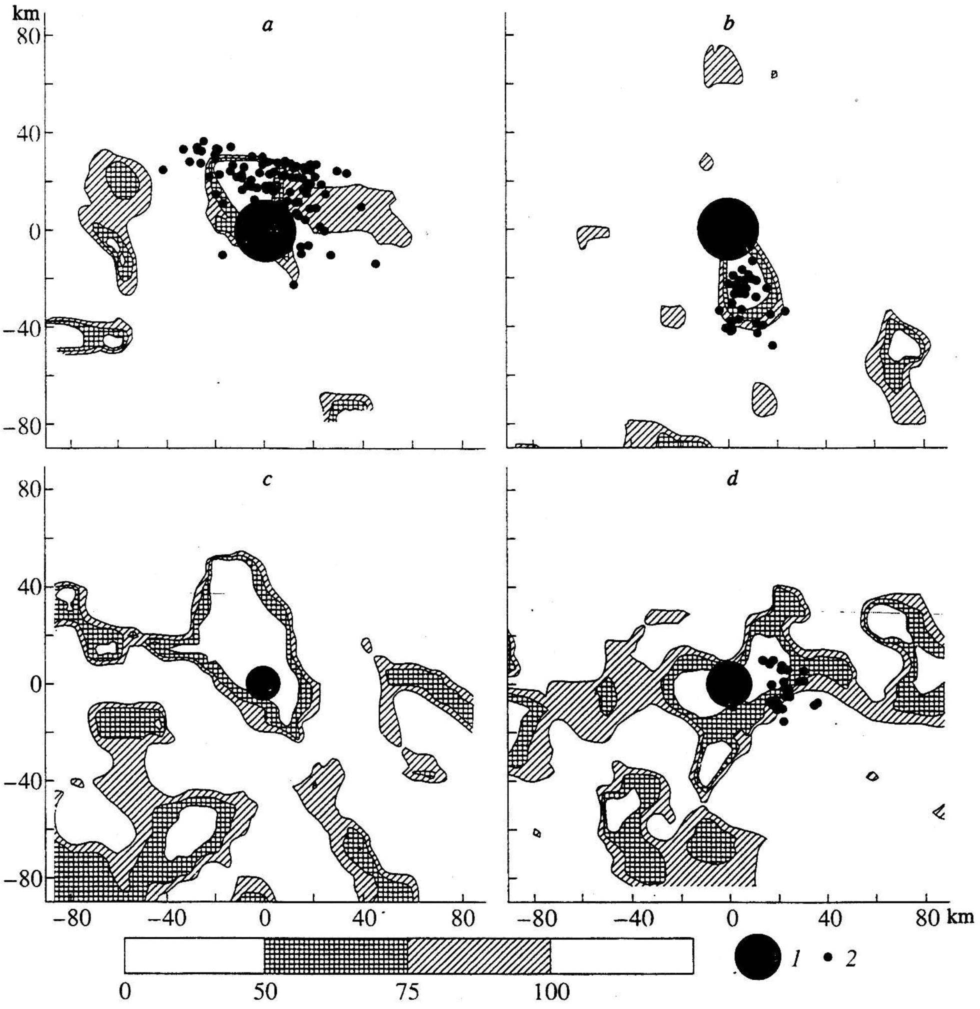

Figure 4 Distributions of S in a 50-km layer along the nodal plane before large earthquakes: *a* - Dec 15, 1971; *b* - Aug 17, 1983; *c* - Oct 4, 1987; *d* - Nov 13, 1993. The coordinates are Cartesian. *1* - Rupture volume of large earthquake, the radius being proportional to rupture length on the map scale; *2* - aftershocks of large earthquake during a few days after the main shock.

We did some additional computations and found that P_c and R behaved in the same manner before most of the quakes considered. The parameter P_c tells us about the degree of earthquake fracturing, hence characterizes the ability of the existing earthquake ruptures to interact and coalesce. The process is described on a qualitative level by the avalanche model referred to above. Lowerings in P_c prior to large earthquakes were reported by many workers [1], [2], [5], [12], [16], [17]. The parameter R tells us how close the seismicity in an elementary area is to the nodal plane of a large earthquake, hence gives the contribution of each elementary volume into the precursory process of a future large earthquake.

The distributions of P_c and R along the nodal plane around the hypocenter of a large quake are random in character when observed long before the shock. One or two zones of lowest R values ($R \leq 5$ km) appear around the hypocenter immediately before the shock. This shows that low-magnitude seismicity tends toward one of the nodal planes of a future main earthquake. Its hypocenter lies either in a zone of the lowest R or between such zones: the 1-day aftershocks fill the area between these zones, for the most part where P_c is at the minimum. However, the hypocenter of the main quake is localized in the region of the lowest R values (the distributions of P_c and R along the nodal plane of a specific event are highly different).

It can thus be inferred that seismicity is localized near the nodal plane of a future main rupture, and this localization region seems to indicate the hypocenter of the future large quake (failure nucleation). The main quake is followed by aftershocks occurring in the region of lower S close to the mainshock hypocenter, thus terminating the failure process associated with the earthquake of interest (Fig. 4).

CONCLUSIONS

1. The precursory processes of most of the large ($K \geq 14$) Kamchatkan earthquakes involve localization of low-magnitude seismicity in the mainshock source volume, expressed as a lowering of $R(t)$. This demonstrates that the low-magnitude fracturing of the material mostly occurs near the nodal plane of the future large quake.

2. The hypocenters of all large earthquakes considered were localized in the regions of the lowest S values. This means that high-magnitude ruptures took place in rock volumes that had been already weakened by low-magnitude events occurring near the mainshock nodal plane.

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