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GEOPHYSICS

Annular Seismicity Structures and the March 11, 2011, Earthquake ($M_w = 9.0$) in Northeast Japan

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Abstract—The characteristics of seismicity prior to the series of eight very strong earthquakes ($M_w = 7.0$–9.0) in Northeast Japan are discussed. Ring seismicity structures that appeared prior to all eight events in two depth ranges of 0–33 and 34–70 km are identified. The epicenters of the main shocks were located near areas of crossing or touching of shallow and deep rings. It was shown that the sizes of shallow rings and threshold magnitudes corresponding to seismicity rings grow with the energy of the main shocks. It was noted that the prognosis with respect to the place and magnitude of the catastrophic earthquake on March 11, 2011, had been made before it based on the data obtained prior to July 1, 2009. Use of the new data obtained prior to March 10, 2011, enabled us to specify this prognosis significantly. We obtained correlation dependences of threshold magnitudes on the energy of the main shocks (with a high correlation coefficients). It was shown that the duration of the period for seismicity rings to emerge in the considered region nearly did not depend on magnitude. The nature of annular structures and the possibility of application of their parameters for prognosis of strong earthquakes were discussed.

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We discuss the characteristics of seismicity prior to the series of eight very strong earthquakes ($M_w = 7.0$–9.0) in Northeast Japan. Ring seismicity structures that appeared prior to all eight events in two depth ranges of 0–33 and 34–70 km have been identified. We obtained correlation dependences of threshold magnitudes on the energy of the main shocks. Application of annular structures parameters allowed us to predict the place and magnitude of the March 11, 2011, very strong earthquake.

It has been shown in [1–5] that prior to strong and very strong earthquakes, annular seismicity structures emerge in subduction zones at various depth ranges. Below, we will consider the characteristics of such structures in Northeast Japan, including those that emerged in the rapture zone of the March 11, 2011, catastrophic earthquake ($M_w = 9.0$). To compare, we also analyzed data on seismicity in the region of the South Kurils.

Since 1900, there were 18 strong earthquakes with $M_w = 7.7$ in the considered region (between 34.5° and 44.5° N) [6] (Fig. 1). In contrast to the regions of Sumatra and Kamchatka, events with $M_w > 8.4$ were not recorded here until 2011. Note that prior to 2011, all the earthquakes with $M_w > 8.0$ occurred north of 39° N.

The characteristics of annular seismicity structures for Northeast Japan were studied, analogously to [1–5], within two depth ranges of 0–33 and 34–70 km. We analyzed the data on earthquakes with magnitudes $M \geq M_{t1}$ and $M \geq M_{t2}$ that occurred around future rapture zones; threshold values M_{t1} and M_{t2} for the first and second depth ranges, respectively, varied from 3.9 to 5.8. We studied the earthquakes that occurred from January 1, 1964, to the day preceding the main shock. We processed the data on seismicity prior to eight strong and very strong earthquakes with $M_w = 7.0$–9.0 (Table 1).

In our previous work [5], we preliminarily discussed the characteristics of annular seismicity structures formed prior to seven large and great earthquakes in the considered region (1989–2008, see table), as well as in the zone of the seismic gap formed prior to the March 11, 2011, earthquake. Ring seismicity structures were identified prior to all seven of these events, similarly to other subduction zones [1–3]. The epicenters of the main shocks were located near the corresponding intersection or contact areas of shallow (h = 0–33 km) and deep (34–70 km) rings. Figure 2 demonstrates annular seismicity structures formed prior to July 1, 2009, in the central part of the future rapture zone of the earthquake with $M_w = 9.0$. It is seen that two annular seismicity structures, namely, shallow ($M_{t1} = 5.0$, $L \sim 95$ km) and deep ($M_{t2} = 5.0$,

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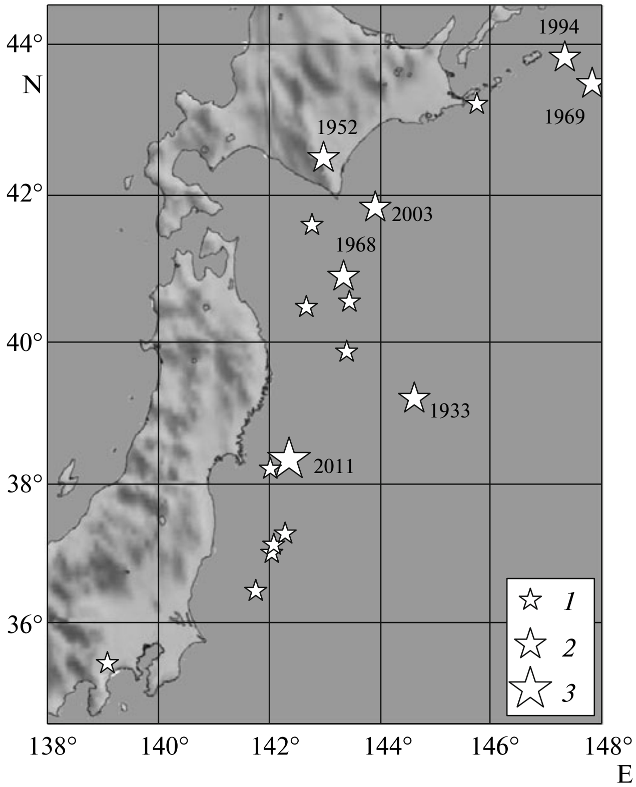

Fig. 1. Epicenters of strong earthquakes in the area of Northeast Japan and the South Kurils from 1900. Magnitudes (M_w): *1*, 7.7–7.9, *2*, 8.1–8.4, *3*, 9.0. Dates are written for events with $M_w > 8.0$.

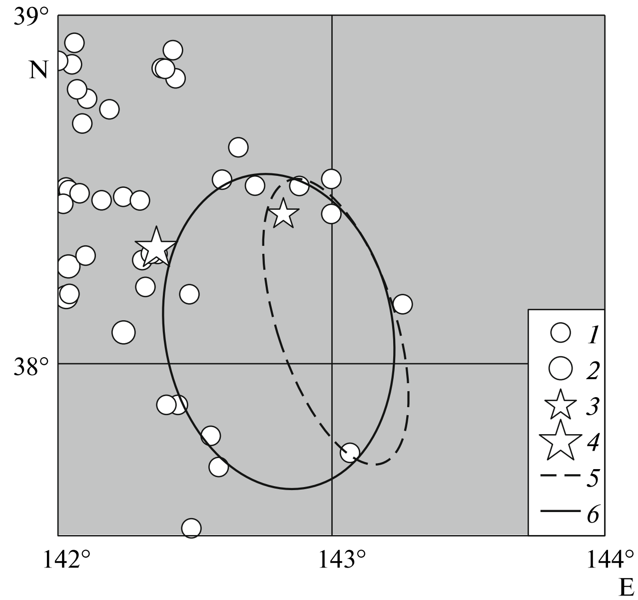

Fig. 2. Annular seismicity structures in the region between 37.5° and 39° N in two depth ranges (based on the data prior to July 1, 2009). *1*, $5.0 \leq M < 6.5$, *2*, $M \geq 6.5$ (34–70 km depth), *3*, epicenter of the March 9, 2011, foreshock, *4*, epicenter of the March 11, 2011, earthquake ($M_w = 9.0$), *5*, shallow ring, *6*, deep ring [5].

$l \sim 100$ km), formed 20 months prior to this event. In addition to this, the epicenter of the strong foreshock (March 9, 2011, $M_w = 7.3$) was located near the crossing area of shallow and deep rings, whereas the epicenter of the main shock was located at the boundary of the deep ring, at a distance of about 45 km from this area. Note that another pair of annular seismicity structures was formed in the southern part of the rapture zone (between 36° and 37° N); its M_{t1} and M_{t2} parameters were the same, and the L and l values were close to those for the rings mentioned.

It follows from Table 1 that L, M_{t1}, and M_{t2} values grow regularly with M_w. An especially high correlation is observed for the $M_{t1}(M_w)$ and $M_{t2}(M_w)$ dependences. In [5], the predictive estimate of magnitude $M_w = 8.4 \pm 0.1$ for the probable very strong earthquake in the region of 37.5°–39° N and 142°–144° E was yielded

Characteristics of annular seismicity structures formed prior to strong and very strong earthquakes in Northeast Japan and the South Kurils

Date (dd.mm.yyyy)	N	E	h, km	M_w	M_{t1}	L, km	ΔT_1, years	M_{t2}	l, km	ΔT_2, years
01.11.1989	39.92°	142.79°	29	7.4	4.0	100	18	4.0	95	18
04.10.1994	43.83	147.33	33	8.3	5.0	80	25	5.1	80	27
28.12.1994	40.54	143.44	16	7.8	4.4	130	23	4.4	85	21
25.09.2003	41.82	143.91	13	8.3	5.0	85	28	5.0	40	29
31.10.2003	37.81	142.62	10	7.0	4.0	30	17	4.0	40	26
28.11.2004	43.01	145.12	39	7.0	4.0	65	31	3.9	40	31
19.07.2008	37.55	142.21	22	7.0	4.0	55	34	4.0	40	35
11.03.2011	38.32	142.37	32	9.0	5.8	170	30	5.3	75	35

Note: L and l are the lengths of long axes of seismicity rings, and ΔT_1 and ΔT_2 are the durations of their formation for the first and second depth ranges, respectively.

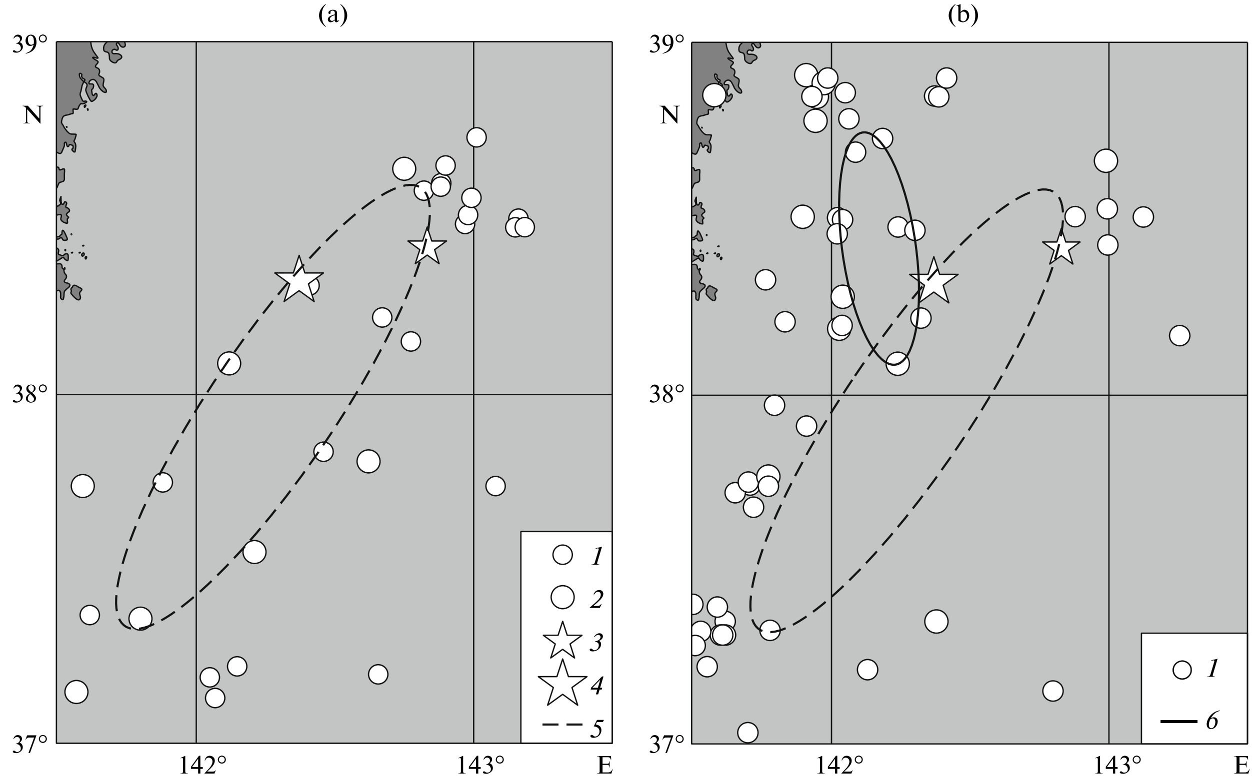

Fig. 3. Annular seismicity structures prior to the March 11, 2011, earthquake: (a) for the depth range of 0–33 km: *1*, $5.8 \le M < 6.5$, *2*, $M \ge 6.5$, *3*, epicenter of the March 9, 2011, foreshock, *4*, epicenter with $M_w = 9.0$ earthquake, *5*, shallow ring, *6*, deep ring; (b) for the depth range of 34–70 km: *1*, $5.3 \le M < 6.5$, *2*, deep ring (the remaining arbitrary notations are the same as in Fig. 3a).

based on these dependences. The same estimate was yielded for the second pair of rings.

Analysis of supplementary data obtained in the period of July 1, 2009–March 10, 2011, enabled us to specify the characteristics of annular seismicity. It follows from Fig. 3 that, prior to the March 11 earthquake, the formed annular seismicity structures were of significantly higher threshold magnitudes: $M_{t1} = 5.8$ for the shallow ring (at $L = 170$ km) and $M_{t2} = 5.3$ for deep ring (at $l = 75$ km depth). The largest magnitudes, M_w, of events within these structures were 7.3 (March 9, 2011) and 7.7 (June 12, 1978), respectively. We emphasize that the epicenter of the main shock in this case was located again in the area of ring crossing. Additionally, note that the main part of annular seismicity structures coincides with the area of maximal coupling of the oceanic and continental plates [7]. Using the mentioned values of M_{t1} and M_{t2}, we were able to give a more accurate prognosis of the M_w value, namely, 9.1 ± 0.4, based on the dependences from [5].

With the new data taken into account, we derived the following formulas connecting the M_{t1} and M_{t2} values with M_w:

$$M_{t1} = 0.87M_w - 2.23, \quad r = 0.98, \tag{1}$$

$$M_{t2} = 0.75M_w - 1.30, \quad r = 0.97, \tag{2}$$

where r is the correlation coefficient.

Comparison with the data obtained in [2–4] for the Sumatra region indicates that for the region of Northeast Japan, the M_{t1} and M_{t2} values grow with M_w significantly faster, whereas the sizes of rings (L and, especially, l) grow more slowly.

It is seen from table that the duration of annular structure formation in the interval of $M_w = 7.0$–9.0 for the considered depth ranges varies from 17 to 34 and from 18 to 35 years, respectively, and virtually does not depend on magnitude. For the strongest events ($M_w = 8.3$–9.0), the scatter of data is significantly less than for weaker ones.

The results obtained in [4] allow us to consider that shallow annular structures outline relatively rigid blocks, on whose boundaries a gradual uplift of deep fluids is induced. Most likely, an analogous process takes place at the boundaries of deep rings, as well. (Note that the conclusion was made in [8, 9] that uplift of fluids in subduction zones occurs mostly owing to earthquakes.) In this case, in the areas of shallow and deep rings crossing or touching, a maximal thickness of two-phase layer is gradually reached with a significant share of fluids. If fluids form a connection network, then stresses accumulate at the roof of this layer, and these stresses may exceed the strength limit of rocks, initiating a slip during a strong earthquake [10]. The fact that the duration of ring formation nearly does not depend on magnitude can be an indirect argument for this interpretation of the ring nature (there are some reasons to believe that this fact is related to the constancy of average rate of fluids uplift [11, 12]).

Thus, instead of the two earthquakes with $M_w \sim 8.4$ expected based on the data obtained prior to July 1, 2009, one earthquake occurred and its magnitude appeared to be significantly higher. This situation does not contradict the general regularities of spatial-temporal self-organization of geological systems. As is known, in self-organized systems, to which the entire Earth belongs as well, the hierarchy of variables exists and this hierarchy is related to difference in scales [13]. The variables of upper hierarchic levels determine the state of the system in general, whereas the less-order variables adapt to them. We can believe that formation of two pairs of relatively large annular structures prior to July 1, 2009, provided for preparation of the very strong earthquake due to uplift of fluids (at least for the reason that it is northern pair of rings that most probably caused a strong foreshock with $M_w = 7.3$).

The presented data indicate that annular seismicity analysis is a promising method for prediction of the place and energy of strong and very strong earthquakes in subduction zones. In addition to this, the current values of ΔT_1 and ΔT_2 can be used for estimation of the time of such seismic events (mid-term prognosis).

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