Mega-earthquake on 11 March 2011 in Japan and aftershock process dynamics' development

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The article provides data on seismic activity and recurrence periods of strongest ($M \geq 7.6$) earthquakes for the historical and instrumental periods of observations in epicenter area of a mega-event. It was shown that a period of recurrence of strongest events in this area was about 40 years. To the east of Honshu island a long seismic gap (~ 800 km) was discovered, located to the south of latitude 39°N and filled recently with aftershocks of the 11.03.2011 mega-earthquake. Significant analogues in aftershocks dynamics of the 2011 Great Japan Earthquake with aftershock sequences of the Sumatra-Andaman (2004, $M_w = 9.3$) and Simushir (2006, $M_w = 8.3$) earthquakes were described. A similarity over time for the first event and over space (field of aftershocks' epicenters) for the second event was noted. The author suggested a possibility of occurrence of a recurrent strong event with magnitude approximately equal to 8, shifted along the main thrust towards the deep oceanic trench.

KEYWORDS: Large earthquake; recurrence of the large earthquakes; seismic gap; mega-earthquake; aftershock sequence; strongest aftershock; field of aftershocks' epicenters; probable scenario.

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Introduction

A catastrophic shallow-focus ($h \sim 30$ km) earthquake has occurred on 11 March 2011 at 0546 GMT (1446 LT) to the east of Honshu island (Japan) at a point with coordinates: $\varphi = 38.32°$N, $\lambda = 142.35°$E (Figure 1). According to the primary operative data of the National Earthquake Information Center (NEIC/USGS) its magnitude M_S was 7.9. Later its magnitude was verified on the basis of M_W moment magnitude and changed to 8.8, and after some time it was accepted as $M_W = 9.0$.

According to the Internet, this event was named as "The Great Japan Earthquake", "The Northeastern Taiheiyou Earthquake", "Tohoku-Chino Taiheiyou-oki Earthquake". Further we shall use the first title.

Due to a fatal confluence of circumstances, this seismic catastrophe has provoked the stronger tsunami waves up to 10–20 m high, which, it their turn, led to a technogenic catastrophe at the Fukushima I nuclear power plant. All these catastrophes occurred at one of the most densely populated regions of Japan. It has called forth high casualties (over 29,000 with those missing), destructions and material losses (over 300 Billion USD, according to the official data provided by the Japanese authorities). It turned into a nation-wide tragedy.

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Large Earthquakes in Epicenter Area of Mega-Event in Historical and Instrumental Periods

The area to the east of Hokkaido, Honshu islands belongs to the Pacific seismic belt, characterized by one of the highest levels of seismicity on Earth. Let us look only at a part of this territory at a size of 5×4 degrees, comprising the epicenter area of the examined earthquake (Figure 1). The coordinates of this area are: $\varphi = 35.0 - 40.0°$ N and $\lambda = 141.0 - 145.0°$ E. According to the catalog [*Usami*, 1979] 10 events of $M \geq 7.6$ (Table 1) were registered at this seismically active zone since 869.

According to Table 1, the large earthquake in the area of the present mega-earthquake occurred in 869 at $M = 8.6$. After this earthquake, in relation to the catalog [*Usami*, 1979], during 742 years no events of $M \geq 7.6$ were registered. The true reason for such pause is unknown. Starting from 1611, 10 large strongest earthquakes have occurred, including the mega-event in 2011. Thus, according to data obtained over 400 years, the recurrence period of large earthquakes in epicenter area of the 11 March 2011 Great Japan Earthquake on lasted for 40 years approximately.

The work [*Tarakanov*, 1995] provides data on structural

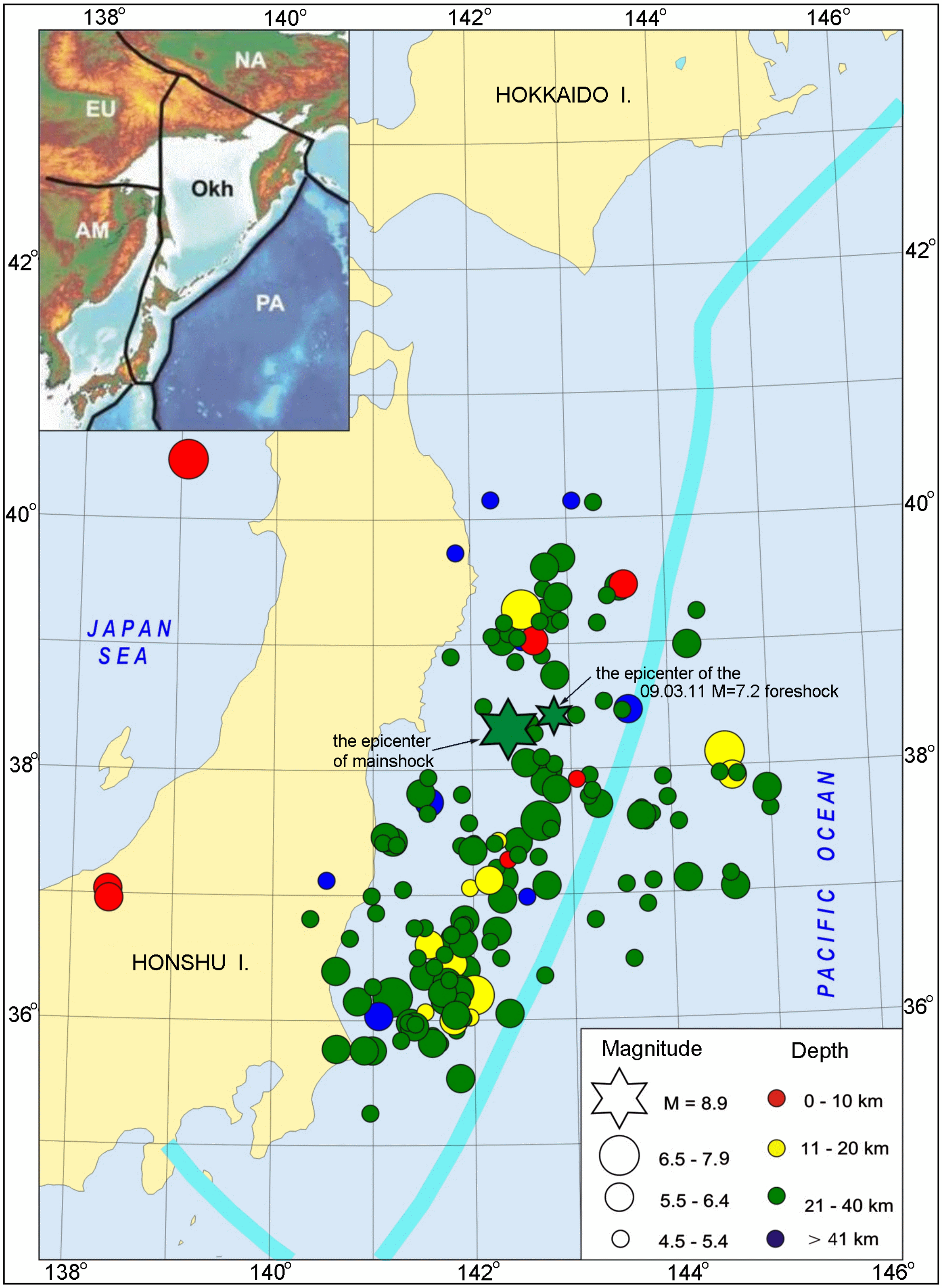

Figure 1. Location of epicenter of the main shock of the 11 March 2011 earthquake (big star), its foreshock (small star) and aftershocks (circles), registered on the first day according to the NEIC/USGS operative catalogue's data. Narrow stripe – the axis of deep oceanic trench. In box – regional scheme of plate borders in the model [*Wei, Seno*, 1998]. NA – North American, EU – Eurasian, AM – Amur, PA – Pacific, OKH – Okhotsk plates.

Table 1. List of earthquakes of $M \geq 7.6$ within the limits of the Japanese seismically active zone with coordinates $\varphi = 35.0 - 40.0°$ N and $\lambda = 141.0 - 145.0°$ E for 869–2010 according to data [*Usami,* 1979]

#	UTC Date, yyyy/mm/dd	Time	Epicenter coordinates φ, °N	λ, °E	Depth, km	Magnitude
1	0869/07/13	Night	38.5	143.8	–	8.6
2	1611/12/02	After 0000	39.0	144.5	–	8.1
3	1646/06/09	–	37.7	141.7	–	7.6
4	1677/04/13	1021	40.0	144.0	–	8.1
5	1717/05/13	–	39.4	142.4	–	7.6
6	1835/07/20	0415	37.9	141.9	–	7.6
7	1897/08/05	0010	38.3	143.3	–	7.6
8	1933/03/02	1731	39.1	144.7	~ 20	8.3
9	1936/11/02	2046	38.2	142.2	$\sim 50 - 60$	7.7
10	1938/11/05	0843	37.1	141.7	20	7.7
11*	2011/03/11	0546	38.3	142.4	32	9.0

Note: * – NEIC/USGS data.

blocks of the Kuril–Kamchatka region, including the area to the east of Hokkaido. Structural block is a part of an area, which differs from other areas according to its seismological parameters and geological-geophysical characteristics of environmental structure. Linear dimensions of three blocks to the east of Hokkaido were 120–180 km. A similar fragmentation of lithosphere was apparently observed in the area to the east of Honshu. Thus, during the latest seismic catastrophe in Japan an extremely improbable scenario was realized, when dislocation embraced several structural blocks. As it was mentioned in the work [*Pinegina*, 2011] 6 blocks were simultaneously involved.

Large Earthquakes to the East of Hokkaido and Honshu Islands in 1900–2010

The data on earthquakes of $M \geq 7.6$ for the period 1900–1952 were taken from the catalog [*Usami*, 1979], for the period 1953–2010 – from JMA catalog [*JMA Earthquake Catalog...*, 2011] (Table 1). Source areas of these earthquakes are shown in Figure 2a.

It was shown in Figure 2a that practically all large earthquakes took place to the north of latitude 39°N, where a congestion of source areas was observed. At the same time to the south of latitude 39°N a vast area of relative calm (seismic gap) was located, about 800 km long. The latest earthquakes in this part of the examined zone occurred in 1923, 1936 and 1938. Taking this into account, a state of relative calm lasted there for at least 75 years. Figure 2b shows that the seismic catastrophe of 11 March 2011 occurred exactly there. Thus, there were still some indications of a possible earthquake of global scale in the area of Honshu, but seismologists paid no attention to it.

Dynamics of Development of Aftershock Process of Japan Mega-Earthquake. Possible Scenario of Aftershock Development of $M \sim 8.0$

According to NEIC/USGS data, during 24 hours after the mega-earthquake about 160 aftershocks of magnitudes from 4.6 to 7.9 were registered (22 aftershocks with $M \geq 6.0$; Figure 1). The magnitude of a strongest aftershock, occurring after ~ 30 minutes after the main event, finally reached, after verification, 7.9 (in the beginning it was equal to $M = 7.1$). During the second day the number of registered aftershocks of $M \geq 4.6$ was 130 (from them 7 aftershocks with $M = 6.0$). On the third day this number went down to $N = 86$ (one aftershock with $M = 6.0$). During a month the intensity of aftershock process gradually declined and reached $\sim 6 - 8$ events ($M \geq 4.6$) a day. At the moment of writing this article (32 days after the major event's occurrence) 940 aftershocks of $M \geq 4.6$ (Figure 3) were registered. Prevailing number of hypocenters were at depth interval of 20–40 km. The aftershocks' epicenters covered a large area about 650 km long with a lateral dimension of about 350 km from the coastline of Honshu up to the deep oceanic trench and even behind it.

The magnitude of two strongest aftershocks, occurring on the first day after the main event, was 7.9 and 7.7. At the moment of preparing this article these magnitude values weren't exceeded. The force difference of the main event and the strongest during 32 days aftershock was about one magnitude unit (or 30 times energy difference). Naturally, a question arises: which scenario is more probable at aftershock sequence development?

In the framework of the first scenario it can be assumed that a further decline of aftershock process intensity will be observed at sporadic outbursts of seismic activity due to aftershocks with magnitude ~ 6. In accordance with another scenario the gradual decline of seismic process will be interrupted by a strongest aftershock of $M \sim 8.0$.

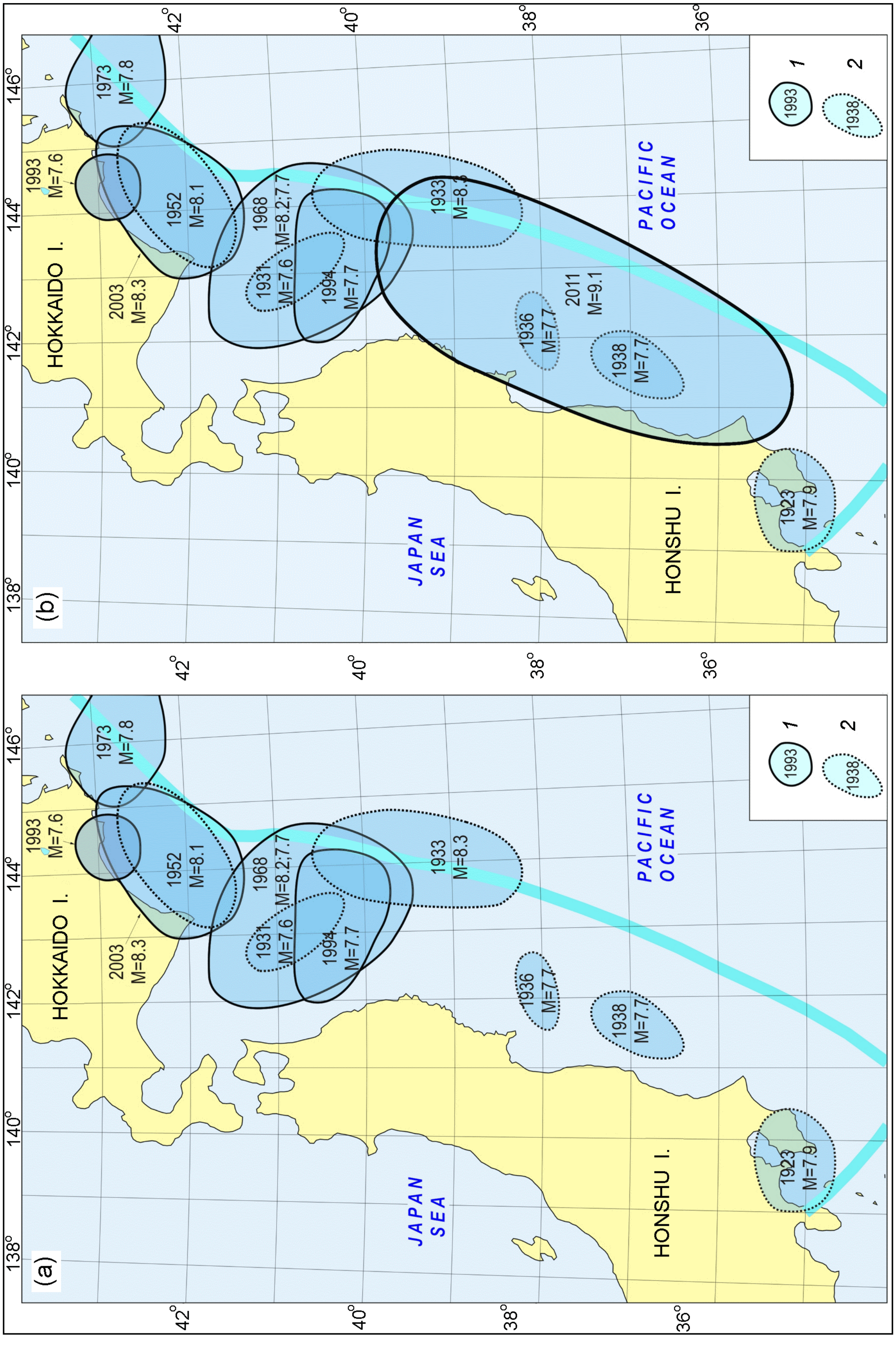

Figure 2. Epicenter areas of large ($M \geq 7.6$) earthquakes in the area to the east of Hokkaido and Honshu in the periods 1900–2010 (a) and 1900–March 2011 (b). The figure illustrates the filling of the seismic gap, located to the South of 39°N, existing till 2011, by aftershocks of the Japan mega-earthquake.

Table 2. Catalog of earthquakes of the Japan region (to the east of Hokkaido and Honshu Islands) of $M \geq 7.6$ for 1900–2010 according to data [*Usami*, 1979] and [*JMA Earthquake Catalog...*, 2011]

Date, yyyy/mm/dd	Time, JST	Epicenter coordinates φ, °N	λ, °E	Depth, km	Magnitude	Source
1923/09/01	1158	35.1	139.5	60	7.9	[*Usami*, 1979]
1931/03/09	1249	41.2	142.5	0	7.6	
1933/03/03	0231	39.1	144.7	0–20	8.3	
1936/11/03	0546	38.2	142.2	50–60	7.7	
1938/11/05	1743	37.1	141.7	20	7.7	
1952/03/04	1023	42.15	143.85	45	8.1	
1968/05/16	0949	40.7	143.6	0	8.2	[*JMA Earthquake Catalog...*, 2011]
1968/05/16	1939	41.4	142.9	40	7.7	
1973/06/17	1255	43.0	146.0	40	7.8	
1993/01/15	2006	42.9	144.4	103	7.6	
1994/12/28	2119	40.4	143.7	0	7.7	
2003/09/26	0450	41.7	144.2	71	8.3	

Moment magnitude M_w for earthquakes in 1968–2003 was shown according to [*Kanamori*, 1983].

For the first time this opinion was expressed in the work [*Tikhonov*, 2011] after 13 days from the moment of the main event.

The first statement was based on a law, established by M. Bath [*Bath*, 1965] for magnitudes' difference $(M_m - M_a)$ of main pulse and strongest aftershock. This difference is approximately equal to 1.2 magnitude unit.

Table 3 shows 14 pairs of events (large main event – strong aftershock) in the examined area for 1900–2010 according to JMA data. The greatest value $M_m - M_a = 1.8$, given in the table, corresponds to a pair of events, which occurred on 21 December 1946. However, this evaluation was characterized by a certain ambiguity. The fact is that the moment of time on 21.12.1946 at 0419 correlates with two strongest ($M = 8.0$, 8.1) earthquakes in JMA catalog. An event of $M = 6.3$ was registered in 3 hours 26 min after them.

It isn't absolutely correct to analyze the distribution of parameter $(M_m - M_a)$ due to a small scale of sampling. Let us limit ourselves only with calculating this parameter's average value for the given seismically active region. It was equal to 0.90 ± 0.44. Consequently, the law of M. Bath can be fulfilled even with some reserve (0.3 magnitude unit).

Second scenario was based on analogy of the aftershock process, which presently takes place to the east of Honshu, with aftershock series of the 26 December 2004 Sumatra-Andaman earthquake on ($M_w = 9.3$). To describe aftershocks of this mega-event, let us use the data of NEIC/USGS. During the first 24 hours after the main pulse about 220 recurrent earthquakes of $M \geq 4.6$ were registered, and in 32 days – 750, i.e. the number, compatible with the Japan series. The strongest aftershock had magnitude $M = 7.5$. It occurred 3 hours 22 min after main event. Therefore, a seismic process regarding to parameter N for these mega-events developed in accordance with a similar pattern. The magnitudes and time of strongest aftershocks are and also compatible. Let us only mention one significant difference in the energy of aftershock processes on the first day of observations: 22 shocks with $M \geq 6.0$ for the first event against 9 for the second.

Before we use the aforementioned analogy, let us look at the time dependence of aftershock sequence of the 2004 Sumatra-Andaman earthquake. Qualitative evaluations, obtained at various stages of development of this sequence, can be further used as reference values at analyzing aftershock series of the 2011 Great Japan earthquake.

Figure 4 shows time intervals dependence between aftershocks of the 2004 Sumatra-Andaman earthquake on the numbers of recurrent aftershocks with $M \geq 4.6$. The diagram was divided in 5 intervals, corresponding to different stages of aftershock process. First interval lasted for two days. It was an area of the most intensive aftershock activity. Pulses followed each other at the frequency of over two events per hour.

Second interval was an area, where an event could be several hours late in comparison to another event. At this stage some episodes of strengthening seismic activity can be predicted, related to emerging recurrent earthquakes of magnitudes around 6–7. Events of $M = 6 - 7$ excite secondary aftershock sequences, which abruptly decreases time intervals between aftershocks.

High frequency of aftershocks within the limits of the third interval was related to cluster activity, concentrated near the point with coordinates 7.90°N, 94.0°E. Such situation took place during the Andaman earthquake from 28 to 30 January 2005.

Fourth interval is the most important for predicting a strongest aftershock. It corresponds to a stage, when time intervals between sequential aftershocks vary in wide range from fractions of hours to a day and more. This stage of the Andaman earthquake started approximately on the 35-th day of aftershock sequence, and ended on the 92-nd day of the sequence, when a strong aftershock of $M = 8.6$ occurred.

Let us note a number of particular characteristics of the 4-th interval, relevant for predicting a strongest aftershock,

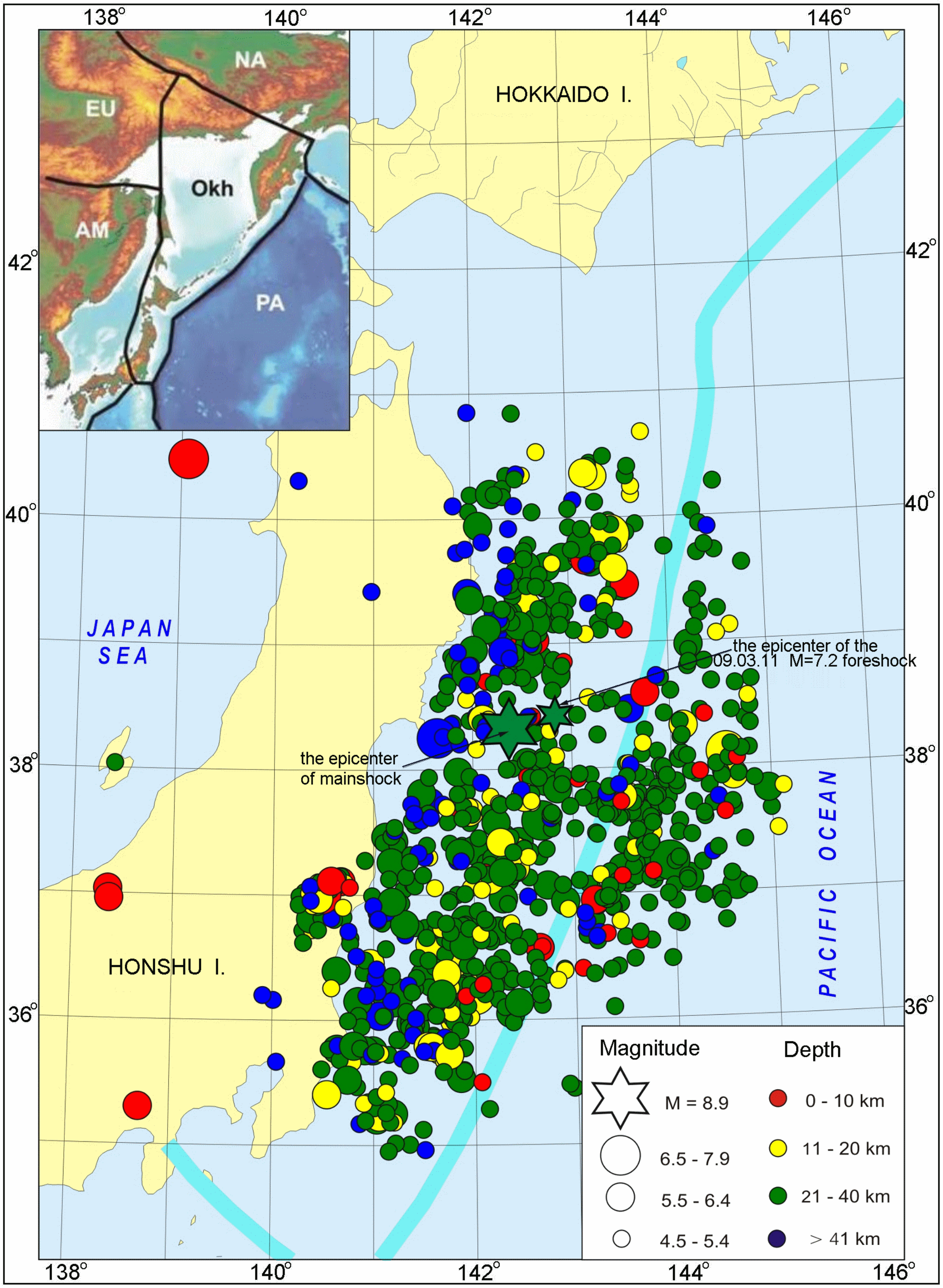

Figure 3. Location of epicenter of main shock of the 11 March 2011 earthquake, its foreshock and aftershocks, registered during 32 days according to the NEIC/USGS operative catalogue's data. See symbols in Figure 1.

Table 3. Earthquakes pairs (strongest main pulse – strong aftershock) in Japan region for 1900–2010 according to JMA data

Date, yyyy/mm/dd	Time, JST	Epicenter coordinates φ, °N	λ, °E	Depth, km	Magnitude	$M_m - M_a$
1922/09/02	0416	24.5	122.2	60	7.6	0.3
1922/09/15	0431	24.5	122.2	60	7.3	0.3
1923/09/01	1158	35.1	139.5	60	7.9	0.6
1923/09/02	1146	34.9	140.2	60	7.3	0.6
1931/03/09	1249	41.2	142.5	0	7.6	1.5
1931/03/10	0256	40.6	143.0	60	6.1	1.5
1933/03/03	0231	39.2	144.5	10	8.1	1.3
1933/03/03	0542	39.8	144.4	40	6.8	1.3
1936/11/03	0546	38.2	142.2	60	7.7	0.6
1937/07/27	0456	38.3	142.1	40	7.1	0.6
1938/11/05	1743	37.1	141.6	20	7.7	0.4
1938/11/05	1950	37.3	141.7	30	7.3	0.4
1944/12/07	1335	33.7	136.2	30	8.0	0.9
1945/01/13	0338	34.7	137.0	0	7.1	0.9
1946/12/21	0419	33.0	135.6	30	8.1	1.8
1946/12/21	0745	33.3	135.2	0	6.3	1.8
1952/03/04	1022	41.8	144.1	0	8.1	1.0
1952/03/04	1040	42.0	144.3	10	7.1	1.0
1953/11/26	0248	34.0	141.7	60	7.4	0.8
1953/11/26	1714	34.0	141.5	70	6.6	0.8
1968/05/16	0948	40.7	143.6	0	8.2	0.5
1968/05/16	1939	41.4	142.9	40	7.7	0.5
1973/06/17	1255	43.0	146.0	40	7.8	0.7
1973/06/24	1143	43.0	146.8	30	7.1	0.7
1994/12/28	2119	40.4	143.7	0	7.7	1.3
1994/12/29	0552	40.1	143.0	0	6.4	1.3
2003/09/26	0450	41.8	144.1	42	8.0	0.9
2003/09/26	0608	41.7	143.7	21	7.1	0.9
Average value of difference $M_m - M_a$						0.90
Standard deviation						0.44

when construction and analysis of dependence, similar to the described one, are implemented in real time. The first characteristics is a sharp decline of velocity of events flow at transferring from the 3-rd interval to the 4-th. The second relates to a sharp increase of variability of character of aftershock process, expressed in a wide spread of points in Figure 4, including anomalous outbursts. Such variable behavior of aftershock process might indicate its instability.

Fifth interval of the aftershock sequence of the Andaman earthquake relates to superposition of aftershocks of the main event and the strongest aftershock, which again led to a sharp increase of intensity of aftershock process.

Before we start an analysis of the analogical graph of the 11 March 2011 Great Japan Earthquake, let us note that its aftershock series might have another number of stages of development and a different duration of each of them. After one month of observations the aftershock process was probably passing through the second stage (Figure 4). At this stage a possibility of predicting (after sharp outbursts in the graph) the increase of activity related to earthquakes of magnitude around 6–7 might appear. For the purpose of verifying of a possible scenario the process must be monitored constantly in near-real time. The constantly updated NEIC/USGS Operative catalog can serve these purposes in case of mega-earthquakes. It can be found at [http://earthquake.usgs.gov/regional/neic/].

Now let us try to give an answer to another important question: if an aftershock process develops in accordance with the Sumatra-Andaman earthquake scenario, where is the most likely location of a seismic center of $M \sim 8.0$? Let us formulate a second provision of a second possible scenario: the most probable location of a second strongest aftershock should be the area of aftershock cluster behind the Japan trench. This provision is based on the analogy of dynamics of filling of aftershock area, observed at the large 15 November 2006 Simushir earthquake ($M_w = 8.3$) [*Tikhonov et al.*, 2008].

It can be seen in Figure 1 that the area of aftershocks located to the east of Honshu was filled unevenly. It can be divided into the main area, which borders with the island, and

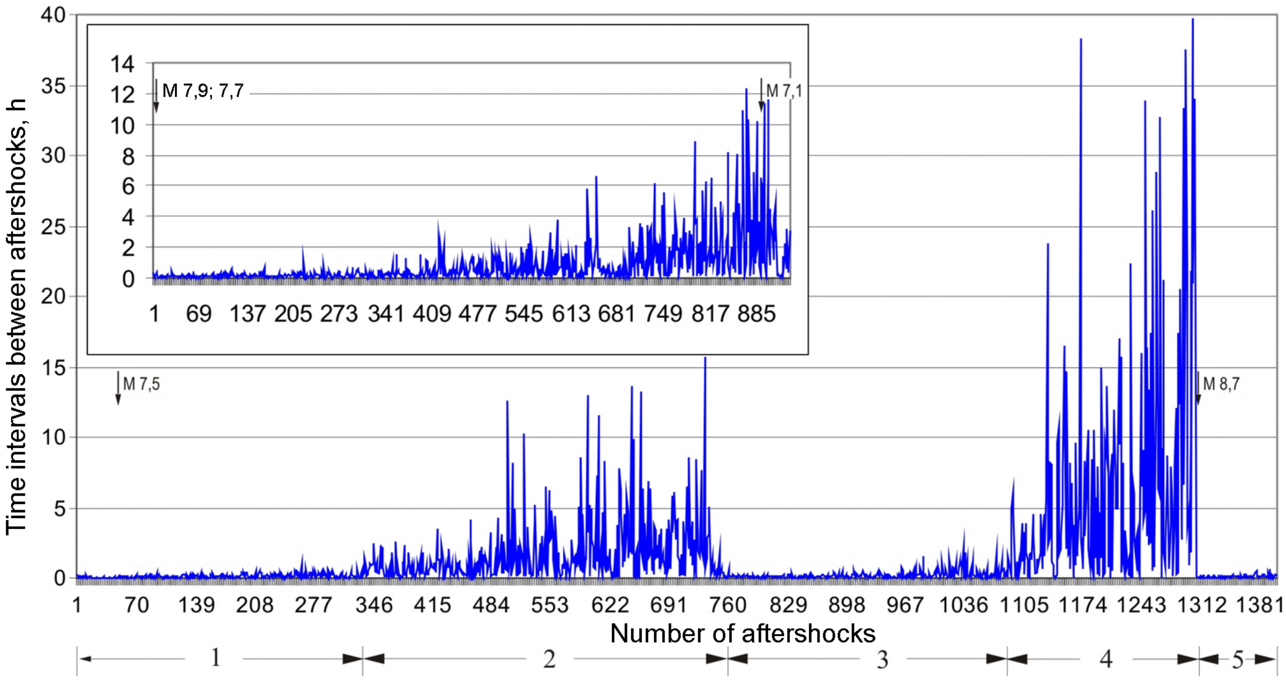

Figure 4. Time intervals' dependence between the 2004 Sumatra-Andaman aftershocks on the numbers of recurrent pulses and analogical dependence for the 2011 Great Japan Earthquake by observations during 32 days (see box). The graph is divided here along a horizontal axis, in 5 parts related to separate stages of aftershock process. Aftershocks of $M \geq 7.0$ are marked by vertical arrows.

an additional, secondary area, located to the north of 37.0°N behind the Japan trench, serving as a dividing border. Same situation was observed at the time of the 15 November 2006 Simushir earthquake ($M_w = 8.3$). Two aftershock clusters were formed: one near Simushir, and the second near the Kuril trench. The second earthquake ($M_w = 8.1$) occurred exactly in this area on 13 January 2007. At that the aftershocks of the first earthquake precisely marked the area, where the second event occurred in two months. Therefore a possibility of recurrence of the same scenario, as in the Middle Kuril islands, to the east of Honshu, cannot be excluded.

Let us mention in the conclusion that the suggested two scenarios don't exclude other versions of continuation of the aftershock process. Both scenarios, the first and the second one, are equally probable, but the author gives more preference to the second scenario.

Conclusion

The 11 March 2011 Great Japan Earthquake ($M_w = 9.0$) was a unique event for the Japan region. Historical earthquake catalog data provide the evidence of the fact that no earthquakes of such scale occurred here during the period of more than 1000 years. It has refuted the point of view that no mega-earthquakes can occur in this region due to the fragmentation of the lithosphere into separate structural blocks with characteristic linear dimensions ~ 150 km.

An evaluation was given to the period of recurrence (~ 40 years) of large ($M \geq 7.6$) earthquakes in the epicenter area of the mega-event at the size of $5° \times 4°$. In the region to the east of Honshu the existence of a seismic gap at the length of ~ 800 km was retrospectively revealed, located to the south of 39°N and filled recently with aftershocks of the mega-earthquake.

Analysis of pairs of events (strongest main event – strong aftershock) in the examined region in 1900–2010 showed that the average value of magnitude difference of main pulse and strongest aftershock was 0.90 ± 0.44 magnitude unit. This must indicate the fact that an aftershock with maximal magnitude has already realized. It was the first probable scenario of completion of the aftershock process.

It was mentioned that there was a significant analogy in attenuation dynamics of aftershock time series of the Great Japan (2011, $M_w = 9.0$) and Sumatra-Andaman (2004, $M_w = 9.3$) earthquakes. Another analogy in spatial distribution of aftershock epicenters of the Japan mega-event and Simushir (2006, $M_w = 8.3$) earthquake. It was suggested on the basis of these analogies that the second scenario with realization of aftershock of $M \sim 8.0$, shifted along the main trust towards the deep oceanic trench, was more probable.

At approximately equal possibility of realization of the first and second scenario the author gives preference to the second scenario.

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