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# Great Japan Earthquake of March 11, 2011: Tectonic and Seismological Aspects

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**Abstract**—The tectonic and seismological aspects of the Great Japan Earthquake, which occurred on March 11, 2011 ($M_w = 9.0$), at the Pacific margin of the northeastern part of Honshu Island, are discussed. The structure and seismotectonic data, seismicity, and the return period of the most powerful ($M \geq 7.6$) earthquakes throughout history and in modern times are represented. It is shown that the return period of the most powerful events is about 40 years, and that of megaearthquakes is 1000 years or more. A seismic gap of about 800 km in length is found in the region under study, located to the south of latitude 39°N and full of after-
2 shocks to the megaearthquake of March 11, 2011. This event is probably connected with the deep thrust along the Benioff zone and its structural front (Oyashio nappe at the middle Pacific continental slope). The after-
2 2 shock sequences of this megaearthquake and the Sumatra-Andaman (2004) megaearthquake are compared. It is found that several of their key characteristics (the number of aftershocks, the magnitude of the main shock, and the time of its occurrence) for 25 days are comparable for both cases with a significant difference in the energies of aftershock processes. A probable scenario for the origination of a repeated shock with $M \sim 8.0$ in the Japan Trench is discussed.

2 **Keywords:** active margin, trench, focal zone, deep thrust, nappe, earthquake, megaearthquake, aftershock sequence, most powerful aftershock, scenario of aftershock development.

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## INTRODUCTION

An earthquake with $M_w = 9.0$ occurred to the east of Honshu Island, Japan, on March 11, 2011, at 05:46 GT, or 14:46 LT (Fig. 1). Such seismic events are megaevents, i.e., earthquakes of a planetary scale. Every catastrophic event is traditionally called by a proper name. This event still has no final conventional name.

According to data from different sources, it was called the Northeastern Taiheiyou Earthquake, Tohoku-Chino Taiheiyou-oki Earthquake, or the Great Japan Earthquake.

Let us note an interesting regularity. Such seismic catastrophes are grouped in time (according to seismic measures). The last such group was observed in the 1960s–1970s, including the Kamchatka earthquake of November 4, 1952 ($M_w = 9.0$); the Chile earthquake of May 22, 1960 ($M_w = 9.6$); and the Alaska earthquake on March 28, 1964 ($M_w = 9.2$).

Forty year later, a new group of earthquakes began forming; this includes the Sumatra-Andaman earthquake of December 26, 2004 ($M_w = 9.3$) and the Chile earthquake of February 27, 2010 ($M_w = 8.8$). The Great Japan Earthquake of March 11, 2011 ($M_w = 9.03$), belongs to this group as well.

It was accompanied by a catastrophic tsunami. Waves 10–15 m (up to 20 m at certain points) in height swept across the northeastern coast of Honshu, penetrating far inland (up to several kilometers) in some places and damaging everything in their way. Gushing over a 6-m embankment near the Fukusima-1 atomic power plant (APP), the tsunami disabled the powering system there, which had been partly destroyed by the earthquake, and initiated technogenic catastrophes unprecedented in consequence.

The islands of Japan are located within the Pacific seismic belt and are characterized by one of the highest seismic level on earth. Nevertheless, no similar earthquakes had been observed in Japan throughout the 20th century or, probably, in all of history. By a fatal concourse of circumstances, these natural and technogenic catastrophes occurred at one of the most populated Pacific coasts. This resulted in 13 100 dead and injured, 17?100 missing people, and over $300 billion in damages and material loss (according to the official data of the government of Japan). The disaster became a national tragedy.

It should be also noted that the events occurred in a well-studied region with a dense network of seismic stations, a modern tsunami warning system, a highly qualified staff, and a population of citizens very prepared for natural disasters [Ueda, 1978; Methods…, 1984; Mogi, 1988].

A description of any damaging earthquake and its consequences is a complex multipronged problem. It

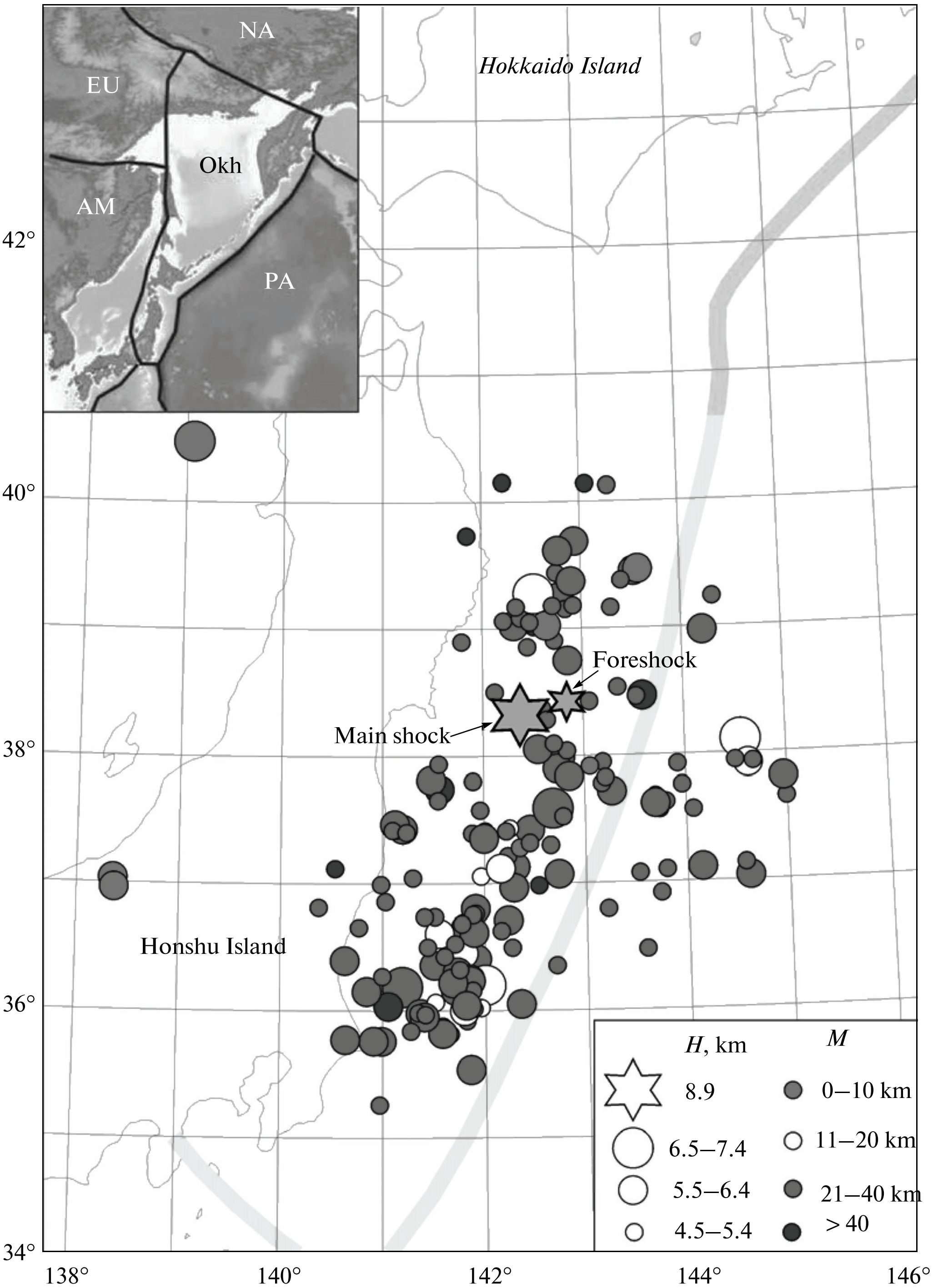


**Fig. 1.** Positions of the epicenter of the main shock of the earthquake of March 11, 2011 (large star), its foreshock (small star), and aftershocks (circles) recorded during the first day according to the NEIC/USGS catalog. The narrow bar is the axis of the deep trench. The inset shows the regional scheme of platform boundaries in the model [Wei and Seno, 1998]. The platforms are North American (NA), Eurasian (EU), Amur (AM), Pacific (PA), and Okhotsk (Okh).

usually includes a review of the seismotectonics of the region under consideration, a rank of this event in a series of similar earthquakes that occurred earlier in this region, a description of the seismicity anticipating the event, a post factum revelation of different forerunner effects, an estimation of the parameters of the main shock and development of the aftershock process, a mapping of macroseismic manifestations, etc.

No doubt a lot of reports, papers, books, and other works will be devoted to the Great Japan Earthquake

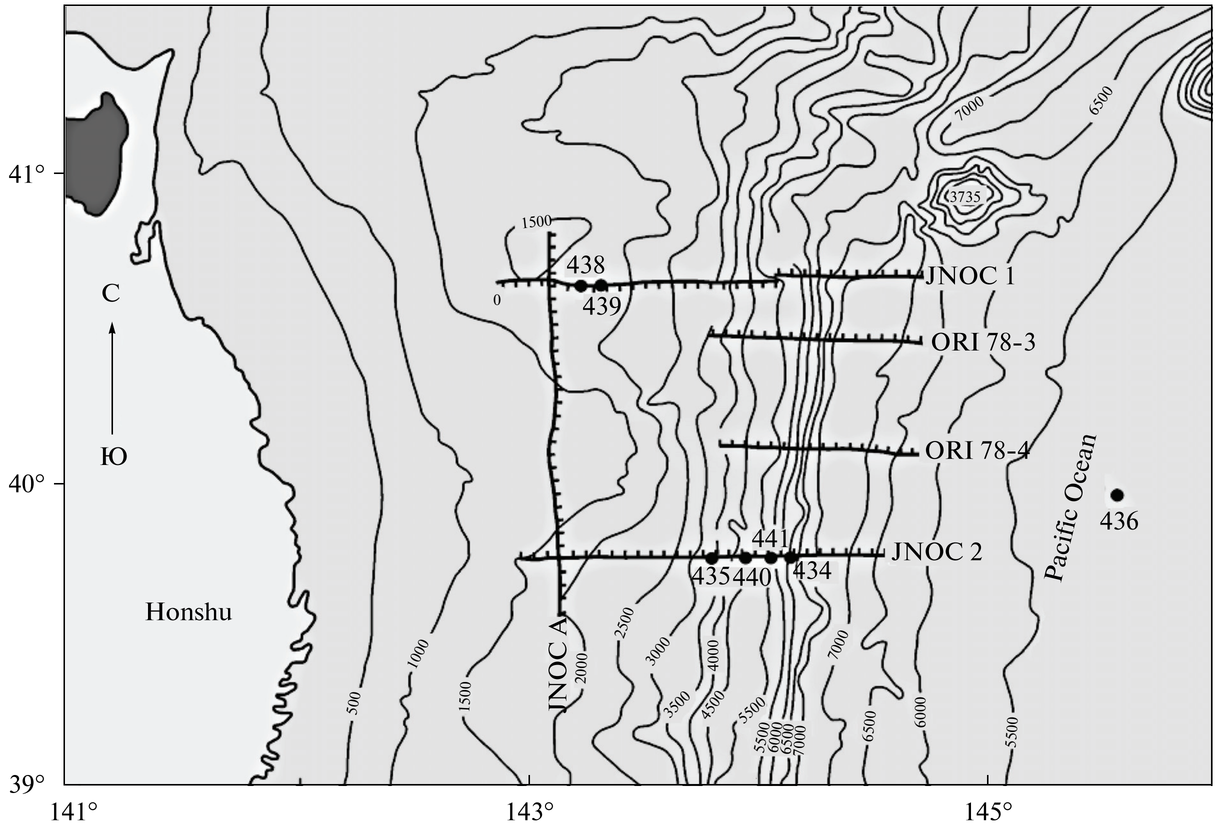


**Fig. 2.** Bathymetric map of the region under study with the positions of the Japan National Oil Company (JNOC) RM-CDP profiles and holes of the 56th cruise of the *Glomar Challenger* [Initial…, 1980].

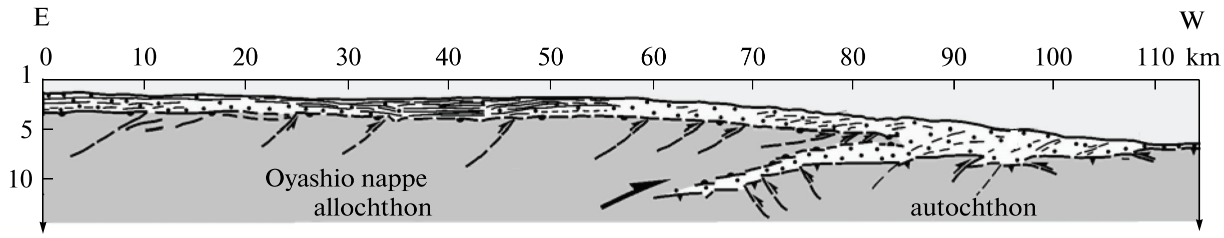


**Fig. 3.** Interpreted JNOC 2 depth profile [Lomtev and Patrikeev, 1983a]. AP is the accretionary prism; FA is the accretion front. The light gray color at the top shows the water layer of the Pacific Ocean, the Cenozoic sedimentary cover, the accretionary prism, and the acoustic basement of the allochthon and autochthon. The dashed lines with arrows show the reflecting areas marking the contraction faults and assuming the shifts along them. The thick arrow shows the direction of motion of the mid-Quaternary Oyashio nappe (allochthon) and Honshu arc to the adjacent floor of the Pacific Ocean.

of 2011. Taking this into account, the aim of this work is to provide for data on the structure and seismotectonics of the Pacific margin of northeastern Honshu Island, i.e., show the cause–effect correlation between tectonic and seismic processes; then, using data on historical and modern earthquakes, give some idea about the return of the most powerful ($M \geq 7.6$) seismic events in this region; and, finally, estimate the scale of the event, the character of the aftershock process development, and probable scenarios for its development based on the online seismic data received during the first 25 days after the megaevent occurred.

## TECTONIC STRUCTURE OF THE REGION

The bathymetry and tectonic structure of the Pacific margin of the Honshu arc (Tohoku) and the Japan Trench (900 km in length and 100 km in width)

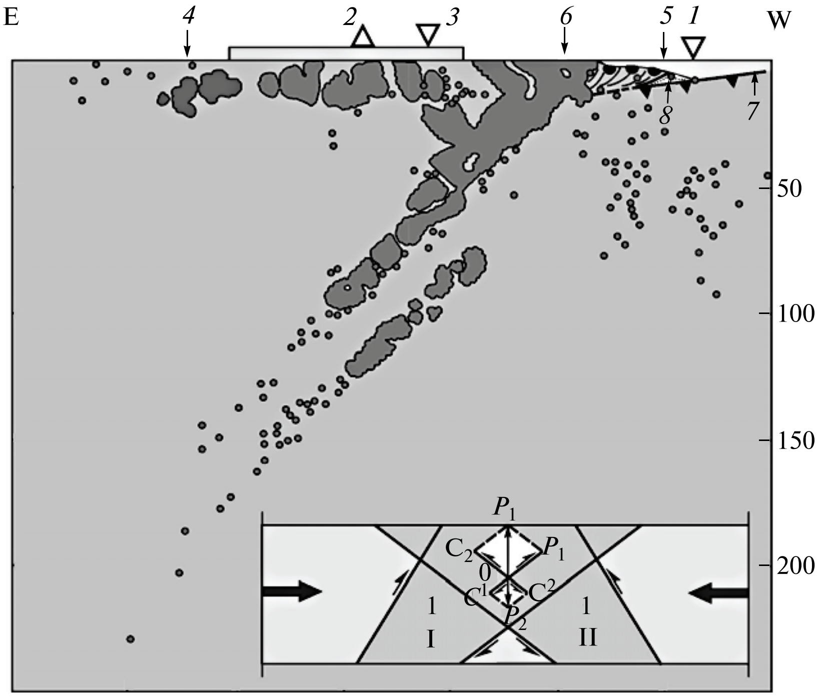


**Fig. 4.** Combined longitudinal profile of opposing focal zones and the JNOC 2 RM-CDP profile [Lomtev and Patrikeev, 1985]: (*1*) the accretion front in the basement of the Pacific slope of the Honshu arc, (*2*) the volcanic front, (*3*) the aseismic front, (*4*) the basement of the Sea of Japan slope of the Honshu arc, (*5*) the Oyashio nappe front, (*6*) the nappe root and the position of the thermal minimum, (*7*) the superface of the movable autochthon (stratum 2), and (*8*) the accretionary prism. Black dots and their clouds are the earthquake focuses in the Benioff and Tarakanoc zones, the region of shallow (crust) seismicity under the Honshu arc, and the adjacent part of the trench of the Sea of Japan. The accretionary prism, the Japan Trench, Honshu arc with the Oyashio nappe in front, and the underlying crust-mantle substratum are distinguished.

have been studied for more than 100 years [Ueda, 1978]. Modern ideas began forming in the 1970s–1980s after the run of the drilling geobeam *Glomar Challenger* ship (Figs. 2, 3) and RM-CDP multichannel seismoprofiling (reflection method: common depth point) [Shiki and Misava, 1980; Initial…, 1980; Matsuzawa et al., 1980]. A geological and geophysical survey of the undersea outskirts of the Japanese Archipelago carried out by the Japan Geological Service headed by Prof. E. Honsa, became an important addition [Geological…, 1978, etc.]. The materials presented below and ideas about the structure and seismotectonics of the region are based on the results of a geological interpretation of the MOV and drilling data in this region [Lomtev, 1989, 2010; Lomtev and Patrikeev, 1983a, 1983b, 1985; Lomtev et al., 1997, 2004, 2007].

A narrow shelf and a wide continental shoulder are distinguished in the relief of the Pacific margin of the northeastern part of Honshu Island (hereinafter, NE Honshu). The latter includes a slope top bench; a middle slope with a broad top terrace and a step at depths of 1–2 and 5 km; respectively; and a lower bench, or inner slope, of Japan Trench based on its accumulative floor composed by Tsugaru turbidities (Figs. 2, 3).

The V-shaped 8-km-thick prominence of the acoustic Oyashio basement covered with the Cenozoic sea basin is clearly pronounced in the structure of the middle slope in the JNOC 2 depth profile. This prominence is composed of Late Cretaceous basic sediments and exposed by hole 439 and, probably, more ancient complexes [Choi, 1987]. With accounting for the data from hole 436 on the marginal swell, by exposing Late Cretaceous rocks (opaque horizon of layer 2 [Initial…, 1980; Patrikeev, 2009], we can conclude that the acoustic basement of the middle slope is doubled between the top terrace and the step (Fig. 3).

Such flat sloping allochthon wedges are called nappes or thrust nappes [Lomtev and Patrikeev, 1985]. The intermittent slope reflecting areas inside the acoustic basement mask overthrust faults, which are connected with friction at the base during the eastward motion of a nappe up to the superface of stratum 2 (autochthon). According to drilling and RM-CDP data, the 25-km-wide inner slope of the Japan Trench is composed by dislocated Cainozoic rocks of an accretionary prism of up to 4 km in thickness, often doubled along the western dipping thrusts (holes 434 and 441 [Initial…, 1980; Lomtev and Patrikeev, 1983a, 1985]).

**Table 1.** List of earthquakes with $M \geq 7.6$ in the seismically active Japanese zone for 869–2010 [Usami, 1979]

| No. | Date | Focal time*, h–min | Coordinates of epicenter | | Depth, km | $M$ |
|---|---|---|---|---|---|---|
| | | | φ°, N | λ°, E | | |
| 1 | July 13, 869 | At night | 38.5 | 143.8 | – | 8.6 |
| 2 | December 2, 1611 | After midnight | 39.0 | 144.5 | – | 8.1 |
| 3 | June 9, 1646 | – | 37.7 | 141.7 | – | 7.6 |
| 4 | April 13, 1677 | 10–21 | 40.0 | 144.0 | – | 8.1 |
| 5 | May 13, 1717 | – | 39.4 | 142.4 | – | 7.6 |
| 6 | July 20, 1835 | 04–15 | 37.9 | 141.9 | – | 7.6 |
| 7 | August 5, 1897 | 00–10 | 38.3 | 143.3 | – | 7.6 |
| 8 | March 2, 1933 | 17–31 | 39.1 | 144.7 | ~20 | 8.3 |
| 9 | November 2, 1936 | 20–46 | 38.2 | 142.2 | 50~60 | 7.7 |
| 10 | November 5, 1938 | 08–43 | 37.1 | 141.7 | 20 | 7.7 |
| 11** | March 11, 2011 | 05–46 | 38.3 | 142.4 | 24 | 8.9 |

Notes: * Greenwich time.
** NEIC/USGS data.

Young thrusts and fold thrusts of the autochthon are eastern dipping due to creeping strata 1–4; they fix the tectonic mobility of the autochthon. Since the ramps on the western edge are dipping in opposite directions, the trench should be considered a contraction structure of the ramp-graben type (more precisely, semigraben) with accounting for its latitude asymmetry.

A refinement of the accretionary prism to the west from 4 km to 100–150 m and less with accounting for drilling data is caused by the stripping and swirling of the Cenozoic sea basin during the nappe motion; therefore, they are combined into the blanket "regional nappe–accretionary prism" tectonic pair. Taking into account the position of the thermal minimum, the blanket deposition balance, and the cross point of opposing focal zones, the position of the Oyashio nappe root was determined at a distance of 90 km to the west of its front, i.e., under the top terrace (see Fig. 4). If the western dip of the autochthon is kept, then the root depth is 10–20 km. Therefore, the significant autochthon plunge is caused by an increasing lithostatic load to the autochthon (the tectonic pair).

Dating the structures of the Pacific margin of NE Tokhoku and the Japan Trench is a complicated problem. Thus, the age of the Japan Trench is determined from Holocene to Cretaceous–Jurassic periods [Lomtev, 1989]. In addition, the discovery of relict-Neogene–early-Quaternary fans of canyons and their valleys on the floor of the NW Pacific [Lomtev, 2010], formed by turbidite underflow [Lomtev et al., 1997,
1 2004; Patrikeev, 2009; Mammerickx, 1980], reliably fixes a mid-Quaternary (about 0.5–1 million years) age of the Japan and other trenches, as determined from a complex of independent signs. Let us note that the Tsugaru canyon, starting in the Tsugaru Strait between Honshu and Hokkaido islands, has the Nakve valley and a large fan after the trench to the south of the Tuscarora fault bench [Lomtev et al., 1997, 2004]. The drift of terrigene sediments from the island arcs and the eastern margin of Asia is dated, according to drilling data, by mid-Miocene or, probably, early-Miocene in grabens [Lomtev et al., 1997, 2004]. Thus, accounting for the data [Geologicheskoe…, 1968], we can conclude that the history of the Honshu arc goes back to the beginning of the Miocene. It obducted to the floor of NW Pacific to about 90 km with formation of the middle (Oyashio bench) and bottom (accretionary prism) slopes and the Japan Trench in the mid-Pleistocene during the Pasadena revolution. The absence of a rift graben (or fault) of comparable width on the Honshu arc higher than 8–9 km in the adjacent depth of the Sea of Japan [Geological…, 1978] capable of compensating for the tectonic doubling of the crust along the Oyashio nappe points out to its allochtonous occurrence and, hence, tectonic mobility.

## THE MOST POWERFUL PAST EARTHQUAKES IN THE EPICENTER REGION OF THE MEGAEVENT

According to [Usami, 1979], seismic events occurred before 1892 are considered historical earthquakes in Japan. In 1893, the Gregorian calendar was introduced there, changing the lunar calendar of Japan; seismographs began to be used for earthquake recording. The works [Musya, 1942–1943, 1949] are the main source of data on more than 6000 historical earthquakes in Japan. For Europeans, the work

[Usami, 1979] is more accessible; it was written in English and includes a catalog of historical ($M \geq 5.9$) and instrumentally recorded earthquakes for 599–1975.

A large number of powerful earthquakes in Japan and around the Japanese islands forces us to limit ourselves by a small area $5 \times 4°$ in size, including the epicenter region of the earthquake under study (see Fig. 1) with the coordinates $\varphi = 35.0°–40.0°$N and $\lambda = 141.0°–145°$E. According to the catalog [Usami, 1979] and data of the Japan Meteorology Agency [JMA…, 2011], 11 events with $M \geq 7.6$ were recorded in this seismically active region from 869 to March 2011 (Table 1).

According to Table 1, the most powerful past earth-
2 quake in the region of the megaearthquake of March 11, 2011, was the event of 869 with $M = 8.6$. Usami estimates its magnitude according to the Richter scale, which has a threshold at $M \sim 8.6$ and higher. The magnitude of the event of 869 could be higher if he uses the Kanamoti scale [Kanamori, 1983]. No such events were observed in the next 742 years, while 10 similar earthquakes occurred during the following 400 years.
2 The present megaearthquake has continued the cycle of seismic activity. Thus, about a 40-year return period of the most powerful earthquakes is observed in the region under study in the activation phase.

## MODERN SEISMICITY OF THE REGION UNDER STUDY

The Pacific margin of NE Honshu relates to the active regions due to its seismicity. A decrease in the error (to 1–2 km) of the earthquake hypocenter detection in the 1970s allowed Japanese seismologists [Hasegawa et al., 1979] to reveal here the two-layer structure of the Benioff focal zone dipping westward to depths of 130–200 km at an angle of 30° (Fig. 4) and different types of seismic dislocations in its upper (thrusts) and lower (faults) planes. In Fig. 4, the Benioff zone (its upper plane) crops out at the middle slope in the Oyashio nappe belt. Hence, this zone can be considered a deep thrust and the nappe can be considered its structure front [Lomtev and Patrikeev, 1985].

In the same period, Sakhalin seismologists headed by R.Z. Tarakanov revealed the bogen structure of the Kuril segment of the Benioff zone and a shallow (50–100 km) opposing focal zone dipping eastward under the marginal swell [Gnibidenko et al., 1980; Tarakanov et al., 1977]. Kropotkin (1978) suggested calling it the Tarakanov zone. The outcrop of this zone at the Pacific coast of Honshu Island is called an aseismic front [Yoshii, 1975]. Thrusts oriented along the zone dipping dominate in focuses at the outcrop of this zone [Hasegawa et al., 1979].

Considering the geography and depth of the main shock of the catastrophic earthquake of March 11, 2011, and its aftershocks, as well as the structure of the Pacific slope, we can conclude that this event was caused by a deep thrust along the Benioff zone, including its structure front (Oyashio nappe). Its scale and energy turned out to be so large that faults of the autochthon [Lomtev, 2001] and opposing Tarakanov focal zone activated. Let us note that the seismicity of the outer slope of the Japan Trench and marginal swell, especially according to seismograph data, is quite high at some places, though it is studied insufficiently, especially as a part of shallow earthquakes [Gnibidenko et al., 1980; Lomtev, 2010].

As follows from Fig. 4, the Benioff and Tarakanov zones intersect under the middle slope, forming a rhombic seismically active structure [Lomtev and Patrikeev, 1983b, 1985]. According to the parallelogram rule, combined shifts of the top terrace in its focuses (in the form of steep and near-vertical thrusts) are capable of exciting tsunami waves by the piston gear scheme, including the last catastrophic events of March 2011 (see the inset in Fig. 4).

The region of shallow (to depths of about 30 km) or crustal seismicity under the Honshu arc is of importance in Fig. 4; it is not directly connected with the opposing focal zones. Analogously with Sakhalin [Lomtev et al., 2007], it can be caused by a gravity eastward strip of the earth's core along the aseismic uppermost lithosphere mantle (bedding strip) with a backcreep zone along the Sea of Japan continental margin of Honshu.

Taking into account the small depths of the Benioff zone and the length of the Honshu arc–Japan Trench system, as well as its position in the reentering structure angle formed by the large Mariana and Idzu-Bonin in the south and Kuril–Kamchatka in the north arc-trench systems and their deep thrusts, we can conclude that the components of longitudinal southern and northern side contraction can play a noticeable role in the seismotectonics of the Honshu arc and Japan Trench.

It is important to pay attention to the increasing water consumption from underground sources and the increasing load to allochtonous crust from numerous objects and infrastructures, which promote an increase in its tectonic mobility; local settlements (Honshu Island); and, apparently, an increase in the preparation length and magnitude of shallow earthquakes.

Finally, key elements in the structure and seicmotectonics of the active Pacific margin of NE Honshu are the focal rhomb, formed by opposing deep thrusts of the Benioff and Tarakanov zones; the young Oyashio nappe; and the broad top terrace (the generation zone of the pistonlike tsunami) in the middle part

**Table 2.** Catalog of earthquakes in the region of Japan to the east of Hokkaido and Honshu islands with $M \geq 7.6$ for 1900–2010

| Date | Focal time, JST h–min | Coordinates of epicenter | | Depth, km | $M$ | Source |
|---|---|---|---|---|---|---|
| | | φ°, N | λ°, E | | | |
| 01.09.1923 | 11–58 | 35.1 | 139.5 | 60 | 7.9 | [*Usami*, 1979] |
| 09.03.1931 | 12–49 | 41.2 | 142.5 | 0 | 7.6 | |
| 03.03.1933 | 02–31 | 39.1 | 144.7 | 0–20 | 8.3 | |
| 03.11.1936 | 05–46 | 38.2 | 142.2 | 50–60 | 7.7 | |
| 05.11.1938 | 17–43 | 37.1 | 141.7 | 20 | 7.7 | |
| 04.03.1952 | 10–32 | 42.15 | 143.85 | 45 | 8.1 | |
| 16.05.1968 | 09–49 | 40.7 | 143.6 | 0 | 8.2 | [JMA…, 2011] |
| 16.05.1968 | 19–39 | 41.4 | 142.9 | 40 | 7.7 | |
| 17.06.1973 | 12–55 | 43.0 | 146.0 | 40 | 7.8 | |
| 15.01.1993 | 20–06 | 42.9 | 144.4 | 103 | 7.6 | |
| 28.12.1994 | 21–19 | 40.0 | 143.7 | 0 | 7.7 | |
| 26.09.2003 | 04–50 | 41.7 | 144.2 | 71 | 8.3 | |

Note: The moment amplitude $M_w$ for earthquakes of 1968–2003 is given according to [Kanamori, 1983].

of the slope. In addition, there is the accretionary prism at the inner slope and strip of strata 1–4 at the outer one (mobile autochthon [Lomtev, 2010]) in the Japan Trench. The peculiarities of the longitudinal contraction from the Kuril–Kamchatka and Mariana arcs (deep thrust) should be also studied.

Let us consider the most powerful earthquakes observed in 1900–2010 to the east of Hokkaido and Honshu islands (Table 2). The focal zones of these earthquakes are shown in Fig. 5a.

As can be seen from Fig. 5a, all the most powerful earthquakes occurred to the north of latitude 39°N, where the focal zones are dense. The event of 1897 ($M = 7.6$) occurred in the same region; its focus is not shown in Fig. 5a, since it is out of the considered time frame. An extensive (800 km) region of relative quiescence was located to the south of latitude 39°N. The last powerful earthquakes occurred in this region in 1923, 1936, and 1938. In view of this, the relative quiescence lasted about 75. It is seen from Fig. 5b that the seismic catastrophe of March 11, 2011, took place in this region. Thus, there were some indications that we should prepare for a strong earthquake near Honshu Island, but seismologists did not pay attention to them.

Periodicities synchronizing the occurrence of powerful earthquakes in different seismically active regions have been studied in [Tikhonov, 2010]. The periodicity $T = 780$ day has been revealed for three regions (to the east of Honshu and Hokkaido islands, Kamchantka, and the South Kurils) for earthquakes with $M \geq 7.6$. According to observation data for about 100 years, time intervals (quiescence and alarm windows) characterizing the periods of decreased and increased occurrence probability of earthquakes with $M \geq 7.7$ have been calculated. The corresponding curve for the first region is shown in Fig. 6; the circle on the curve corresponds to the occurrence time of the Great Japan Earthquake of March 11, 2011. It occurred in the end of an alarm window (December 24, 2009–March 20, 2011); i.e., it obeys the general regularity observable over the last 100 years.

## THE MAIN SHOCK AND DYNAMICS OF THE PROCESS DEVELOPMENT OF AFTERSHOCKS

According to online data from the National Earthquake Information Center of the U.S. Geological Survey (NEIC/USGS), the hypocenter was located to the east of Honshu Island at the point $\varphi = 38.32°N$, $\lambda = 142.37°E$ at a depth of $h = 24.4$ km (see Fig. 1). The earthquake resulted from the crust shifts in the contact zone of the Pacific and North American (Okhotsk) platforms [Wei and Seno, 1998] (see the inset in Fig. 1). The focal mechanism according to the data is in a good agreement with that according to the data of the Harvard Scientific Center (http://www.globalsmt.org). According to these definitions, the azimuth of the first nodal plane course was 162°, the slope angle was 17°, and the slide angle was 45°; for the second nodal plane, these parameters were 28°, 78°, and 102°, respectively. Such a mechanism corresponds to the thrust-type motion in a focus if the second nodal plane is taken as working with accounting for the fact that its course azimuth agrees with the first-day aftershock cloud course. According to preliminary estimates

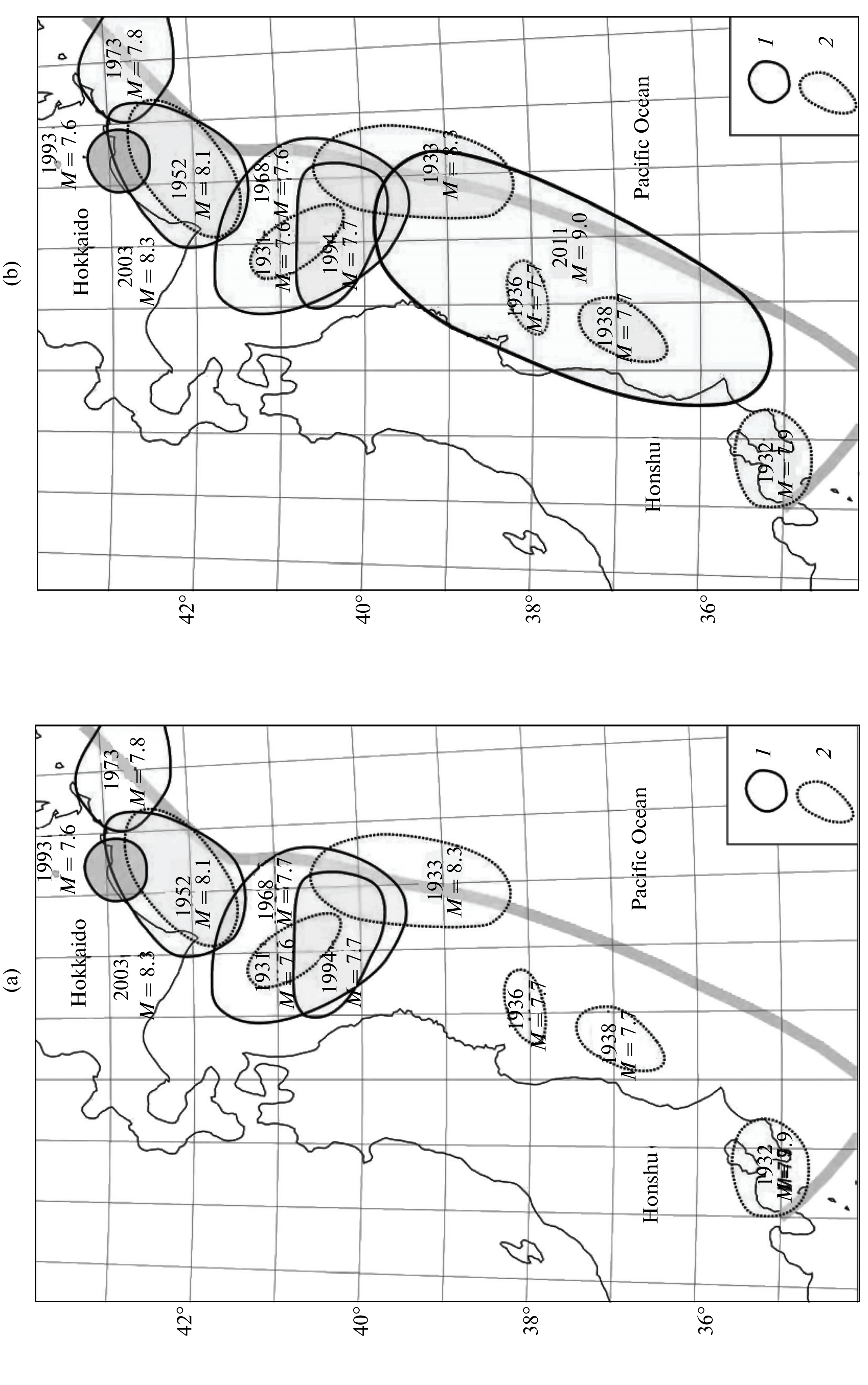


**Fig. 5.** Focuses of the most powerful ($M \geq 7.6$) earthquakes to the east of Hokkaido and Honshu islands for (a) 1900–2010 and (b) 1900–March 2011. The figure shows the filling of the seismic gap located to the south of latitude 39°N and existing before 2011, with aftershocks of the earthquake of March 11, 2011. (*1*) The focal regions contoured according to the data of the first-day aftershocks and (*2*) not very accurate boundaries of focal regions.

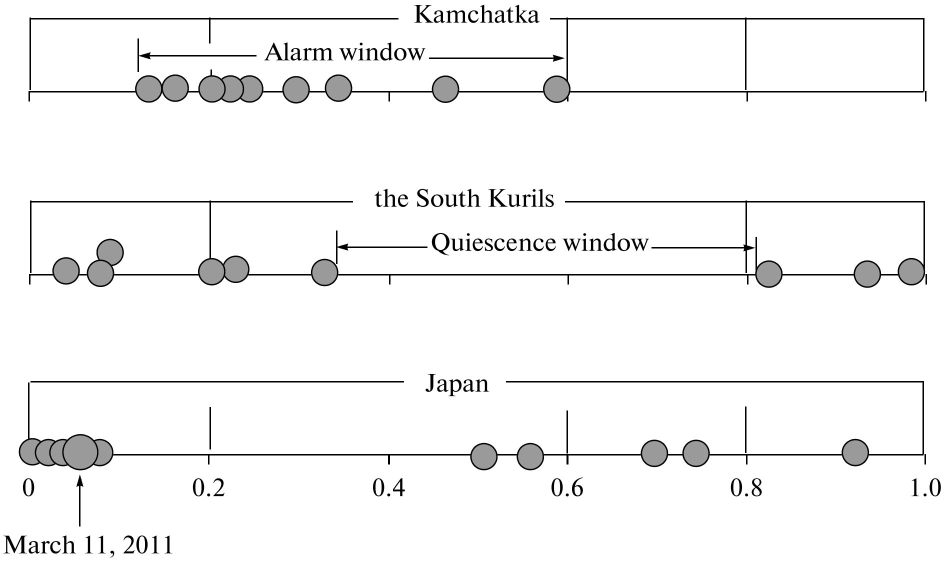


**Fig. 6.** Mapping of clusters of the most powerful ($M \geq 7.7$) shallow earthquakes in regions of Kamchatka, the South Kurils, and the islands of Japan (to the east of Hokkaido and Honshu) onto the summary involute of the ring (0 and 1 is the same point) corresponding to the period $T = 780$ day. The earthquake catalog data [New…, 1977; JMA…, 2011; Earthquakes…, 2003–2009] for 1900–2001 (the first and the third regions) and 1918–2003 (the second region). The number of clusters in the samples $n = 9$.

received from GPS observations, the horizontal shift was about 4.5 m toward the Pacific Ocean.

The initial phase of the aftershock sequence after
2 the megaearthquake to the east of Honshu Island was apparently recorded by remote seismic stations, in particular, those belonging to the global NEIC/USGS network. Instruments at JMA stations returned off-scale readings or were broken. According to the NEIC/USGS data, about 160 shocks with $M = 4.6$–
2 7.1 were recorded during the first day after the megaearthquake (22 of them had $M \geq 6.0$; Fig. 1). The aftershock process developed from the north to the south toward Tokyo. The magnitude of the most powerful aftershock, which originated 39 min after the main shock, was 7.1. Looking ahead, let us note that this value was not exceeded for 25 days.

About 130 aftershocks with $M \geq 4.6$ were recorded on the second day (seven of them had $M \geq 6.0$), and only 86 were recorded on the third day (one shock with $M = 6.0$). About 875 aftershocks were recorded in 25 days (Fig. 7).

Most hypocenters were located at depths of 20–40 km. The aftershock epicenters covered a large area 650 km in length and about 350 km in width from the Honshu coast to the deep trench and even behind it.

The general character of the aftershock sequence damping is shown in Fig. 8. For comparison, there is an analogous plot for the Sumatra-Andaman earthquake of December 12, 2004, with $M = 9.3$.

It can be seen from Fig. 8 that the behavior of seismic processes with respect to the parameter $N$ is similar for these megaevents, except for the first day, when the energies, i.e., the numbers of powerful ($M \geq 6.0$) aftershocks, differ significantly: 22 aftershocks for the first event and only 9 for the second one.

For comparison, let us consider the number of aftershocks for the Sumatra-Andaman earthquake, which were recorded by USGS over 25 days. It recorded about 680 aftershocks with $M \geq 4.6$, i.e., a quite comparable number. The most powerful aftershock with $M = 7.5$ originated 3 h 22 min after the main shock; the fault length in the focus was 1300 km [Kosobokov, 2005]. Thus, the number of aftershocks, the magnitude of the most powerful shock, and the time of its occurrence were comparable in both cases at a significant difference in the aftershock-process energies.

The difference in energies between the main shock and an aftershock (the strongest over 25 days) is about two units of magnitude (1000-fold relative to energy) in both cases. A vital question arises: is there a probability for a more powerful aftershock of the Great Japan Earthquake than that observed 39 min after the main shock ($M = 7.1$)? We know the answer for the Sumatra-Andaman earthquake: an aftershock with $M = 8.6$ occurred three months after the main shock.

There are two answers, probable and improbable, and we believe the former, according to which one more catastrophic earthquake with $M = 8.0 \pm 0.5$ is probable at NE Honshu. What is the basis for this opinion? First, the law—discovered by M. Botom [Bath, 1965]—for the difference between the magni-

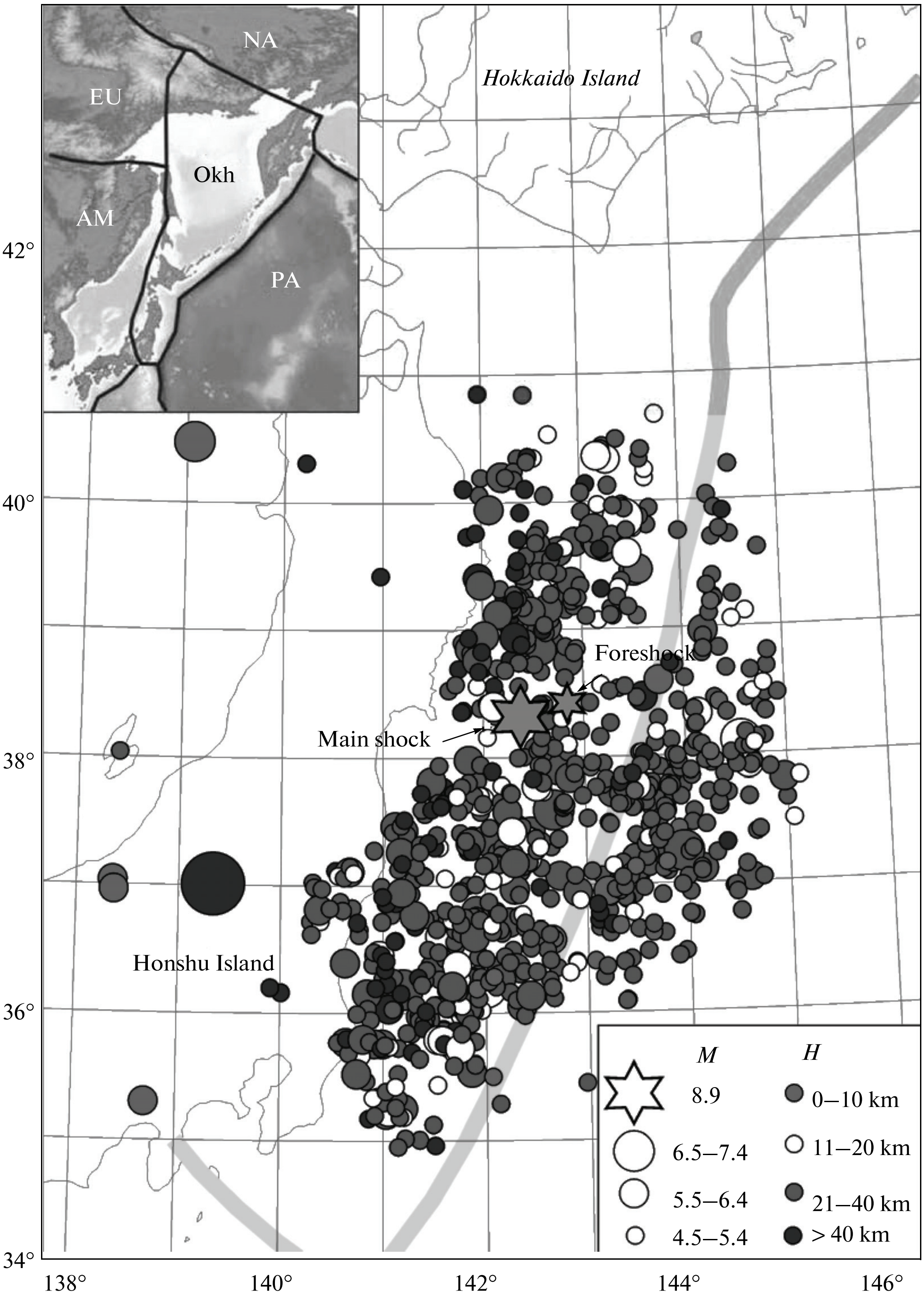


**Fig. 7.** Positions of the epicenter of the main shock of the earthquake of March 11, 2011, and its foreshock and aftershocks recorded over 25 days according to the NEIC/USGS catalog. See notations in Fig. 1.

tudes of the main shock and the most powerful aftershock, which is estimated as 12 units of magnitude; second, the similarity of aftershock processes after the Japanese megaevent and the Sumatra-Andaman earthquake (see Fig. 5 in [Rodkin and Tikhonov, 2011]).

The difference in magnitudes of the main shock and the most powerful aftershock over 25 days—equal

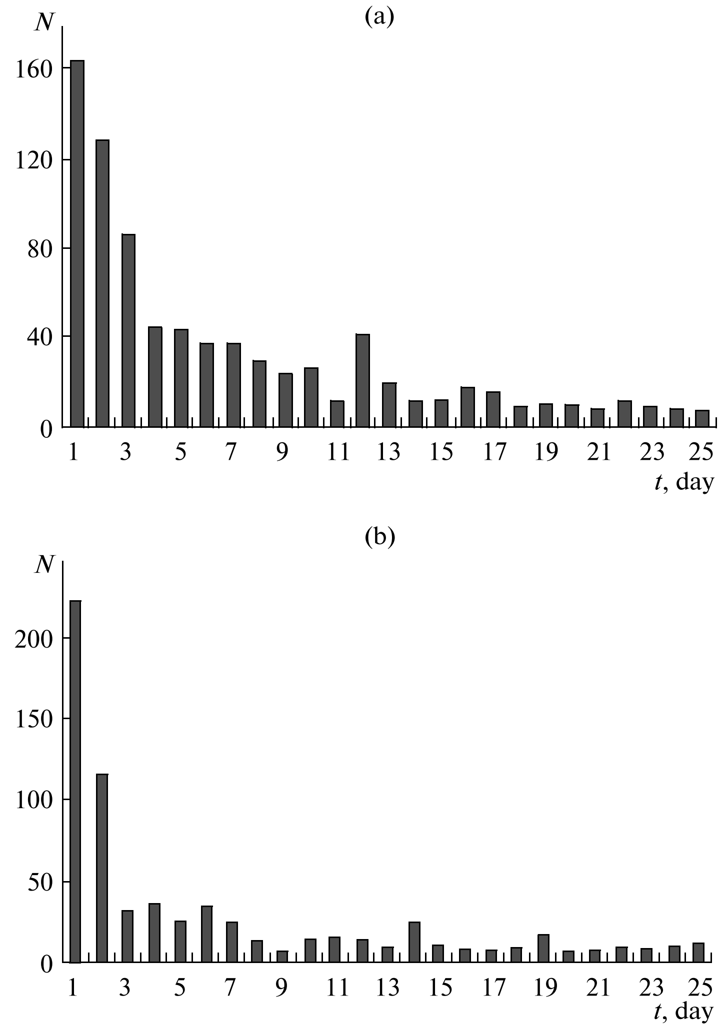


**Fig. 8.** Hystograms characterizing the aftershock sequence damping of (a) the Great Japan Earthquake of March 11, 2011, and (b) the Sumatra-Andaman earthquake of December 12, 2004. $N$ is the number of aftershocks with $M \geq 4.6$ per day.

to 1.9 units of magnitude—is a unique case for the powerful Japanese earthquakes in the region under study. Table 3 presents 14 pairs of events (the most powerful main shock–strong aftershock) in this region in 1900–2010 according to JMA data. The highest value $M_{main} - M_{aft} = 1.8$ in the table corresponds to the pair of events occurring on December 21, 1946. However, this estimate is somehow uncertain, because there were two powerful earthquakes ($M = 8.0$ and 8.1) at 04:19 on December 21, 1946, in the JMA catalog; an event with $M = 6.3$ was recorded 3 h 26 min later.

An analysis of the parameter distribution ($M_{main} - M_{aft}$) is not quite correct due to the small size of the sample; therefore, let us restrict ourselves by calculating the mean value of this parameter for the considered seismically active region. It was equal to 0.90 ± 0.44. Hence, the Bot law is true for Japanese earthquakes with something to spare (0.3 of units of magnitude).

Another important question is as follows: if the aftershock process develops according to the Sumatra-Andaman scenario, where is the most probable location of the focus with $M = 8.0 \pm 0.5$? In our opinion, the development of the scenario relative to its location, which was observed during the most powerful Simushir earthquakes on November 15, 2006 ($M_w = 8.3$), and January 13, 2007 ($M_w = 8.1$), is probable [Tikhonov et al., 2008].

As is seen from Figs. 1 and 3, the aftershock region is filled irregularly for 25 days. We can distinguish here the basic aftershock concentration adjacent to the island and the secondary region, located to the north of latitude 37.0°N behind the deep trench, which serves a boundary. This spatial feature of the aftershock field was noted in [Rodkin and Tikhonov, 2011] for a recording range of 15 days.

In the 2006 Simushir earthquake, two aftershock zones were also observed: the first one near Simushir

**Table 3.** Pair of earthquakes (the most powerful main shock–strong aftershock) near the islands of Japan for 1900–2010 according to the JMA

| Date | Focal time, JST h–min | Coordinates of epicenter | | Depth, km | $M$ | $M_{main} - M_{aft}$ |
|---|---|---|---|---|---|---|
| | | φ°, N | λ°, E | | | |
| 02.09.1922 | 04–16 | 24.5 | 122.2 | 60 | 7.6 | 0.3 |
| 15.09.1922 | 04–31 | 24.5 | 122.2 | 60 | 7.3 | |
| 01.09.1923 | 11–58 | 35.1 | 139.5 | 60 | 7.9 | 0.6 |
| 02.09.1923 | 11–46 | 34.9 | 140.2 | 60 | 7.3 | |
| 09.03.1931 | 12–49 | 41.2 | 142.5 | 0 | 7.6 | 1.5 |
| 10.03.1931 | 02–56 | 40.6 | 143.0 | 60 | 6.1 | |
| 03.03.1933 | 02–31 | 39.2 | 144.5 | 10 | 8.1 | 1.3 |
| 03.03.1933 | 05–42 | 39.8 | 144.4 | 40 | 6.8 | |
| 03.11.1936 | 05–46 | 38.2 | 142.2 | 60 | 7.7 | 0.6 |
| 27.07.1937 | 04–56 | 38.3 | 142.1 | 40 | 7.1 | |
| 05.11.1938 | 17–43 | 37.1 | 141.6 | 20 | 7.7 | 0.4 |
| 05.11.1938 | 19–50 | 37.3 | 141.7 | 30 | 7.3 | |
| 07.12.1944 | 13–35 | 33.7 | 136.2 | 30 | 8.0 | 0.9 |
| 13.01.1945 | 03–38 | 34.7 | 137.0 | 0 | 7.1 | |
| 21.12.1946 | 04–19 | 33.0 | 135.6 | 30 | 8.1 | 1.8 |
| 21.12.1946 | 07–45 | 33.3 | 135.6 | 0 | 6.3 | |
| 04.03.1952 | 10–22 | 41.8 | 144.1 | 0 | 8.1 | 1.0 |
| 04.03.1952 | 10–40 | 42.0 | 144.3 | 10 | 7.1 | |
| 26.11.1953 | 02–48 | 34.0 | 141.7 | 60 | 7.4 | 0.8 |
| 26.11.1953 | 17–14 | 34.0 | 141.5 | 70 | 6.6 | |
| 16.05.1968 | 09–48 | 40.7 | 143.6 | 0 | 8.2 | 0.5 |
| 16.05.1968 | 19–39 | 41.4 | 142.9 | 40 | 7.7 | |
| 17.06.1973 | 12–55 | 43.0 | 146.0 | 40 | 7.8 | 0.7 |
| 24.06.1973 | 11–43 | 43.0 | 146.8 | 30 | 7.1 | |
| 28.12.1994 | 21–19 | 40.4 | 143.7 | 0 | 7.7 | 1.3 |
| 29.12.1994 | 05–52 | 40.1 | 143.0 | 0 | 6.4 | |
| 26.09.2003 | 04–50 | 41.8 | 144.1 | 42 | 8.0 | 0.9 |
| 26.09.2003 | 06–08 | 41.7 | 143.7 | 21 | 7.1 | |
| Mean value of the difference $M_{main} - M_{aft}$ | | | | | | 0.90 |
| Rms deviation | | | | | | 0.44 |

Island and the second one near the Kuril Trench. The second earthquake with $M_w = 8.1$ occurred only in the second zone. In this case the aftershocks of the first earthquake clearly showed a linearly elongated region near the trench where the second event occurred two months later.

Thus, we cannot exclude the repetition of a scenario similar to that which developed in the Middle Kurils. A further accumulation of data on the aftershock sequence of the Great Japan Earthquake of March 11, 2011, will allow us to confirm this assumption or reject it.

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SPELL: 1. Mammerickx, 2. Megaearthquake, 3. Lithospheric, 4. Misawa