

A Long-term Earthquake Forecast for the Kuril–Kamchatka Island Arc for the Period 2006–2011 and a Successful Forecast of the $M_s = 8.2$ Middle Kuril Earthquake of November 15, 2006

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Abstract—Results are reported from continuous long-term earthquake prediction work for the Kuril–Kamchatka island arc using the patterns of seismic gaps and the seismic cycle. A five-year forecast (April 2006 to April 2011) for all portions of the Kuril–Kamchatka seismogenic zone is presented. According to this, the most likely locations of future $M \geq 7.7$ earthquakes include the Petropavlovsk-Kamchatskii area where the probability of an $M \geq 7.7$ earthquake causing ground motions of intensity VII to IX in the town of Petropavlovsk-Kamchatskii is 48% for 2006–2011, and the area of Onkotan I. and the Middle Kuril Islands where the probability of an $M \geq 7.7$ earthquake was estimated as 26.7%. The forecast was fulfilled on November 15, 2006, when an $M_s = 8.2$, $M_w = 8.3$ earthquake occurred in the Middle Kuril Islands area. An updated long-term forecast is presented for the Kuril–Kamchatka arc for the period from November 2006 to October 2011. These forecasts provide good reasons to enhance seismic safety by strengthening buildings and structures in Kamchatka.

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INTRODUCTION

Long-term earthquake prediction is one of the most important lines of research in the work of prediction and assessment of earthquake hazard. The Kuril–Kamchatka island arc is the most active seismic region in Russia. The seismicity observed there is of the highest intensity found on Earth. It was for this region and other similar structures that in 1965–1968 Fedotov put forward a method of long-term earthquake prediction based on patterns of likely locations for future great earthquakes (seismic gaps) and on the seismic cycle concept [9, 10]. The method has been continually used and refined over time. Twenty basic works dealing with the method and a review of the 1962–2002 results can be found in [12]. The most recent reference in that book provides a forecast for 2001–2005 and describes the state of the art as of 2002 [16]. An evaluation of the previous forecasts and a forecast for 2004–2008 can be found in [14].

Long-term earthquake prediction involves the study of seismicity patterns, the development and refinement of long-term forecasts, as well as acquisition of such data on earthquake hazard as are required for preparedness measures to reduce human and material losses. The results derived by the method were the basis for six governmental decrees and decisions adopted in 1986–2001 and later on regarding seismic preparedness in Kamchatka ([12] and elsewhere).

At present the method is being used to forecast several seismicity characteristics of the Kuril–Kamchatka island arc for the next five years. The locations of future great ($M \geq 7.7$) earthquakes are identified (seismic gaps); these are segments of the arc where no earthquakes of this size have occurred during the past 80 years. The most active strip in the Kuril–Kamchatka seismogenic zone, generating earthquakes in the depth range 0–80 km, of length 2100 km and width 100 km, is divided into 20 portions on the average to predict for these portions the phases of the seismic cycle, to indicate the seismic gaps, to determine the relative hazards presented by these gaps, to predict the seismicity rate A_{10} (the annual number of small, i.e., $K_s = 10$ or $M = 3.2$, earthquakes per 10^3 km² area, the notion of K_s being defined in [11]), the magnitudes M of earthquakes to be expected with probabilities 0.8, 0.5, and 0.15, the maximum credible magnitudes, and the probabilities of great ($M \geq 7.7$) earthquakes, see [12, 14, 15, 16, 20–22] and elsewhere. The long-term forecasts for great earthquakes, as developed during 1965–2005, have a success rate of 0.8–0.9 [12].

Long-term earthquake forecasts are developed in application to the next five years, because the parameters that underlie the forecasts are derived from data for the preceding five years, their values are predicted for the next five years, and finally, because $M \geq 7.7$ earthquakes occur once every five years in the entire Kuril–Kamchatka arc on the average (see [9, 12, 14, 15, 16, 20, 21] and elsewhere), also Section 1 in this paper.

Forecasts are updated every six months, or more frequently when large earthquakes occur and the seismicity parameters for the preceding five years are significantly affected. The resulting forecasts are compared with forecasts derived by other techniques, say, M8 [3, 7, 14–17, 20, 22 and elsewhere].

The present method can also be used for other regions worldwide that have similar structure, geodynamics, and seismotectonics. One recent example of using the method in other regions is provided by [14] where a retrospective earthquake forecast was developed for the September 25, 2003, $M = 8.1$ Hokkaido earthquake.

The long-term forecast for the Kuril–Kamchatka arc for the period 2001–2005 is given in [16] and that for 2004–2008 in [14]. The present paper contains a forecast developed in April 2006 for the period April 2006 to April 2011, see Section 2 later in this paper.

Eight months elapsed since the forecast was developed, when an $M_s = 8.2$, $M_w = 8.3$ earthquake occurred in the Middle Kuril Is. area on November 15, 2006. This was the largest event to have occurred at the Kuril–Kamchatka arc since the December 5, 1997, $M = 7.8$ – 7.9 Kronotskii earthquake [17, 22]. The Middle Kuril earthquake occurred according to the long-term forecasts developed for 2001–2005, 2004–2008, and for the period April 2006 to April 2011 [9, 10, 12, 14 and elsewhere]. (Several investigators have thought an $M > 7.7$ earthquake to be impossible in the area, see [5, 8] and elsewhere). This successful confirmation of a long-term forecast is discussed in Section 3. First forecasts of large ($M \geq 6$) aftershocks following the Middle Kuril earthquake are also provided in Section 5. An updated long-term forecast for the period November 2006 to November 2011 was developed after the Middle Kuril earthquake and the first ten days of its aftershock sequence; the forecast incorporated the changes in the previous seismic gaps in the Middle Kuril Is. area and the resulting rearrangement in the probabilities of $M \geq 7.7$ earthquakes for the other portions of the Kuril–Kamchatka seismogenic zone, see Section 4.

Section 5 contains some supplementary material, discusses the results of this work and improvements on the technique, as well as reports the practical applications of the forecasts.

The Conclusion lists the main results.

1. ON THE DEVELOPMENT OF LONG-TERM EARTHQUAKE FORECASTS FOR THE KURIL–KAMCHATKA ARC FOR THE PERIODS APRIL 2006 TO APRIL 2011 AND NOVEMBER 2006 TO OCTOBER 2011

The long-term earthquake forecast for the Kuril–Kamchatka arc for April 2004 to March 2009 was given in [14]. Afterwards the forecasts were updated three times every six months in 2004–2005. They were developed for the following five-year intervals: Novem-

ber 2004 to October 2009, June 2005 to May 2010, and September 2005 to September 2010.¹ Each such update used seismological data for the five preceding years, the time window and the data set being varied by 1/5. The method of calculation was being refined.

No $M \geq 7.7$ earthquakes occurred at the Kuril–Kamchatka arc during 2004–2005, and the changes to the three forecasts referred to above were slight. The most important result remained unchanged, i.e., the highest probability for an $M \geq 7.7$ earthquake to occur during the next five years was invariably around the largest town of the region, Petropavlovsk-Kamchatskii. The probability values in different computation options were in the range 46.9–48.5%.

In sections 2 and 4 of the present paper we describe and compare two later long-term forecasts for the Kuril–Kamchatka arc developed for the periods April 2006 to April 2011 and November 2006 to October 2011. Before proceeding to a discussion of the forecasts, it is advisable to recall a number of basic concepts underlying the method and the ways to calculate the quantities to be predicted.

The Kuril–Kamchatka arc is basically a major elongate seismotectonic feature extending for 2000 km. One hundred years of seismological observation have shown that the seismicity levels of large portions of the arc more than 100 km in along-arc extent are to a first approximation the same. Some decrease in the seismicity level may have taken place in the Middle Kuril Is. area, but the November 15, 2006, $M_w = 8.3$ Middle Kuril earthquake showed that here too, $M \geq 7.7$ earthquakes can occur.

It was found from instrumental and historical data that the mean duration of a seismic cycle, or the time interval T between two successive $M \geq 7.7$ earthquakes at a location, is normally distributed: $T_1 = 140 \pm 60$ years or $T_2 = 120 \pm 50$ years [10, 12, 18, 21 and elsewhere]. These expressions are used to find the probability of occurrence for $M \geq 7.7$ earthquakes during the next five years. The probability of occurrence for such earthquakes during the first 80 years of a cycle is low, ~ 0.16 . However, the probability of occurrence for $M \geq 7.7$ earthquakes after the first 80 years of a cycle until its termination is equal to 0.84. The locations where no $M \geq 7.7$ earthquakes have occurred during 80 years or longer are considered likely locations of future great earthquakes, or seismic gaps [9, 12].

The seismic cycle is divided into three phases: (I) the aftershock phase of 10–15 years; (II) a prolonged phase of seismic stability; (III) the terminating phase of foreshocks lasting 10–15 years. The relative hazard presented by a seismic gap and the probability of phase III

¹ These forecasts were registered at the Council of the Institute of Volcanology and Seismology and the Kamchatka Branch of the Geophysical Service of the Russian Academy of Sciences, were given in weekly reports of the Council, reported to the Russian Academy of Sciences, to state organizations and local authorities, and were described in scientific reports.

are assessed by looking at the deviations of several seismicity parameters from their average values during phase II. The parameters include the seismicity rate A_{10} , which is the normalized annual number of small earthquakes of energy class $K_S = 10$, $M = 3.2$ per 10^3 km² area (the K_S scale is given in [11]); D , which is the relative seismic energy release: $D(t) = E_2(t)/E_1$ where $E_2(t)$, J/yr $\times 10^3$ km² is the normalized seismic energy released in the portion concerned during time t , and E_1 is the average normalized amount of seismic energy released in the Kuril–Kamchatka seismogenic zone [10, 12, 15, 18, 20, 21 and elsewhere].

The values of A_{10} and D are determined in 5-year intervals for large portions of the seismogenic zone, 200×100 km to 100×50 km in size, the average area being 150×75 km or 11×10^3 km². These last figures are close to the average rupture area for $M \geq 7.7$ earthquakes.

Further parameters are $P(A_{10})$ and $P(D)$, the probabilities for A_{10} and D to exceed by chance the observed A_{10} and D during phase II in a cycle. The parameter $B = P(A_{10}) \times P(D)$ shows the relative hazard associated with a seismic gap.

The present paper uses one more parameter, A_{11} , which is the yearly number of class $K_S = 11$ or $M = 4.3$ earthquakes per 10^3 km² area. This parameter is convenient to use, because earthquakes of this size are complete in many catalogs. The probability that A_{11} will exceed the corresponding observed value in the large rupture area of a great earthquake 10–15 years prior to it by chance is denoted by $P(A_{11})$. The relative hazard of a seismic gap is also assessed by the parameters $B_1 = P(A_{10}) \times P(D) \times P(A_{11})$ and $B_2 = P(A_{10}) + P(D) + P(A_{11})$.

The seismic process during phase III of a seismic cycle may be complex in character, involving clusters of events, seismic quiescences, foreshocks, etc. However, most of the phenomena observed in the large rupture area of a future $M \geq 7.7$ earthquake and around it during the last 5–10 years of a cycle include significant increases in A_{10} , D , and A_{11} [12, 14–16, 20, 21 and elsewhere].

The prediction of A_{10} is based on the $\log A_{10}(t) \pm \sigma$ relation as developed for the seismic cycle. The magnitudes of moderate earthquakes expected with probabilities $P = 0.8, 0.5$, and 0.15 are found from the relation $\log D(t) \pm \sigma$ relevant to the seismic cycle.

The maximum credible magnitude $M_{\max}$ is estimated from the size of the seismic gap. The size of an earthquake-generating portion is incorporated in the calculation of predicted probabilities. The value of $M_{\max}$ is found from the relation that connects rupture length L and magnitude M for major earthquakes at the Pacific seismic belt [15, 20]. The construction of long-term forecasts for the Kuril–Kamchatka arc and the methods used to calculate the predictable quantities which were being

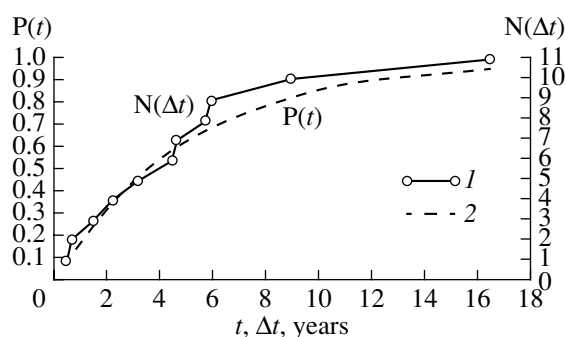


Fig. 1. Number $N(\Delta t)$ of $M \geq 7.7$ Kuril–Kamchatka earthquakes as a function of the associated interevent interval Δt and the probability of occurrence for such earthquakes $P(t)$ as a function of waiting time t : (1) empirical plot showing the distribution of the number N of recorded earthquakes in relation to time interval Δt , years based on the eleven Δt intervals observed in 1952–2006; (2) theoretical plot of probability of earthquake occurrence $P(t)$ as a function of waiting time t , years calculated from the Poisson distribution $P(\Delta t \leq t) = 1 - e^{-\lambda t}$ with $\lambda = 0.2$.

refined over time are described in numerous publications, e.g., [10, 12, 14, 15–18, 20, 21].

Now we will provide additional information on the time intervals relevant to the above predicted probabilities for the occurrence of $P(M \geq 7.7)$ for all designated portions of the Kuril–Kamchatka main seismogenic strip.

The durations of time intervals Δt between great ($M \geq 7.7$) earthquakes in the entire Kuril–Kamchatka arc for the period 1904–2006 are presented in Table 1.

The $M \geq 7.7$ Kuril–Kamchatka earthquakes are completely reported for the period 1904–2006 [1, 4, 8 and elsewhere]. Table 1 lists 21 such earthquakes. The earthquake pairs no. 1 (1904), 13 (1969), and 16 (1978) are treated as single events. Earthquake 3 (1917) may have occurred outside the chosen prediction strip for Kuril–Kamchatka earthquakes (Section 2, Fig. 2). Earthquake 5 (1918) may have been an aftershock of earthquake 4, while no. 7 (1923) may be similarly treated as a large aftershock of the great Kamchatka earthquake no. 6. Part of the earthquake 8 (1952) rupture area which occurred off Hokkaido I. is outside the prediction strip. The average interevent time for the 19 earthquakes in 1904–2006, Table 1, is 5.7 years. The figure is so large, because a quiet interval of 29 years intervened between the great $M = 8.5$ Kamchatka earthquakes of 1923 and 1952.

The distribution of large Kuril–Kamchatka earthquakes ($M \geq 7 \frac{3}{4}$) in time for the period 1904–1963 was studied in [9, 12]. It was found that the distribution of the number of events in time intervals is a poor fit to the Poisson law, and the probability of a random appearance for the 1924–1951 quiet period is low. The data available at the time were in favor of the hypothesis that the large 1904–1963 Kuril–Kamchatka earthquakes were not random, but were related events which

Table 1. 1904–2006 earthquakes of the Kuril–Kamchatka arc, $M \geq 7.7$, $H < 100$ km

No.	Year	Date	Time, h, min	Location	N deg	E deg	H , km	M	Δt , years
1	1904	25.VI	14.45	Southern Kamchatka	52.0	159.0	15–60	7.7	
	1904	25.VI	21.00		52.0	159.0	15–60	7.7	
2	1915	1.V	05.00	East of Onkotan I.	48.4	155.5	30 ± 30	8.3	11
3	1917	30.I	02.45	Kamchatskii Bay	55.2	164.5	5–20	8.1	1.8?
4	1918	7.IX	17.16	East of Urup I.	45.6	151.1	40 ± 20	8.2	1.7
5	1918	8.XI	04.38	Southeast of Urup I.	44.9	151.4	40 ± 40	7.9	0.1
6	1923	3.II	16.01	East of Kamchatka	53.0	161.0	10–40	8.5	4.3
7	1923	24.II	07.34	Kamchatskii Bay	55.0	162.4	10–40	7.7	0.1?
8	1952	04.III	01.22	Southeast of Hokkaido	41.9	143.7	50 ± 10	8.3	29
9	1952	4.XI	16.58	Kamchatskii	52.3	161.0	10–40	8.5	0.7
10	1958	6.XI	22.58	Iturup	44.5	148.5	40 ± 20	8.2	6
11	1959	4.V	07.15	Cape Shipunskii	53.1	160.3	20 ± 10	7.7	0.5
12	1963	16.i	05.17	Urup	44.8	149.5	47 ± 10	8.1	4.5
13	1969	11.VIII	21.27	South Kuril	43.6	147.8	40 ± 10	8.2	5.8
	1969	11.VIII	21.27		43.6	147.2	38 ± 15	7.8	
14	1971	15.XII	08.29	Kamchatskii Bay	55.9	163.4	20–30	7.9	2.3
15	1973	17.VI	03.55	Kunashir	43.2	145.9	55 ± 10	7.9	1.5
16	1978	23.III	03.15	East of Iturup	43.9	148.9	40	7.8	4.7
	1978	24.III	19.47		43.9	149.1	39	8.0	
17	1994	13.X	13.22	Shikotan	43.7	147.6	33	8.0	16.5
18	1997	5.XII	11.26	Kronotskii	54.7	162.4	33	7.9	3.2
19	2006	15.XI	11.14	Middle Kuril	46.7	153.2	28	8.2	9.0

Note: Listed are the earthquakes that occurred in the prediction strip (Fig. 2). The earthquake pairs of 1904, 1969, and 1978 are treated as single events. Earthquake 3 (January 30, 1917) may have actually been outside the strip. Δt , years denotes time intervals between successive earthquakes (the rupture areas are shown in Fig. 2).

clustered in active periods lasting 30–40% of the total observation time.

However, the 1952–2006 sequence of twelve Kuril–Kamchatka earthquakes, nos. 8 through 19 (Table 1), is much more uniform. The mean value of the eleven interevent times for 1952–2006 is 5.0 ± 4.4 years. This distribution is close to the exponential one in the Poisson process with the parameter $\lambda = 1/\sigma \approx 0.21$ [6]. (The parameter was previously estimated as $\lambda \approx 0.2$ [16]).

When the period from 1951–2006 is divided into eleven 5-year intervals, it appears that two intervals contain two events each, seven intervals contain a single event each, and there are two intervals without any $M \geq 7.7$ events. Thus, either one or two $M \geq 7.7$ earthquakes occurred in 9 cases out of 11 (or in 82%), while there were no such earthquakes in two cases out of 11 (18%).

We now are going to estimate the probability of time intervals with no $M \geq 7.7$ earthquake that last longer than 5 years.

Figure 1 shows the rate of $M \geq 7.7$ Kuril–Kamchatka earthquakes, $N(\Delta t)$, as a function of interevent

time Δt (curve 1) and the probability of occurrence for such earthquakes $P(t)$ as a function of waiting time t (curve 2). The second curve was calculated from the relation $P(t) = 1 - e^{-\lambda t}$, where P is the probability of a next earthquake occurring during a waiting time t , and λ is the parameter in the Poisson distribution [6]. Judging from curves 1 and 2, the time intervals between successive $M \geq 7.7$ earthquakes are below 5 years in 66% of the cases, while Δt exceeding 10 years is a possible, but rare event whose probability is below 0.1.

We now state certain assumptions and observed patterns based on the above.

It is assumed that the seismic process is to a first approximation identical in large portions of the Kuril–Kamchatka seismogenic zone whose dimensions vary in the range $(5–20) \times 10^3$ km².

Each of about 20 portions of the zone is experiencing an independent seismic cycle the particular phase of which is dependent on the occurrence time t_0 of the preceding $M \geq 7.7$ earthquake; the cycle lasts 140 ± 60 or 120 ± 50 years.

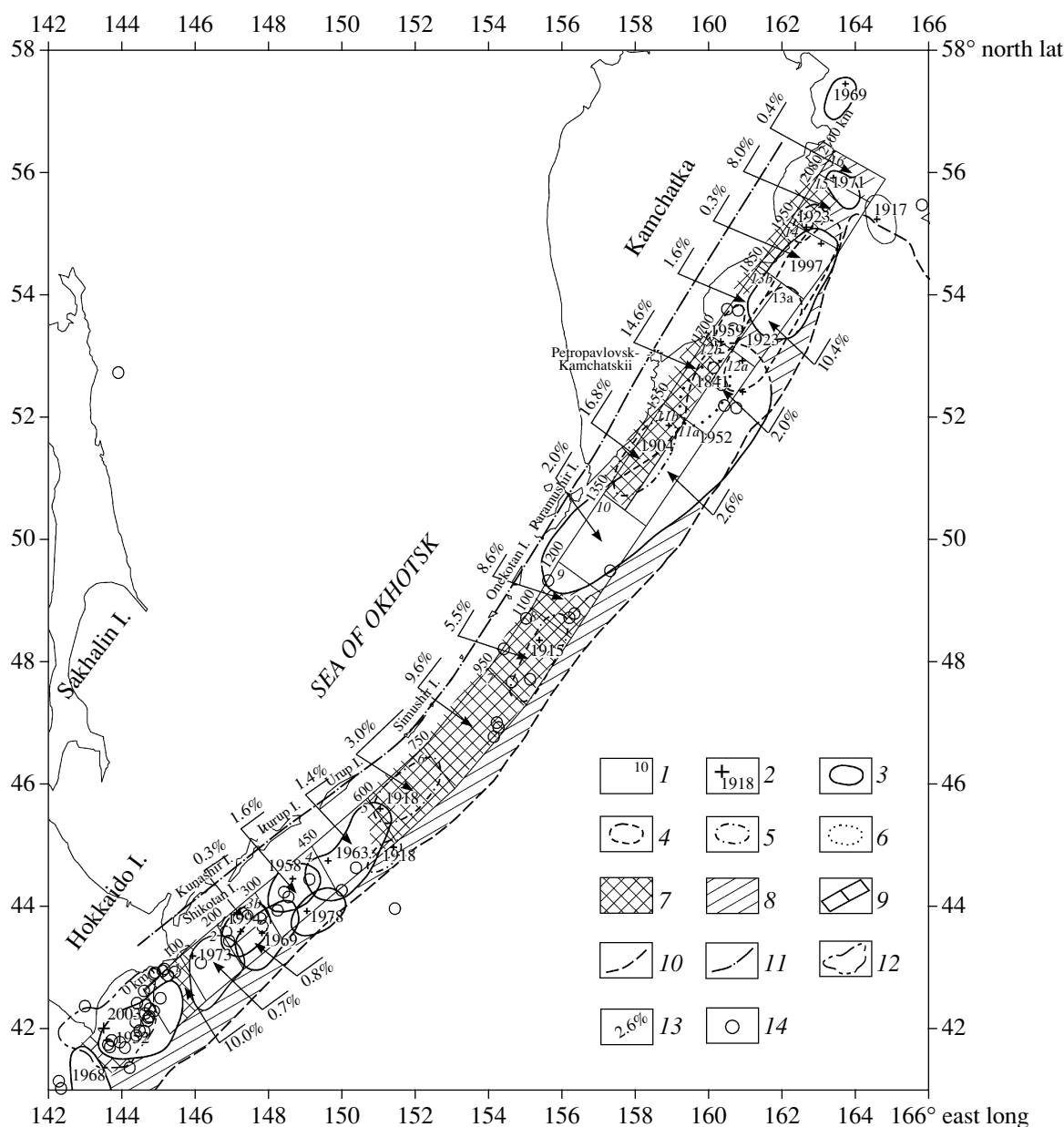


Fig. 2. Map showing the long-term earthquake forecast for the Kuril–Kamchatka arc for the period April 2006 to April 2011, the rupture areas of the 1904–2006 $M \geq 7.7$, Kuril–Kamchatka earthquakes, $H = 0–80$ km, and the probabilities for the occurrence of such earthquakes during the period April 2006 to April 2011 in all portions of the prediction strip: (1) portion number, (2) instrumental epicenters of $M \geq 7.7$ main shocks, (3) boundaries of $M \geq 7.7$ earthquake rupture areas found to within 10 km, (4) segments of these boundaries when determined to lower accuracy, (5) probable rupture areas of the 1904–1918 $M \geq 7.7$ earthquakes, (6) inferred rupture area of the 1841 earthquake, (7) the most probable locations of future $M \geq 7.7$ earthquakes, (8) possible locations of such earthquakes, (9) boundary of prediction portions, (10) trench axes, (11) axis of the Kuril–Kamchatka volcanic belt, (12) boundary of the September 25, 2003, $M = 8.1$ earthquake rupture area, (13) probabilities of $M \geq 7.7$ earthquakes for April 2006 to April 2011, (14) epicenters of $M \geq 5.5$, $H = 0–80$ km earthquakes which occurred between March 2001 and March 2006. The average probability for the occurrence of $M \geq 7.7$ Kuril–Kamchatka earthquakes in the same location during 5 years is 3.6–4.2%.

Great earthquakes recur in the entire Kuril–Kamchatka arc every 5 years on an average and are treated to a first approximation as independent events. The next $M \geq 7.7$ earthquake is certain to occur, the probability of the event being 1. Based on past experience, the probability of one or two $M \geq 7.7$ earthquakes during

5 years is equal to ≈ 0.8 . For this reason, if the probability of an earthquake during 5 years is assumed to be 1, which is consistent with the mean repeat time, the occurrence of time intervals with no $M \geq 7.7$ earthquakes makes the actual probability of such an event equal to about 0.8.

The probability of a five-year interval without an $M \geq 7.7$ earthquake is about 0.2.

The occurrence of two successive five-year intervals with no $M \geq 7.7$ earthquakes is a rare event whose probability is below 0.1.

Earthquakes of $M \geq 7.7$ in different portions of the Kuril–Kamchatka seismogenic zone are assumed to be independent, mutually exclusive events whose probabilities can be added.

Based on the above assumptions, it is assumed for approximate calculations that the mean total probability of occurrence for an $M \geq 7.7$ earthquake during 5 years in all the twenty portions is equal to 100% [12, 14, 16 and elsewhere]. That means that the occurrences of $M \geq 7.7$ earthquakes in different seismogenic portions during 5 years are regarded as mutually exclusive events the sum of whose probabilities equals 1. It has been taken into account that an $M \geq 7.7$ earthquake occurs during 5 years with probability 0.8.

In the case where the time t_0 of the occurrence of the preceding $M \geq 7.7$ earthquake in a seismogenic portion of interest is known, the probability of the occurrence of the next such earthquake in any fixed time interval (t_1, t_2) later than t_0 may be estimated from the normal distribution of seismic cycle duration, $T_1 = 140 \pm 60$ or $T_2 = 120 \pm 50$ years. The two corresponding probabilities for the occurrence of $M \geq 7.7$ earthquakes were estimated for areas of lower seismic hazard where such earthquakes have occurred during the past 80 years. It has been taken into account that, if no $M \geq 7.7$ earthquake has occurred until the present time t_{curr} , then the probability of its later occurrence remains equal to one. The dimensions of the seismogenic portions were incorporated by the corrections $L/150$ km, where L is the length of the portion in kilometers and 150 km is the mean length of the portions. The probabilities $P_3(M \geq 7.7)$ and $P'_3(M \geq 7.7)$ will thus be found for $T_1 = 140$ years and $T_2 = 120$ years, as well as the respective mean probabilities for individual portions and the sum of the probabilities for the occurrence of such earthquakes, $\Sigma P_3(M \geq 7.7)$, in all portions where $t_{\text{curr}} - t_0 \leq 80$ years [10].

The sum of the probabilities for the occurrence of $M \geq 7.7$ earthquakes in the remaining portions of the prediction strip, the seismic gaps, is assumed to equal $[1 - \Sigma P_3(M \geq 7.7)]$. In practice this turns out to be 0.8–0.9. This part of the total probability is assigned to the gaps in proportion to the value of $(1 - B)$ for each gap. These calculations also incorporate the relative dimensions of the gaps.

As mentioned above, the sum of the probabilities of the occurrence of mutually exclusive events, $M \geq 7.7$ earthquakes in all portions of the seismogenic zone during 5 years, is assumed to be equal to one. The values of $P(M \geq 7.7)$ thus calculated refer to the next 5 years.

Five-year intervals with no $M \geq 7.7$ earthquakes were observed in 18% of the cases during the period

1952–2006. Consequently, the value of $P(M \geq 7.7)$ for the seismic gaps may be lower by an average amount of ~ 0.2 compared with the observed mean probability of a single $M \geq 7.7$ earthquake in the Kuril–Kamchatka arc during 5 years.

These forecasts are largely based on seismicity data for the preceding 5 years. The forecasts constructed in 2006 for the present paper were based on the catalogs of the Geophysical Service, Russian Academy of Sciences, the International Seismological Centre (ISC), the US Geophysical Service (USGS–NEIC), and several others.

Now we turn to a consideration of the forecasts developed for April 2006 to April 2011 and for November 2006 to November 2011.

2. LONG-TERM EARTHQUAKE FORECAST FOR THE KURIL–KAMCHATKA ARC, PERIOD APRIL 2006 TO APRIL 2011, MADE IN MARCH 2006

The present long-term forecast was developed using the method (Section 1) based on the patterns of seismic gaps and the seismic cycle. It was made in April 2006 for the following five years, April 2006 to April 2011, as an update of the previous forecast (October 2005). The following quantities are predicted for the twenty portions of the Kuril–Kamchatka seismogenic zone: the phase of the seismic cycle; seismicity rate A_{10} ; magnitudes M of moderate and large earthquakes to be expected with probabilities 0.8, 0.5, and 0.15; maximum credible magnitudes; probabilities of occurrence P for great $M \geq 7.7$ earthquakes. Also indicated are seismic gaps, which are the most likely locations of future great earthquakes, along with their relative hazard values (Fig. 2, Table 2). The values of $P(M \geq 7.7)$ were determined from the three parameters A_{10} , D , and A_{11} . For comparison purposes Table 2 also lists the probabilities $P(M \geq 7.7)$ and the relative hazards for the seismic gaps derived for the long-term forecast for the period 2001–2005 based on the parameters A_{10} and D .

Forecast for the Kuril–Kamchatka Arc. The main results of the long-term forecast for the period of April 2006 to April 2011, for all the twenty portions into which the Kuril–Kamchatka seismogenic zone has been divided (Table 2, Figure 2), are as follows.

The most likely locations of future $M \geq 7.7$ earthquakes for the period April 2006 to April 2011 continue to be the portions around the town of Petropavlovsk-Kamchatskii:

For the Avacha Bay (portion 12b, Fig. 2), the probability for an $M \geq 7.7$ earthquake to occur between April 2006 and April 2011 and to cause ground motions with intensity levels up to IX at Petropavlovsk-Kamchatskii remains very high, 14.6%;

For southern Kamchatka (portion 11b), the probability of an $M \geq 7.7$ earthquake causing ground motions

Table 2. Long-term earthquake forecast for the Kuril–Kamchatka arc for the period April 2006 to April 2011 ($H \leq 80$ km) based on the parameters A_{10} , D , A_{11} , and a comparison with the October 2004 probabilities of great earthquakes

Portion	Δ , km	Location	Phase of the cycle and its estimate from the 2001–2006 data (March 2001 to March 2006)				Forecast for April 2006 to April 2011							Forecast for September 2004 to September 2009			
			Phase	$P_1 = P(A_{10})$	$P_2 = P(D)$	$P_3 = P(A_{11})$	$B = (P_1 P_2 P_3)$	$A_{10} (P \sim 0.7)$		$P \sim 0.8$	$P \sim 0.5$	$P \sim 0.15$	$M_{\max}$	$P(M \geq 7.7)\%$	Likely sequence	Likely sequence	
								A_{10}	$A_{10} \pm \sigma$								
1	0–100	Cape Sirikha to Nemuro Peninsula	III	0.21	0.01	0.94	0.002	1.2–3	0.8–4.5	6.0	6.5	7.0	7.8	10.0 (3.9)	4 (7)	13.2	2
2	100–200	Nemuro Peninsula to Zelenyi I.	II					1.2	0.8–1.9	5.8	6.3	6.8		0.7 (0.5)		0.6	
3a	200–300	Shikotan I., SE	II					1.2	0.8–1.9	5.7	6.2	6.7		0.8 (0.6)		0.7	
3b	200–300	Shikotan I., NW	I					2.1→1.4	0.9–3.1	6.0	6.4	6.9		0.3 (0.2)		0.3	
4	300–450	Iturup I.	II					1.2	0.8–1.9	5.9	6.4	6.9		1.6 (1.4)		1.5	
5	450–600	Vries Strait to Urup I.	II					1.2	0.8–1.9	5.9	6.4	6.9		1.4 (1.1)		1.3	
6	600–750	Cape Castricum to Bussol' Strait	III?	0.98	0.98	0.73	0.70	1.2–3	0.8–4.5	6.0	6.5	7.0	8.0	3.0 (7.7)	9 (5)	1.4–4.4	9
7	750–950	Simushir I. to Kruzenshtern Strait	III?	0.98	0.54	0.86	0.45	1.2–3	0.8–4.5	6.2	6.7	7.2	8.2	9.6 (11.7?)	5 (3)	9.4	5
8	950–1100	Shiashkotan I.	III?	0.99	0.58	0.95	0.55	1.2–3	0.8–4.5	6.0	6.5	7.0	8.0	5.5 (3.5)	8 (8)	7.2	7
9	1100–1200	Onekotan I. to Third Kuril Strait	III	0.87	0.16	0.90	0.13	1.2–3	0.8–4.5	6.0	6.4	7.0	7.9	8.6 (5.8)	6 (6)	7.7	6
10	1200–1350	Paramushir I. to Cape Lopatka	II					1.2	0.8–1.9	5.9	6.4	6.9		2.0 (2.7)		1.9	
11a	1350–1550	Southern Kamchatka, SE	II					0.8	0.6–1.1	5.8	6.3	6.8		2.6 (3.6)		2.5	
11b	1350–1550	Southern Kamchatka, NW	III	0.64	0.87	0.25	0.14	1.3–3	0.8–4.5	6.0	6.5	7.0	8.0	16.8 (18.3)	1 (2)	10.6	4
12a	1550–1700	Avacha Bay to Cape Shipunskii, SE	II					1.2	0.8–1.9	5.7	6.2	6.7		2.0 (2.7)		1.9	
12b	1550–1700	Avacha Bay to Cape Shipunskii, NW	III	0.20	0.79	0.19	0.03	1.2–3	0.8–4.5	5.9	6.4	6.9	8.0	14.6 (20.5)	2 (1)	19.6	1
13a	1700–1850	Kronotskii Bay, SE	III?	0.89	0.82	0.37	0.27	1.2–3	0.8–4.5	5.9	6.4	6.9	8.0	10.4 (3.6)	3	5.3	8
13b	1700–1850	Kronotskii Bay, NW	II					2.6	1.7–3.9	5.9	6.4	6.9		1.6 (1.3)		1.5	
14	1850–1950	Kronotskii Peninsula	I					3.1→1.9	1.2–4.5	6.0	6.5	7.0		0.3 (0.2)		0.2	
15	1950–2050	Kamchatskii Bay	III?	0.32	0.69	0.83	0.18	1.2–3	0.8–4.5	6.0	6.5	7.0	7.9	8.0 (8.5)	7 (4)	12.9	3
16	2050–2100	Kamchatskii Peninsula	II					0.8	0.6–1.1	5.7	6.2	6.7		0.4 (0.3)		0.3	
		Estimate of critical probability values		0.062	0.308	0.06	0.0012							$\Sigma = 100.0$		$\Sigma = 101$	

Note: This table contains forecasts of seismicity characteristics for April 2006 to April 2011. Probable phases of the seismic cycle are indicated for all the twenty portions. Index III marks those portions where no $M \geq 7.7$ earthquakes have occurred during the last 80 years and where the probability that the final phase III of the seismic cycle has set in is considerable. Question marks are attached to those portions where the probability of such an event is lower. B is a parameter that shows the relative hazard of a seismic gap; A_{10} is seismicity rate; $P \sim 0.8$, 0.5 , and 0.15 are the probabilities of $M = 5.7$ – 7.2 earthquakes; $M_{\max}$ is the maximum credible magnitude; $P(M \geq 7.7)$ denotes predicted probabilities of great earthquakes. The values of $P(M \geq 7.7)$ in parentheses denote those for 2001–2005. The average long-term value is $P(M \geq 7.7) = 3.6$ – 4.2% .

with a level up to VIII at Petropavlovsk-Kamchatskii is equal to 16.8%;

For the southeastern Kronotskii Bay (portion 13a), the probability of an $M \geq 7.7$ earthquake causing ground motions with a level up to VII at Petropavlovsk-Kamchatskii is equal to 10.4%.

The total probability of $M \geq 7.7$ earthquakes causing ground motion intensities with levels of VII to IX at Petropavlovsk-Kamchatskii occurring in the three portions of the greatest hazard (11b, 12b, and 13a) is equal to 41.8%.

Earthquakes that can produce shaking of intensity VII to VIII at Petropavlovsk-Kamchatskii are less likely to occur in portions 11a, 12a, and 13b. The total probability for occurrence of $M \geq 7.7$ earthquakes in portions 11a, 11b, 12a, 12b, 13a, and 13b and the production of ground motions of intensity VII–IX at Petropavlovsk-Kamchatskii may thus be as high as 48.0% (Table 2). In more detail, the probability of earthquake shaking with intensity IX at Petropavlovsk-Kamchatskii between April 2006 and April 2011 is equal to 14.6%, while that for VIII and VII is 33.4%.

There still remains a considerable probability ($P = 8.0\%$) for an $M \geq 7.7$ earthquake in portion 15, Kamchatka Bay (Fig. 2, Table 2).

In the Middle Kuril Islands, there is high earthquake hazard for portions 9, 7, and 8, which include the area from Onkotan I. to the Middle Kuril Islands (Fig. 2, Table 2), the total probability being 23.7%; together with portion 6 (Bussol' Bay), which is a seismic gap as well, the figure is 26.7%.

Compared with the forecast given in October 2005, the probability for portion 7—that of the greatest hazard in the Middle Kuril Islands—has increased from 7.9 to 9.6%. (It was in this portion that the November 15, 2006, $M_S = 8.2$, $M_w = 8.3$ earthquake occurred, see Section 3).

The probability for portion 1, the Nemuro Peninsula, remains high (Fig. 2, Table 2). According to recent estimates, the portion remains third or fourth in degree of hazard ($P = 10.0\%$ for April 2006 to April 2011).

$P(M \geq 7.7) = 8\%$ for the Kamchatka Bay, portion 15.

In the other portions of the Kuril–Kamchatka seismogenic zone, the probability of great earthquakes $P(M \geq 7.7)$ is equal to the mean probability, which is 3.6–4.2%, or else very much (by a factor of 10–15) less than the mean.

The above was the long-term earthquake forecast given eight months before the November 15, 2006, $M_S = 8.2$, $M_w = 8.3$ Middle Kuril earthquake.

As mentioned above, the forecast was accepted by the Council on Prediction of Earthquakes and Volcanic Eruptions, Institute of Volcanology and Seismology, Far East Division, Russ. Acad. Sci. and the Kamchatka Branch, Geophysical Service, Russ. Acad. Sci., and was sent to fourteen addresses of organizations and specialists as weekly reports of the Council, the organizations including, among others, the Russian Ministry of

Emergencies, the Administration of the Kamchatka Region, the Russian Expert Council (with the Ministry of Emergencies and the Russian Academy of Sciences).

3. A SUCCESSFUL FORECAST OF THE NOVEMBER 15, 2006, $M_S = 8.2$ MIDDLE KURIL IS. EARTHQUAKE

When the work on long-term earthquake prediction had just started, and the first map of the Kuril–Kamchatka $M \geq 7.7$ earthquakes was being made in 1965, it was found that there were no reliable historical and instrumental data on the occurrence of such earthquakes in the area of the Middle Kuril Is. and Shishkotan I. (a length of 750–950 km along the Kuril–Kamchatka arc, see Fig. 2). For this reason the area (portion 7) was classified as one of likely locations for future $M \geq 7.7$ earthquakes, or seismic gaps [9]; it is bounded on the northeast by the May 1, 1915, $M = 8.3$ earthquake rupture area and on the southwest by the November 8, 1918, $M = 8.2$ one (Table 1, Fig. 2). The boundaries of those rupture areas could only be determined very approximately, from the coordinates of their 4–5 larger aftershocks [1, 9], and were refined later [15] using the catalog [4].

By 2001, more than 80 years had elapsed since these great earthquakes, the current time of the seismic cycle in their rupture areas exceeded $140 - \sigma = 140 - 60$ years, so we classified these locations in 1995–2000 as likely to generate $M \geq 7.7$ earthquakes, or seismic gaps. The longest gap then appeared in the Kuril–Kamchatka arc, 500 km long at distances of 650 to 1150 km along the arc, containing portions 6, 7, 8, and 9 in Fig. 2 [12, 16 and elsewhere].

This portion of the Kuril island arc exhibits several features that distinguish it from the southern and northern parts, the South and North Kuril Islands. There is no outer island arc like the Lesser Kuril chain in the south, no great earthquakes have been recorded, and the crustal structure is different. Based on these and some other features of this area, some investigators believed that the maximum earthquake magnitude cannot exceed $M = 7.5 \pm 0.2$ there [5, 8 and elsewhere].

However, the leading tectonic feature is continuous along the entire Kuril–Kamchatka arc and its Kuril part; it consists of a deep-sea trench, a continuous Benioff zone, and the volcanic belt. There are also transverse faults cutting across the arc, and other features in its tectonic structure. However, the rupture areas of $M = 7.7$ – 8.5 earthquakes have dimensions between 100 and 600 km. These areas, as considered in our long-term prediction method, are superposed upon smaller tectonic features. Long-term forecasts as developed for large portions of the Kuril–Kamchatka arc assume, to a first approximation, that the arc is a homogeneous extended seismotectonic structure and the seismicity in different large portions of the arc, its segments 100–200 km long or longer, is the same.

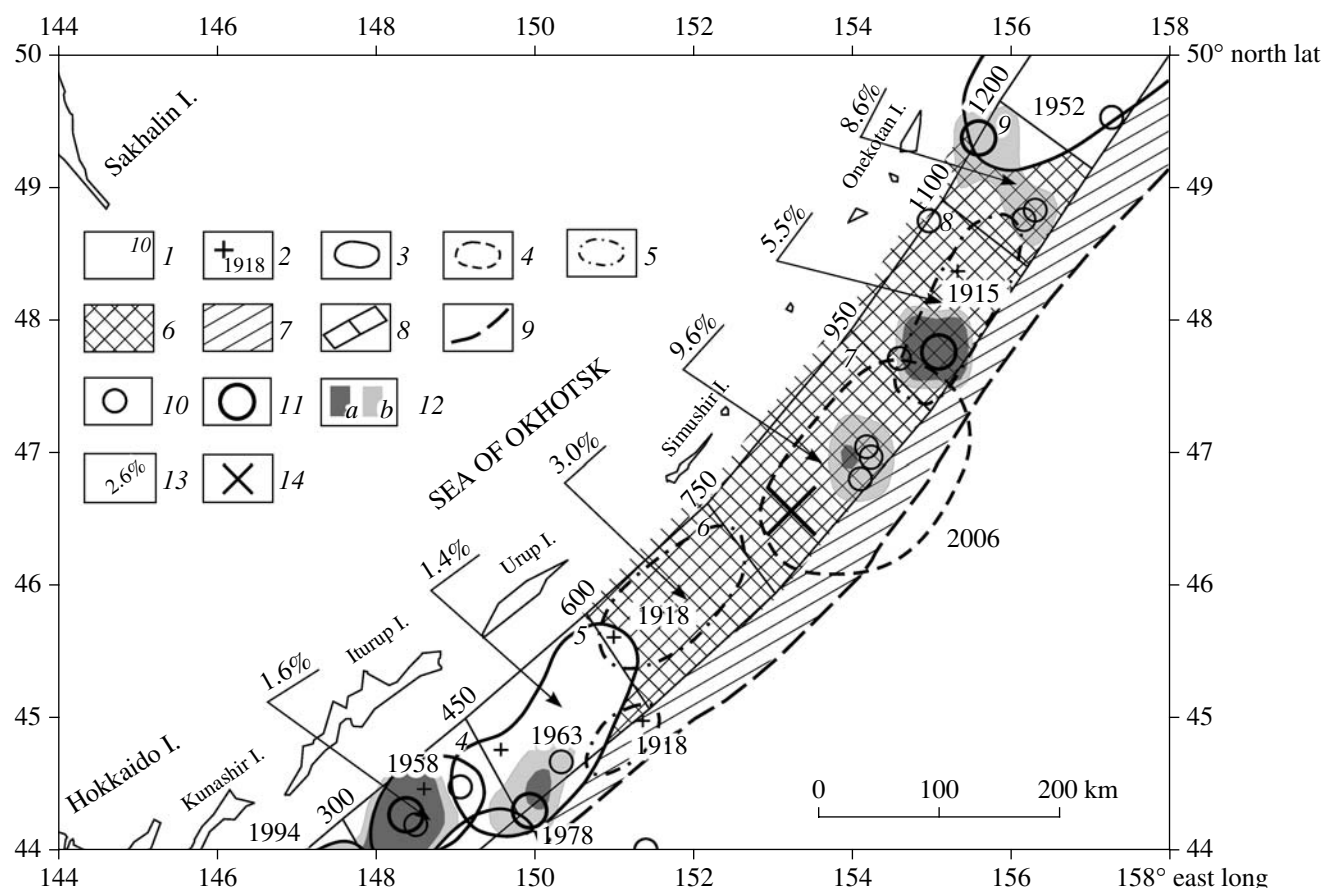


Fig. 3. Map showing the rupture areas of the 1915–2006 $M \geq 7.7$ Kuril–Kamchatka earthquakes with depth $H = 0-80$ km, the seismic gaps, isolines of $1-B$ based on the March 2001 to March 2006 data, as well as earthquake epicenters for this period: (1) number of portion, (2) instrumental epicenters of $M \geq 7.7$ main shocks, (3) boundary of $M \geq 7.7$ earthquake rupture areas determined to within 10 km, (4) segments of the same boundaries determined to lower accuracy, (5) probable rupture areas of the 1915–1918 $M \geq 7.7$ earthquakes, (6) the most probable locations of such future earthquakes, (7) possible locations of such future earthquakes, (8) boundary of prediction portions, (9) trench axis, (10) epicenters of $5.5 \leq m_b < 6.0$ earthquakes for the period March 2001 to March 2006, (11) epicenters of $m_b \geq 6$ earthquakes for the period March 2001 to March 2006, (12) isolines of $1-B$ for two levels, (a) 0.9 and (b) 0.7, (13) probability of earthquake occurrence $P(M \geq 7.7)$ for the period April 2006 to April 2011, (14) epicenter of the November 15, 2006, $M_w = 8.3$, $M_s = 8.2$ Middle Kuril earthquake

On November 15, 2006, the $M_w = 8.3$, $M_s = 8.2$ Middle Kuril earthquake occurred, and its rupture area filled the entire seismic gap in portion 7 (Table 1, Figs. 2–6). This event proved that $M \geq 7.7$ earthquakes can occur in the Middle Kuril Islands area.

The increased probability of a great earthquake in the area of the November 15, 2006, $M_w = 8.3$, $M_s = 8.2$ Middle Kuril Is. earthquake has invariably been predicted since 1965. The associated gap was marked as such in the first (1965) map of $M \geq 7.7$ earthquake rupture areas and the likely locations of future events this size in the Kuril–Kamchatka seismogenic zone [9]. Afterwards this seismic gap, portion 7, distance 750 to 1000 km (750–950 km in Fig. 2), was indicated as one of the most likely locations of future $M \geq 7.7$ earthquakes in the five-year long-term forecasts published for 1965–1970, 1971–1975, and the subsequent five intervals, until and including 1996–2000 [9, 12, 14, 15 and elsewhere]. The relative hazard of portion 7 was

estimated in 1965–2005 from the five-year data using the parameter $B = P(A_{10}) \times P(D)$ [12, 16 and elsewhere]. In 1965–2000 portion 7 was the third by hazard level in 3 of 7 cases among the 6–7 gaps that were available during that period, and among all the twenty identified portions of the seismogenic zone. Based on the data for April 2001 to March 2006, concerning the relative hazard of the seismic gaps using the parameter $B = P(A_{10}) \times P(D) \times P(A_{11})$ and incorporating the size of portions L (Table 2), portion 7 has become the fifth among the twenty by hazard level in the entire Kuril–Kamchatka arc, and the first among the four portions (6–9), which make a seismic gap 550 km long off the Middle Kuril Islands and Shishkotan I. (Fig. 2, Table 2).

According to the long-term forecast for the Kuril–Kamchatka arc, the period April 2006 to April 2011 (Table 2, Fig. 2), the highest probability of an $M \geq 7.7$ earthquake was in the Petropavlovsk-Kamchatskii area, in portions 11b, 12b, and 13a (Fig. 2). The seismic gaps

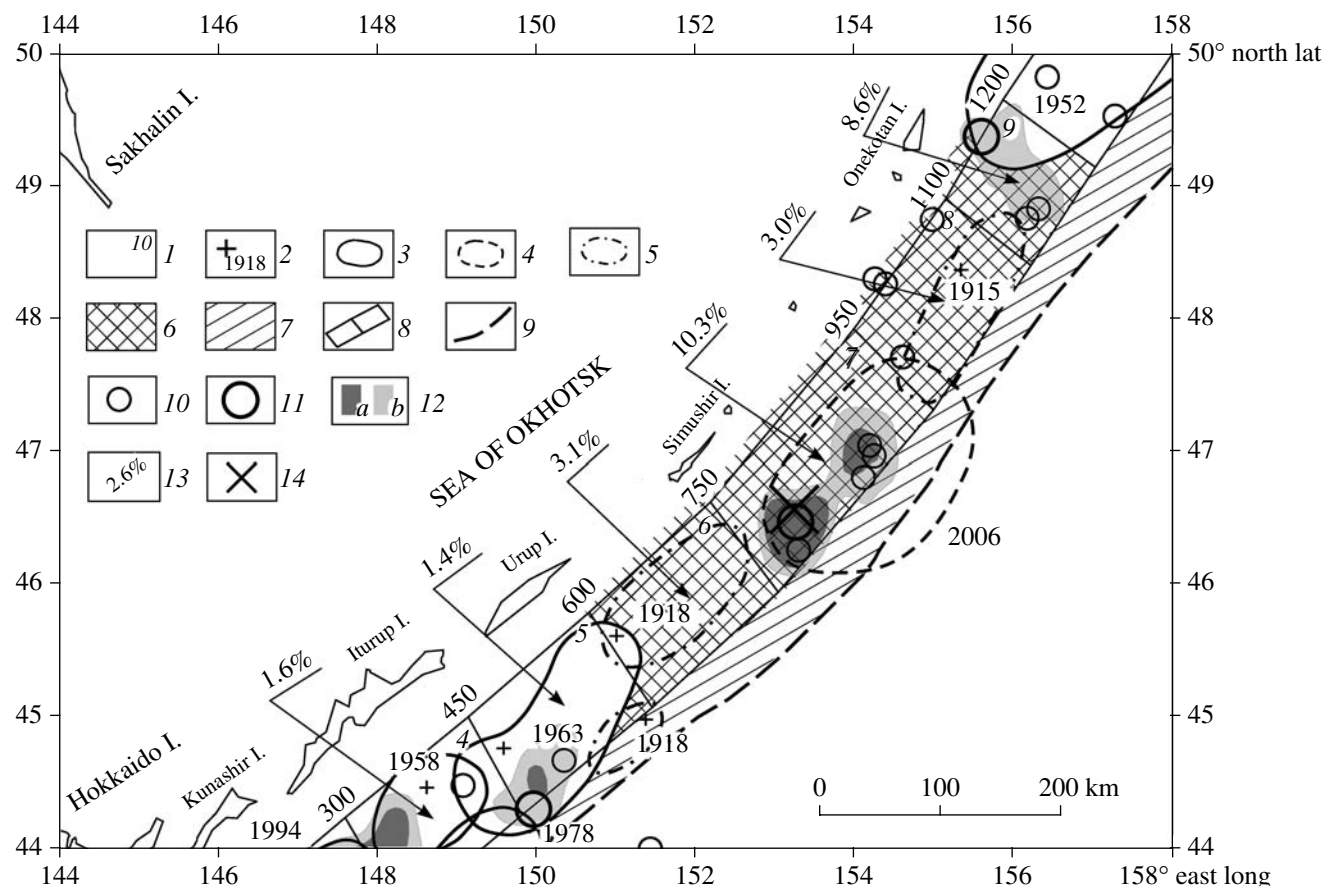


Fig. 4. Map showing the rupture areas of the 1915–2006 $M \geq 7.7$ Kuril–Kamchatka earthquakes in the depth range $H = 0$ –80 km, the seismic gaps, isolines of $1-B$ based on the data between November 15, 2001, and November 14, 2006, as well as earthquake epicenters for that period: (1) number of portion, (2) instrumental epicenters of $M \geq 7.7$ main shocks, (3) boundaries of $M \geq 7.7$ earthquake rupture areas determined to within 10 km, (4) segments of the same boundaries determined to lower accuracy, (5) likely rupture areas of the 1915–1918 $M \geq 7.7$ earthquakes, (6) the most probable locations of future $M \geq 7.7$ earthquakes, (7) possible locations of such future earthquakes, (8) boundary of prediction strip, (9) trench axis, (10) epicenters of $5.5 \leq m_b < 6.0$ earthquakes for the period November 15, 2001, to November 14, 2006, (11) epicenters of $m_b \geq 6.0$ earthquakes for the period November 15, 2001, to November 14, 2006, (12) isolines of $1 - B$ for two levels, (a) 0.9 and (b) 0.7, (13) probability of earthquake occurrence $P(M \geq 7.7)$ for the period November 2006 to November 2011, (14) epicenter of the November 15, 2006, $M_w = 8.3$, $M_s = 8.2$ Middle Kuril earthquake

available there extend for 450 km along the Kuril–Kamchatka arc. The total probability of earthquake occurrence in these portions is $\Sigma P(M \geq 7.7) = 16.8 + 14.6 + 10.4 = 41.8\%$. Those posing the greatest hazard are portions 11b and 12b situated off southern Kamchatka and in the Avacha Bay in the Petropavlovsk-Kamchatskii area.

The total probability of an $M \geq 7.7$ earthquake in the other major gap, off the Middle Kuril Islands and Shikotan I. (portions 6–9, Fig. 2), was $\Sigma P(M \geq 7.7) = 3.0 + 9.6 + 3.5 + 8.6 = 24.7\%$; among these, portion 7 was the most dangerous according to the forecast. It was in this portion that the $M_w = 8.3$, $M_s = 8.2$ Middle Kuril earthquake occurred on November 15, 2006 (Table 1, Figs. 3–5). That was another confirmation that the long-term prediction for the Kuril–Kamchatka arc in progress since 1965 is reliable [9, 10, 12]. This was the seventh time since 1965 that the forecast of the

next-to-occur $M \geq 7.7$ earthquake was correct. The event again occurred in an identified seismic gap. In the case under consideration, the instrumental epicenter and the aftershocks of the November 15, 2006, earthquake were a neat fit between the rupture areas of the May 1, 1915, $M = 8.1$ and the September 7, 1918, $M = 8.3$ earthquakes (Figs. 2 through 5).

Again, as had been the case with the October 13, 1994, $M = 8.0$ Shikotan [19] and the December 5, 1997, $M = 7.9$ Kronotskii [18, 22] earthquakes, this great quake occurred in the gaps that had been considered to present the highest hazard.

These results corroborate the long-term earthquake forecast for the Kuril–Kamchatka arc, highlighting the Petropavlovsk-Kamchatskii area as the most likely location for a next $M \geq 7.7$ earthquake. The most fortunate thing was that this great Kuril–Kamchatka earthquake occurred off the nearly unpopulated Middle

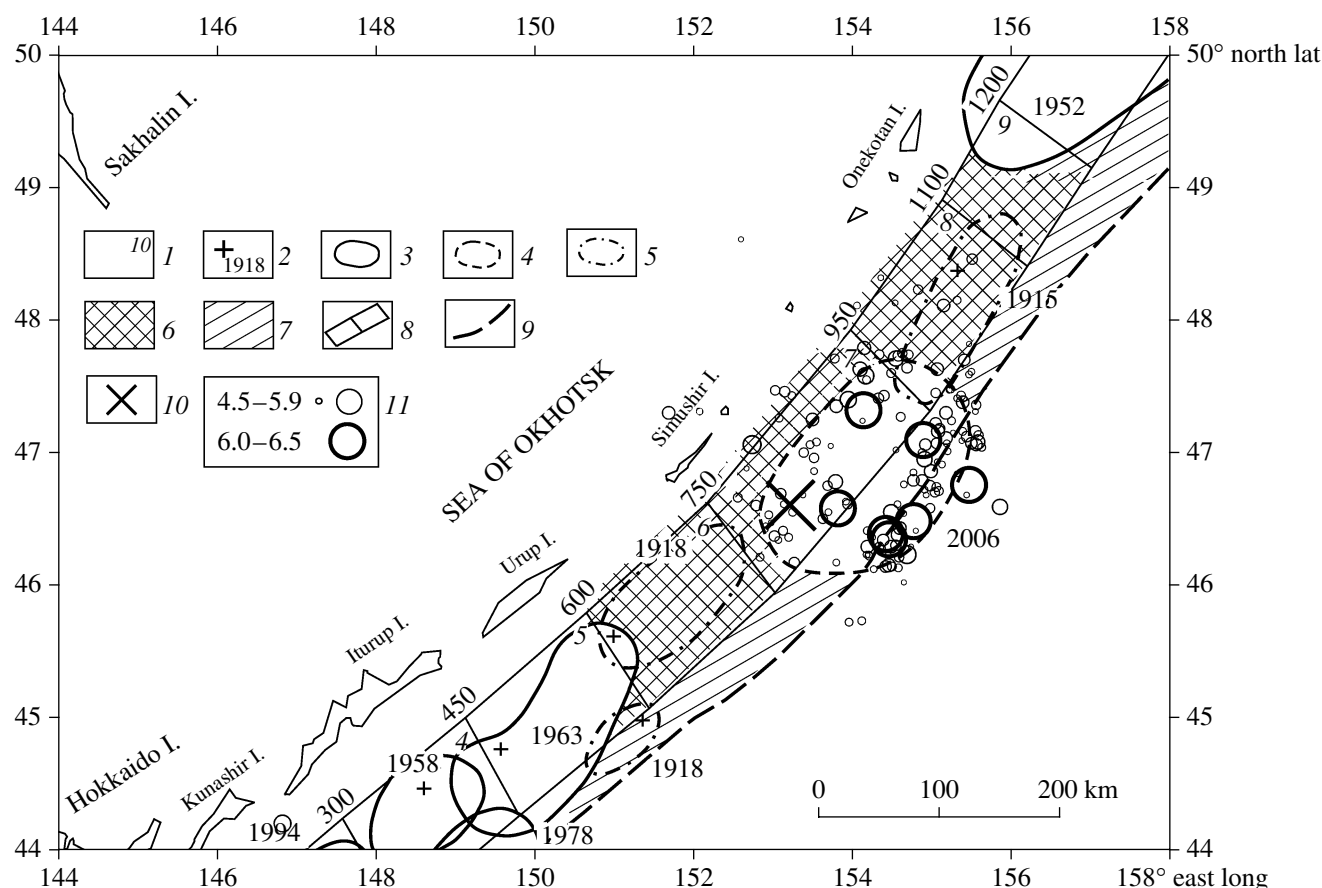


Fig. 5. Map showing the rupture areas of the 1915–2006 $M \geq 7.7$ Kuril–Kamchatka earthquakes in the depth range $H = 0$ –80 km, the seismic gaps, as well as aftershocks of the Middle Kuril earthquake: (1) number of portion, (2) instrumental epicenters of the $M \geq 7.7$ main shocks, (3) boundaries of $M \geq 7.7$ earthquake rupture areas determined to within 10 km, (4) segments of the same boundaries determined to lower accuracy, (5) likely rupture areas of the 1915–1918 $M \geq 7.7$ earthquakes, (6) the most probable locations of future $M \geq 7.7$ earthquakes, (7) possible locations of such future earthquakes, (8) boundary of prediction portions, (9) trench axis, (10) epicenter of the November 15, 2006, $M_S = 8.2$ Middle Kuril earthquake, (11) epicenters of the 10-day $m_b = 4.5$ –5.9 and 6.0–6.5 aftershocks

Kuril Islands rather than near the largest town in Kamchatka and the Kuril Islands, namely, Petropavlovsk-Kamchatskii, where it could have caused very grave consequences.

The precursory period before the November 15, 2006, Middle Kuril earthquake was a very long one, lasting over 100 years. The earthquake occurred against a quiet background without the ruptures of the previous $M \geq 7.7$ earthquakes and their aftershocks having any great effect. A pronounced foreshock activity had preceded that event during the last 2.5 months. Of great interest are the source mechanism, the seismotectonic setting, the extremely small tsunami, and the subsequent long-continued aftershock sequence (the time at which this paper was written in final form is a mere 20 days since the main shock). All these questions should be addressed by future research.

The evaluation of the forecast for this earthquake is supplemented in the present paper by some data on its precursory 2001–2006 period, its foreshocks, and first

observations of the aftershocks. Figure 3 shows a long-term earthquake forecast map for the Middle Kuril Islands and adjacent portions of the Kuril island arc for the period April 2006 to April 2011. The forecast was made seven months before the November 15, 2006, Middle Kuril earthquake. The map displays the main seismogenic strip, the rupture areas of the past $M \geq 7.7$ earthquakes, the seismic gaps, and the predicted probabilities $P(M \geq 7.7)$ for the occurrence of $M \geq 7.7$ earthquakes during the period April 2006 to April 2011 (Fig. 2, Table 2).

In addition, we show the earthquakes of $m_b = 5.5$ –5.9 and $m_b \geq 6.0$ for the preceding five years (March 2001 to March 2006) and isolines of the predictive parameter $1 - B = 1 - P(A_{10}) \times P(D) = 0.7$ –0.9. The probability of a great earthquake $P(M \geq 7.7)$ in a seismic gap is proportional to $1 - B$. The values of $1 - B$ were determined in circles of diameter 75 km for five-year intervals. This time–space window is adequate for monitoring the precursory phenomena before $M \geq 7.7$ earthquakes. It should be stressed that isolines of $1 - B$

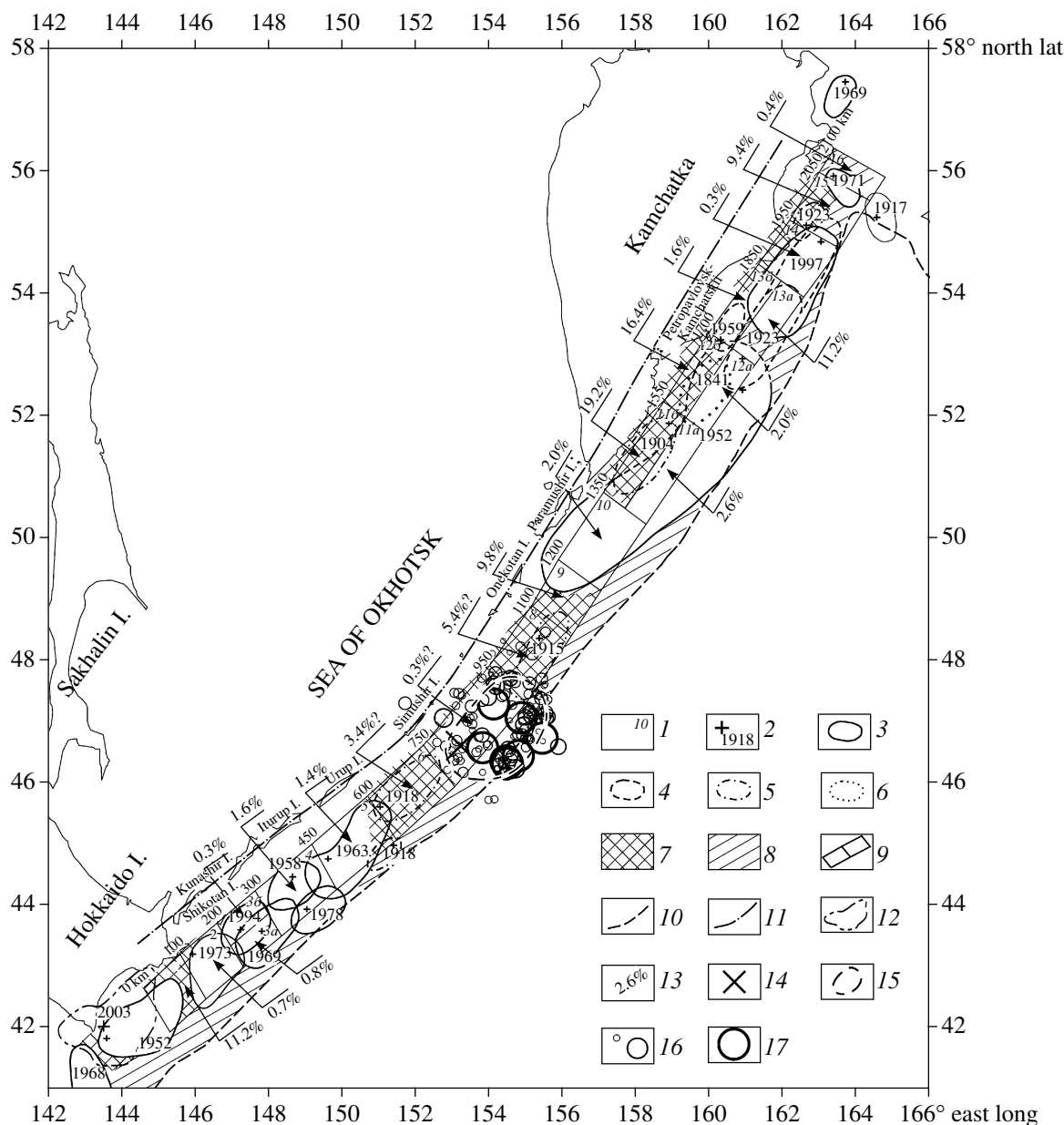


Fig. 6. Map showing the long-term forecast for the Kuril–Kamchatka arc for the period November 20, 2006, to October 2011 as updated after the November 15, 2006, $M_w = 8.3$, $M_S = 8.2$ Middle Kuril earthquake, the rupture areas of the 1904–2006 $M \geq 7.7$ Kuril–Kamchatka earthquakes in the depth range $H = 0-80$ km, and the probabilities of occurrence for such earthquakes for the period December 2006 to October 2011 in all portions of the prediction strip: (1) number of portion, (2) instrumental epicenters of $M \geq 7.7$ main shocks, (3) boundaries of $M \geq 7.7$ earthquake rupture areas determined to within 10 km, (4) segments of the same boundaries determined to lower accuracy, (5) likely rupture areas of the 1904–1918 $M \geq 7.7$ earthquakes, (6) inferred rupture area of the 1841 earthquake, (7) the most probable locations of future $M \geq 7.7$ earthquakes, (8) possible locations of such future earthquakes, (9) boundary of prediction portions, (10) trench axes, (11) axis of the Kuril–Kamchatka volcanic belt, (12) boundary of the September 25, 2003, $M = 8.1$ earthquake rupture area, (13) probabilities of $M \geq 7.7$ earthquakes for the period November 20, 2006, to October 2011, (14) epicenter of the November 15, 2006, $M_S = 8.2$ Middle Kuril earthquake, (15) preliminary boundary of its rupture area, (16) epicenters of the 10-day $m_b = 4.5-5.9$ aftershocks, (17) epicenters of the 10-day $m_b = 6.0-6.5$ aftershocks. The average probability of occurrence for $M \geq 7.7$ Kuril–Kamchatka earthquakes at the same location during 5 years is equal to 3.6–4.2%

determined in averaging circles of diameter 75 km allow identification of local highs in that parameter in large portions of the Benioff zone, and this is an advantage of these isolines. The average estimate of 1 – B over the entire portion may generally differ from such

local estimates of it, and seems both a better balanced and a more reliable quantity.

Figure 3 shows a preliminary (dashed) boundary of the Middle Kuril earthquake rupture area as outlined by the 10-day aftershocks alone. In the long-term predic-

tion method considered here we determine the boundary of an $M \geq 7.7$ earthquake rupture area from isolines of $A_{10} = 10$ and $D = 1$, in addition to the $M \geq 6$ aftershocks for the first year [12, 18, 21]. The boundary of the November 15, 2006, Middle Kuril earthquake rupture area is thus to be revised in a year hence.

Figure 4 shows a similar map based on the time window advanced by 7 months (November 15, 2001 to November 14, 2006), that is, ending immediately before the November 15, 2006, earthquake. A comparison of the two maps in Figs. 3 and 4 reveals those changes in the seismic precursory phenomena before the November 15, 2006 earthquake which had occurred during the 7 months before that date.

The largest events in the period March 2001 to March 2006 occurred in portion 8 where it abuts portion 7 (mostly in the beginning of the five-year interval) and in the central part of portion 7. They find their reflection in the highs of isolines of $(1 - B) = 0.7$ – 0.9 (Fig. 3). There was a seismicity increase in the central part of the future rupture area during the last 7 months before the November 15, 2006, Middle Kuril earthquake. However, the most significant increase took place at the mainshock epicenter, in the southwestern part of the rupture area, during the last 1.5 months. The maximum $(1 - B) > 0.9$ at the future epicenter, the cluster of events at the center of the future rupture area, and the seismicity maximum recorded in portion 8 before the main shock, all clearly delineated the axial line of the impending $M_w = 8.3$ earthquake.

Figures 3 and 4 show $P(M \geq 7.7)$ plotted for portions 4 through 9 along the Kuril–Kamchatka arc, those under prediction by our method for the period April 2006 to April 2011 (Fig. 3, Table 2) and for November 2006 to November 2011 (the second forecast is described in Section 4).

Figure 5 shows the aftershocks of the $M_w = 8.3$, $M_S = 8.2$ Middle Kuril earthquake which occurred during the first 10 days. One notices a swarm of aftershocks in the trench area containing five $M \geq 6$ aftershocks of the six that had occurred in November 15–16, 2006. The foreshock area was relatively quiet.

The overall impression one gets from Figs. 3–5 is that the long-term forecast of a possible location for the next $M \geq 7.7$ Kuril–Kamchatka earthquake has proved to be very accurate, and that the 2–3 most hazardous seismic gaps have been identified correctly in the twenty prediction portions, 8–9 gaps being available. The observed vigorous foreshock activity is also consistent with the main scenario for the seismic process as used in our prediction method.

In addition to long-term forecasts, before and after an $M \geq 7.7$ earthquake we provide an assessment of the seismic situation and a forecast of large ($M \geq 6$) aftershocks following $M \geq 7.7$ Pacific earthquakes [12, 13, 17, 19, 22, 23 and elsewhere]. Such forecasts were developed the next day after the April 21, 2006, $M_S = 7.9$ Olyutorskii earthquake and the November 15, 2006,

$M_w = 8.3$, $M_S = 8.2$ Middle Kuril earthquake. They are briefly reviewed in Section 5.

Each $M \geq 7.7$ earthquake affects the distribution of seismic gaps, consequently, the forecast for the Kuril–Kamchatka arc is updated for the next five years. Such an updated forecast is presented in Section 4.

4. THE LONG-TERM FORECAST FOR THE KURIL–KAMCHATKA ARC FOR THE PERIOD NOVEMBER 20, 2006, TO OCTOBER 2011

The long-term forecast for the Kuril–Kamchatka arc made in April 2006 for the period April 2006 to April 2011 was presented in Section 1. It was updated as usual after the lapse of six months (seven in this particular case), to date from October 23, 2006, for the next five-year interval, November 2006 to October 2011, i.e., three weeks before the November 15, 2006, Middle Kuril earthquake.² It was not appreciably different from the preceding forecast made for the period April 2006 to April 2011 (Section 2, Table 2, Fig. 2). For this reason the associated table and map showing the long-term forecast as of October 23, 2006, which was updated on November 19, 2006, are not given in this paper, only its main quantities are listed.

The October 23, 2006, long-term forecast divides the Benioff zone of the Kuril–Kamchatka arc into 20 portions (Tables 2 and 3, Figs. 2 and 6). The most hazardous location in the Kuril–Kamchatka arc was the Petropavlovsk-Kamchatskii area with the following estimates.

The total probability for $M \geq 7.7$ earthquakes to occur off southern Kamchatka, in the Avacha and Kronotskii bays (Fig. 2, portions 11a, 11b, 12a, 12b, 13a, 13b) and to cause shaking of intensity VII to IX at Petropavlovsk-Kamchatskii may reach 49.6% during the period November 2006 to October 2011. In particular, the probability of an earthquake causing intensity IX shaking at Petropavlovsk-Kamchatskii is 14.6%, the figure for VIII and VII intensity being 35.0%.

The second highest hazard existed in the area of Onkotan I. to the Middle Kuril Is. (portions 7–9, Fig. 2). The total probability of an $M \geq 7.7$ earthquake in the area for the next five years was 21.9%, while the probability for this area plus portion 6 (the Bussol' Strait, this too being a seismic gap), was 25.0%.

Substantial probabilities of $M \geq 7.7$ earthquakes also existed in other seismic gaps: 8% in the Kamchatka Bay (portion 15) and 10.1% in the Nemuro Peninsula (portion 1, Fig. 2).

As to the other portions of the Kuril–Kamchatka arc seismogenic zone, the probability of great earthquakes

² The forecast was considered by and registered at the Council on Prediction of Earthquakes and Volcanic Eruptions, Institute of Volcanology, Far East Division, Russ. Acad. Sci. and the Kamchatka Branch, Geophysical Service, Russ. Acad. Sci. on October 23, 2006.

Table 3. Long-term earthquake forecast for the Kuril–Kamchatka arc for the period November 20, 2006 to October 2011 ($H \leq 80$ km) made immediately after the November 15, 2006, $M_S = 8.2$ Middle Kuril earthquake using the parameters A_{10} , D , and A_{11} , and a comparison of this with the forecast made in October 2004

Portion	Δ , km	Location	Phase of the cycle and its estimate from the 2001–2006 data (October 2001 to November 2006)					Forecast for November 2006 to October 2011						Forecast for September 2004 to September 2009	
			Phase	$P_1 = P(A_{10})$	$P_2 = P(D)$	$P_3 = P(A_{11})$	$B = (P_1 P_2 P_3)$	A_{10} ($P \sim 0.7$)		$P \sim 0.8$	$P \sim 0.5$	$P \sim 0.15$	$M_{\max}$	$P(M \geq 7.7)\%$	Likely sequence
								A_{10}	$A_{10} \pm \sigma$						
1	0–100	Cape Sirikha to Nemuro Peninsula	III	0.19	0.01	0.94	0.002	1.2–3	0.8–4.5	6.0	6.5	7.0	7.8	11.2 (5.3)	3–4 (7)
2	100–200	Nemuro Peninsula to Zelenyi I.	II					1.2	0.8–1.9	5.8	6.3	6.8		0.7 (0.5)	
3a	200–300	Shikotan I., SE	II					1.2	0.8–1.9	5.7	6.2	6.7		0.8 (0.6)	
3b	200–300	Shikotan I., NW	I					2.1→1.4	0.9–3.1	6.0	6.4	6.9		0.3 (0.2)	
4	300–450	Iturup I.	II					1.2	0.8–1.9	5.9	6.4	6.9		1.6 (1.4)	
5	450–600	Vries Strait to Urup I.	II					1.2	0.8–1.9	5.9	6.4	6.9		1.4 (1.1)	
6	600–750	Cape Castricum to Bussol' Strait	III?	0.97	0.99	0.73	0.71	1.2–3	0.8–4.5	6.0	6.5	7.0	8.0	3.4? (7.1)	8 (6)
7	750–950	Simushir I. to Kruzenshtern Strait	I					1.2–3	0.8–4.5	6.2	6.7	7.2	8.2	0.3? (10.8)	(4)
8	950–1100	Shiashkotan I.	III?	0.996	0.73	0.97	0.69	1.2–3	0.8–4.5	6.0	6.5	7.0	8.0	5.4? (3.2)	7 (8)
9	1100–1200	Onokotan I. to Third Kuril Strait	III	0.89	0.16	0.90	0.13	1.2–3	0.8–4.5	6.0	6.4	7.0	7.9	9.8 (8.0)	5 (5)
10	1200–1350	Paramushir I. to Cape Lopatka	II					1.2	0.8–1.9	5.9	6.4	6.9		2.0 (2.7)	
11a	1350–1550	Southern Kamchatka, SE	II					0.8	0.6–1.1	5.8	6.3	6.8		2.6 (3.6)	
11b	1350–1550	Southern Kamchatka, NW	III	0.63	0.55	0.23	0.09	1.3–3	0.8–4.5	6.0	6.5	7.0	8.0	19.2 (17.0)	1 (2)
12a	1550–1700	Avacha Bay to Cape Shipunskii, SE	II					1.2	0.8–1.9	5.7	6.2	6.7		2.0 (2.7)	
12b	1550–1700	Avacha Bay to Cape Shipunskii, NW	III	0.24	0.72	0.19	0.03	1.2–3	0.8–4.5	5.9	6.4	6.9	8.0	16.4 (19.0)	2 (1)
13a	1700–1850	Kronotskii Bay, SE	III?	0.87	0.81	0.37	0.26	1.2–3	0.8–4.5	5.9	6.4	6.9	8.0	11.2 (3.3)	3–4
13b	1700–1850	Kronotskii Bay, NW	II					2.6	1.7–3.9	5.9	6.4	6.9		1.6 (1.3)	
14	1850–1950	Kronotskii Peninsula	I					3.1→1.9	1.2–4.5	6.0	6.5	7.0		0.3 (0.2)	
15	1950–2050	Kamchatskii Bay	III?	0.33	0.69	0.83	0.19	1.2–3	0.8–4.5	6.0	6.5	7.0	7.9	9.4 (11.6)	6 (3)
16	2050–2100	Kamchatskii Peninsula	II					0.8	0.6–1.1	5.7	6.2	6.7		0.4 (0.3)	
		Estimates of critical probability values		0.062	0.308	0.06	0.0012							$\Sigma = 100.0$	$\Sigma = 101$

Note: This table contains forecasts of eight seismicity characteristics for the period November 20, 2006, to October 2011. Probable phases of the seismic cycle are indicated for all the twenty portions. Index III marks those portions where no $M \geq 7.7$ earthquakes have occurred during the last 80 years and where the probability that the final phase III of the seismic cycle has set in is considerable. Question marks are attached to those portions where the probability of such an event is lower. B is a parameter that shows the relative hazard of a seismic gap; A_{10} is seismicity rate; $P \sim 0.8, 0.5$, and 0.15 are the probabilities of $M = 5.7$ – 7.2 earthquakes; $M_{\max}$ is the maximum credible magnitude; $P(M \geq 7.7)$ denotes predicted probabilities of great earthquakes. The values of $P(M \geq 7.7)$ in parentheses denote those for 2001–2005. The average long-term value is $P(M \geq 7.7) = 3.6$ – 4.2% . The estimated probabilities of great earthquakes $P(M \geq 7.7)$ and their sequence of occurrence are in bold type.

$P(M \geq 7.7)$ during five years was equal to the mean value (3.6–4.2%) or much (by factors of 10–15) less than the mean.

To sum up, the greatest hazard posed by future great ($M \geq 7.7$) earthquakes as predicted by our long-term forecast just before the November 15, 2006, Middle Kuril earthquake was for Petropavlovsk-Kamchatskii and the Middle Kuril Islands with a total probability of about 75%. The forecast was realized on November 15, 2006, when an $M_w = 8.3$, $M_S = 8.2$ earthquake occurred off the Middle Kuril Islands. That was another success of the long-term earthquake prediction work for the Kuril–Kamchatka arc.

As has been pointed out in Section 3, the forecast correctly pinpointed the likely location of the earthquake (the seismic gap) and identified the two most hazardous locations for the next great earthquake in the Kuril–Kamchatka arc.

Similar successful forecasts were published before the Shikotan, South Kuriles earthquake (October 4, 1994, $M = 8.1$) and the Kronotskii earthquake off eastern Kamchatka (December 5, 1997, $M = 7.9$) [17, 19, 22 and elsewhere].

Once an earthquake of this size occurred and filled one of the most likely locations for $M \geq 7.7$ earthquakes, the probability for similar-sized events to occur near the Middle Kuril Islands decreased, while that in the other seismic gaps increased. Accordingly, the forecast for the next five years has been updated. The forecast is largely preliminary in nature, considering that the great Middle Kuril earthquake occurred only 5 days ago, and its aftershocks continue to occur. A more accurate forecast can be developed when most of the aftershocks have occurred.

The updated forecast for the Kuril–Kamchatka arc we made on November 19 is shown in Fig. 6, Table 3, where the epicenter of the November 15, 2006, main shock with $M_w = 8.3$, $M_S = 8.2$ is indicated together with its aftershocks for the period November 15–17, 2006, with magnitudes $M = 4.3$ – 6.5 , as well as the preliminary boundary of the mainshock rupture area which will be subject to further revision when most of the aftershocks have occurred.

The rupture area exactly fills the seismic gap between the rupture areas of the May 1, 1915, $M = 8.0$ and the September 7, 1918, $M = 8.3$ earthquakes. The rupture area of the Middle Kuril earthquake is located in portion 7 (Figs. 5 and 6) which presented the greatest hazard in the Middle Kuril Is. area according to the preceding long-term forecast. The probability of the next great earthquake in portion 7 will be considerably lower during the next decades, after the first year of aftershock occurrence, when phase I of the seismic cycle will take place (aftershocks) to be followed by phase II (a stable seismic regime).

Having that circumstance in view, as well as the fact that the seismicity of portion 8 dramatically increased during the first 5 days after the earthquake, we calcu-

lated new probabilities for all portions of the Kuril–Kamchatka Benioff zone for the next 5 years, November 20, 2006 to October 2011 (Table 3, Fig. 6) using the method given in [12].

The chief difference between this, preliminary, forecast for the Middle Kuril Is. and the preceding forecast is that the probability of a new $M \geq 7.7$ earthquake occurring in portion 7 (Fig. 2, 6) has decreased to a value as low as 0.3%.

Simultaneously, the probability of such earthquakes increased from 48.0 to 53.0% from April 2006 to November 19, 2006, in the Petropavlovsk-Kamchatskii area off southern Kamchatka, and in the Avacha and Kronotskii bays (portions 11a, 11b, 12a, 12b, 13a, 13b in Fig. 6; Table 3). In particular, the probability of intensity IX ground motions at Petropavlovsk-Kamchatskii increased from 14.6 to 16.4%. The probability of intensity VII–VIII ground motions at Petropavlovsk-Kamchatskii increased from 33.4 to 36.6%.

These estimates will be updated after the first month of the aftershock sequence, when about 70% of all the 1-year aftershocks will have occurred.

The map in Fig. 6 presents a visual demonstration of how the seismic gap off the Middle Kuril Is. and Shikotan I., portion 7, which has been empty during more than 100 years, was at last so neatly filled.

It has been found that the aftershocks that occur during the first ten days after Kuril–Kamchatka and Japanese $M \geq 7.7$ earthquakes average 65% of their number after 1-year [12, 13, 19, 22, 24 and elsewhere].

It is very likely that the aftershocks that occur later than the first 10 days will fill, not only portion 7 (Figs. 5 and 6), but also will penetrate into the adjacent portions 6 and 8. The effect may be to inflate A_{10} and D , unless those aftershocks have been eliminated from the estimates, hence B , $(1 - B)$, and $P(M \geq 7.7)$ may be different from those indicated in Table 3 and Fig. 6. For this reason the values of $P(M \geq 7.7)$ for portions 6 and 8 have question marks appended to them, and will be updated later. Observations during the next months and years will reveal the changes occurring in the aftershocks of that event, which is of great interest from the standpoint of seismology and seismotectonics.³

³ This paper was submitted to the journal on December 14, 2006. A month later, another great earthquake occurred in the eastern part of the November 15, 2006, Middle Kuril earthquake rupture area. The basic parameters for this event are given by the Geophysical Service, Russ. Acad. Sci. at the town of Obninsk as follows: occurrence time (Moscow) is 7:23:19.4 January 13, 2007, epicenter coordinates are 46.25°N, 154.46°E, depth of focus 10 km, $M_S = 8.2$. The epicenter was in the trench. According to the “aftershock scenario” [12, 13, 19, 22, 24 and elsewhere], the largest aftershock of an $M \geq 7.7$ earthquake that occurs during the first year will have magnitude $M = 7.5$ – 7.9 with probability 0.67. The January 13, 2007 earthquake was larger than that. Its occurrence confirms our concluding sentence in Section 4 of this paper.

5. RESULTS AND DISCUSSION

This section is concerned with several issues. We begin by considering the prediction of the most important quantities for practice, namely, probabilities of occurrence for $M \geq 7.7$ earthquakes in all portions of the Kuril–Kamchatka arc, and then discuss the estimation of relative hazard for the seismic gaps that were identified in 2001 to November 2006 from seismological observations during the period 1996 to October 2006, before the November 15, 2006, Middle Kuril, $M_w = 8.3$, $M_s = 8.2$ earthquake.

The relative hazard of a seismic gap is proportional to $(1 - B)$, which indicates the probability that the portion in question is in phase III, the final one of the seismic cycle. The expression $B = P(A_{10}) \times P(D)$ has been long used to determine B , where $P(A_{10})$ and $P(D)$ are the probabilities of observed values of A_{10} and D in phase II, the stable phase. It was assumed that A_{10} and D are nearly unrelated in large (11×10^3 km² on the average) areas of the seismogenic zone. In recent years the parameter A_{11} was added to A_{10} and D , so that the quantities $B_1 = P(A_{10}) \times P(D) \times P(A_{11})$ and $B_2 = 1/3[P(A_{10}) + P(D) + P(A_{11})]$ began to be used to find the relative probabilities $P(M \geq 7.7)$. These two quantities allow estimation of the range of B in the case of poor correlation of A_{10} , D , and A_{11} , and where there is a strong interdependence.

Table 4 lists ten estimates of $P(M \geq 7.7)$ for the Kuril–Kamchatka gaps obtained in the period 2001 to November 2006 using B , B_1 , and B_2 . We indicate five-year intervals for the period 2001 to October 2011 to which the forecasts are relevant, and show that the probabilities $P(M \geq 7.7)$ in the forecasts developed in 2001 to November 2006 had a low scatter in all seismic gaps: the standard deviations of $P(M \geq 7.7)$ as found for each portion lie in the range 1.3–3.3%.

This stability of the estimates was largely due to the fact that no $M \geq 7.7$ earthquakes occurred in the Kuril–Kamchatka arc seismogenic zone during the period from 2001 to October 2006 to affect the map of great earthquakes and seismic gaps and to alter the division into portions of that part of the seismogenic zone for which the forecasts were made.

Two $M \geq 7.7$ earthquakes occurred during that period south and north of the prediction strip as defined for the Kuril–Kamchatka arc.

An $M = 8.1$ earthquake occurred off southeastern Hokkaido on September 25, 2003. The epicenter and the rupture area are shown in Figs. 1 and 2. A retrospective long-term earthquake forecast was made for that area to show that the area was second in earthquake hazard level in the Hokkaido–Kuril Is.–Kamchatka Region during the period 2001–2003 [14].

The Olyutorskii $M = 7.8$ earthquake occurred April 20, 2006, in the Koryak upland close to the western coast of the Bering Sea (epicenter coordinates are 61.06°N, 167.58°E, depth of focus 3.5–42.0 km). Its rupture area is situated on the extension of Kamchatka

geologic and tectonic features, but is 500 km northeast of the Kuril–Kamchatka prediction strip, so that no forecasts were made for the area.

As has been mentioned, it follows from Table 4 that the mean values of $P(M \geq 7.7)$ derived by three different methods used to calculate B are very similar. The important fact is that the standard deviations of the means of $P(M \geq 7.7)$ are small, lying within 1.3–3.3%. Table 4 corroborates that the greatest hazard exists for the town of Petropavlovsk-Kamchatskii and southern Kamchatka; the associated probabilities $P(M \geq 7.7)$ as calculated before the November 15, 2006 earthquake for the next five years were equal to $16.5 \pm 2.2\%$ and $15.0 \pm 3.3\%$, respectively.

Table 4 shows that the second greatest hazard had been invariably associated with the Middle Kuril Is., portions 6–8, since 2001 until November 15, 2006, the mean probability for portion 7 being $P(M \geq 7.7) = 10.4 \pm 1.4\%$.

The most significant event in the Kuril–Kamchatka arc during the period 2001–2006 took place November 15, 2006, when a correctly predicted earthquake of $M_w = 8.3$, $M_s = 8.2$ occurred off the Middle Kuril Is. and Shiashkotan I., a quake of this size having been considered to be impossible there by several investigators. This important event and the relevant forecast have been discussed in Section 3, so we turn to other issues that were little touched upon in sections 1 through 4.

It is helpful to bear in mind in assessing Table 4 that correct advance long-term forecasts were available for the two recent great earthquakes occurring at the Kuril–Kamchatka arc, viz., the October 4, 1994, Shikotan $M = 8.1$ earthquake off the South Kuril Is. (Figs. 1 and 2) and the $M = 7.8$ – 7.9 Kronotskii earthquake occurring December 5, 1997 off Kamchatka (Figs. 1 and 2). The forecasts contained statements to the effect that the rupture areas of these quakes were among the 2–3 most likely locations of future great earthquakes [17, 20, 23].

The preceding great Kuril–Kamchatka earthquakes of magnitude $M \geq 7.7$ which occurred in 1969, 1971, 1973, and 1978, were also in predicted seismic gaps (Figs. 2 and 6) [12 and elsewhere].

The previous sections, 1 through 4, were first and foremost concerned with long-term forecasts of the events that present the greatest hazard, $M \geq 7.7$ earthquakes. In addition, several other quantities and characteristics were predicted for five-year periods: the phase of the seismic cycle, the seismicity rate A_{10} , the magnitudes of moderate earthquakes expected with probabilities 0.8, 0.5, and 0.15; and others (Tables 2 and 3). Sections 1–4 will now be supplemented by indicating the success in forecasting these quantities.

The forecasts were evaluated periodically at the end of each five-year prediction period [12, 14, 15, 16, 20, 21]. After the first 20 years of long-term prediction work during 1965–1985 it turned out that the forecasts of A_{10} made at probability 0.7 for all portions had a success rate of 73%; the forecasts of magnitude M to be

Table 4. Estimated probabilities of great earthquakes $P(M \geq 7.7)$ in seismic gaps for 2001 to October 2006 based on the parameters B , B_1 , and B_2

Portion	Δ , km	Location	Phase	$B = P(A_{10})P(D)$						$B_1 = P(A_{10}) \times P(D)P(A_{11})$		$B_2 = (P(A_{10}) + P(D) + P(A_{11}))/3$		Estimates of P based on B , B_1 , and B_2	
				2001–2005	IV 2004–III 2009	XI 2004–X 2009	VI 2005–V 2010	IX 2005–IX 2010	XI 2006–X 2011	IX 2005–IX 2010	IV 2004–III 2005	IX 2005–IX 2010	XI 2006–X 2011	P_{mean}	σP
1	0–100	Cape Sirikha to Nemuro Peninsula	III	5.7	11.1	13.2	14.4	11.4	10.7	10.3	10.1	11.0	10.4	10.9	2.1
2	100–200	Nemuro Peninsula to Zelenyi I.	II												
3a	200–300	Shikotan I., SE	II												
3b	200–300	Shikotan I., NW	I												
4	300–450	Iturup I.	II												
5	450–600	Vries Strait to Urup I.	II												
6	600–750	Cape Castricum to Bussol' Strait	III?	7.7	4.4	4.4	4.4	3.4	3.2	3.1	3.1	5.0	4.7	4.4	1.3
7	750–950	Simushir I. to Kruzenshtern Strait	III?	11.7	11.6	9.4	9.7	10.9	12.4	7.9	10.9	8.7	9.7	10.4	1.4
8	950–1100	Shiashkotan I.	III?	3.5	9.4	7.2	9.2	9.0	6.2	5.9	3.0	6.3	4.8	6.5	2.2
9	1100–1200	Onekotan I. to Third Kuril Strait	III	9.6	8.1	7.7	4.7	10.2	9.4	9.0	8.6	7.5	6.7	8.2	1.5
10	1200–1350	Paramushir I. to Cape Lopatka	II												
11a	1350–1550	Southern Kamchatka, SE	II												
11b	1350–1550	Southern Kamchatka, NW	III	18.3	17.1	10.6	8.7	11.5	15.3	17.1	18.2	15.3	18.2	15.0	3.3
12a	1550–1700	Avacha Bay to Cape Shipunskii, SE	II												
12b	1550–1700	Avacha Bay to Cape Shipunskii, NW	III	20.5	18.9	19.6	17.2	14.5	13.8	14.9	14.6	15.8	15.6	16.5	2.2
13a	1700–1850	Kronotskii Bay, SE	III?	3.6	4.9	5.3	5.0	10.6	6.7	10.6	10.7	9.4	9.3	7.6	2.6
13b	1700–1850	Kronotskii Bay, NW	II												
14	1850–1950	Kronotskii Peninsula	I												
15	1950–2050	Kamchatskii Bay	III?	12.5	5.3	12.5	10.6	9.3	8.7	8.1	8.0	7.5	7.2	9.0	2.2
16	2050–2100	Kamchatskii Peninsula	II												

Note: The positions of portions 1–16 are indicated in Figs. 2 and 3. The average $P(M \geq 7.7)$ for five-year intervals is 3.6–4.2% for all portions.

Table 5. The average rate of successful five-year forecasts for A_{10} and $M(P = 0.8)$ for 18–21 portions of the Kuril–Kamchatka seismogenic zone in 1965–2005

Years	$A_{10} \pm \sigma$ $P = 0.7$	$M = 5.7-6.1$ $P = 0.8$	Source
1965–1985	0.73	0.65	[15]
1986–1990	0.78	0.38	[16]
1991–1995	0.50	0.38	[16]
1996–2000	0.52	0.52	[16]
2001–2005	0.45	0.40	

Note: $A_{10} \pm \sigma$ are the intervals of seismic activity predicted for 5 years with probability $P = 0.7$; $M(P = 0.8)$ are earthquake magnitudes in the range $M = 5.7-6.2$ predicted for 5 years with probability $P = 0.8$. Shown is the success rate.

expected with probability 0.8 had a rate of 65%, and the forecasts of magnitude M to be expected with probability 0.5 had a rate of 32% [15, 20, 21]. The above figures have persisted with little variation during later years.

Table 5 lists average success rates for $A_{10} \pm \sigma$ and for $M = 5.7-6.1$ earthquakes to be expected with probability $P = 0.8$ in different portions of the prediction zone during five-year time intervals in 1986–1990, 1991–1995, 1996–2000 quoted from [15, 16, 20, 21], as well as for the period 2001–2005 as calculated in this study. It can be seen from Table 5 that the forecasts of $A_{10} \pm \sigma$ and $M(P = 0.8)$ have been successful in over half of the cases. The reduced success rates for $A_{10} \pm \sigma$ and $M(P = 0.8)$ in 2001–2005 may have been due to incomplete reporting of smaller earthquakes, in particular, in the Middle Kuril Is. area, as well as to lack of $M \geq 7.7$ earthquakes during that period, since such events enhance the seismicity rate in adjacent portions.

A useful addition to the long-term earthquake prediction method consists in “seismic scenarios”, or average sequences of large ($M \geq 6$) foreshocks and aftershocks of $M \geq 7.7$ Pacific earthquakes [12, 13, 17, 19, 20, 22–24 and elsewhere]. The sequences have been constructed for the foreshocks that occur during a month prior to $M \geq 7.7$ Pacific earthquakes and for the first year of aftershocks. These “seismic scenarios” are systematically used to assess the seismic situation when $M \geq 6$ earthquakes or swarms of earthquakes occur in seismic gaps, as well as to forecast hazardous aftershocks following $M \geq 7.7$ earthquakes. The scenarios provide short-term forecasts of large earthquakes when $M \geq 6$ events occur in seismic gaps, and forecast large aftershocks of $M \geq 7.7$ earthquakes during one year after their occurrence [12, 13, 17, 19, 20, 22–24 and elsewhere].

The first scenario was developed in 1990 and at once handed over in full form to the administration and the civil defense headquarters of Kamchatka Region to take preparedness measures in anticipation of damaging earthquakes, as well as to civil engineers who are engaged in the construction or strengthening of earth-

quake-resistant buildings in Kamchatka [12, 19, 24]. Examples of assessing a seismic situation with the help of seismic scenarios can be found in [13, 19, 22–24] and elsewhere.

The seismic scenarios were used to correctly predict aftershocks of the October 13, 1994, magnitude 8.1 Shikotan, South Kuril earthquake (Table 1, Figs. 2 and 6) [12, 20 and elsewhere] and those of the December 5, 1997, magnitude 7.9 Kronotskii, Kamchatka earthquake (Table 1, Figs. 2 and 6) [12, 17, 23 and elsewhere].

The scenarios were used after a magnitude 6.5 earthquake which occurred in a seismic gap, portion 11b, off southern Kamchatka on August 24, 2006, the average probability of an $M \geq 7.7$ earthquake in the gap being 15% during five years (Fig. 2, Tables 2 and 5). The estimates stated that the probability of that event being the foreshock of an $M \geq 7.7$ earthquake was about 10% during several days after it and substantially decreased after 10 days.

The seismic scenarios were also used in a similar manner twice in 2006 to predict large ($M \geq 6$) aftershocks following the April 20, 2006, magnitude 7.8 Olyutorskii earthquake and those of the November 15, 2006, $M_w = 8.3$, $M_s = 8.2$ Middle Kuril Is. earthquake (Section 3).

The April 20, 2006, magnitude 7.8 Olyutorskii earthquake occurred outside the prediction strip, about 500 km from it, the epicenter being at the point 61.07°N and 167.06°E. Since the seismic scenario was developed for application to all great earthquakes along the Pacific seismic belt, it was used to predict the aftershock process of this earthquake also.

Forecasts of sequences of large aftershocks were handed over to the Council on Prediction of Earthquakes and Volcanic Eruptions, Institute of Volcanology and Seismology and the Kamchatka Branch, Geophysical Service. The Council sent its forecasts to 14 addresses, including the administration of Kamchatka Region, the Ministry of Emergencies, and the Russian Expert Council, Russian Academy of Sciences.

The expected and observed numbers of $M \geq 6$ aftershocks for both of these earthquakes are given in Table 6.

One notices consistent results for the aftershocks of the Olyutorskii earthquake in the magnitude range $M = 6.0-6.4$ and lower sums of all $M \geq 6$ aftershocks. This can be explained by the relatively low mainshock magnitude ($M = 7.8$) and, accordingly, by fewer $M \geq 6.5$ aftershocks.

The aftershocks of the Middle Kuril earthquakes were especially intensive during the first tens of minutes. Five $M \geq 6$ aftershocks occurred during half an hour, among them the largest aftershock of the first 10 days, magnitude 6.5. Subsequently the intensity of the aftershock process stabilized and was at the level envisaged by the seismic scenario for the first ten days.

Table 6. The numbers of $M \geq 6$ aftershocks observed for the April 20, 2006, $M = 7.8$ Olyutorskii earthquake and the November 15, 2006, $M_S = 8.2$ Middle Kuril earthquake compared with the numbers predicted by the seismic scenario

Days	Aftershock magnitude	n , number of aftershocks		
		Aftershock scenario	Olyutorskii earthquake	Middle Kuril earthquake
2	6.0–6.4	3	3	6
	≥ 6	4–5	3	7
10	6.0–6.4	4	4	6
	≥ 6	7	4	7
30	6.0–6.4	5	5	–
	≥ 6	8	6	–
230	6.0–6.4	6	5	–
	≥ 6	10	6	–

Note: The data on the larger aftershocks of the November 15, 2006, Middle Kuril earthquake are available only for the 10-day period after the main shock. The subsequent aftershock occurrence will be considered in later publications.

Overall, seven $M \geq 6$ aftershocks had occurred during the first ten days, which is consistent with the scenario.⁴

We also remark that the November 15, 2006, Middle Kuril earthquake was preceded by a large foreshock swarm lasting 1.5 months (Fig. 4), so that the seismic scenario could be used to provide a short-term forecast of that earthquake.

The results by the present long-term prediction method were compared in 2005–2006 with those from other long-term and intermediate-term prediction methods as applied to Kamchatka and the entire Kuril–Kamchatka arc, starting with M8, RTL, the method based on coda waves, etc. [2, 3, 7 and elsewhere]. These issues and the state-of-the-art in long-term earthquake prediction worldwide were discussed in [10, 15], such a discussion being outside the scope of the present paper.

CONCLUSION

(1) Results are discussed from the 2005–2006 work on long-term earthquake prediction for the Kuril–Kamchatka arc; this work relies on a method based on the patterns of seismic gaps and the seismic cycle [9, 10, 12, 14, 21, 25, and elsewhere]. We provide information

on the method and its developments, present long-term forecasts for the Kuril–Kamchatka arc for the period April 2006 to April 2011 (Section 2) made in April 2006 before the November 15, 2006, Middle Kuril earthquake of $M_w = 8.3$, $M_S = 8.2$; and the forecast for the period November 2006 to October 2011 (Section 4) as of November 19, 2006, after the earthquake, which incorporates the changes wrought by that event in the seismic process.

(2) Similarly to previous work using the method described in [12, 14 and elsewhere, we delineate the rupture areas of $M \geq 7.7$ earthquakes that have occurred in the Kuril–Kamchatka seismogenic zone during the past 80 years and the seismic gaps between them; the seismogenic zone is divided into about 20 portions, depending on the locations of these rupture areas and seismic gaps (Sections 1, 2, and 4). For these portions, 50×100 to 100×200 km in size, we predict for five-year intervals the following: the phase of the seismic cycle, seismicity rate A_{10} , earthquake magnitudes to be expected with probabilities 0.8, 0.5, and 0.15, the maximum credible magnitude, the probability of great earthquakes $P(M \geq 7.7)$, the most likely locations of the next $M \geq 7.7$ earthquakes (seismic gaps), and the relative hazard of the seismic gaps.

The estimate of relative hazard to be ascribed to the seismic gaps, $P(M \geq 7.7)$, is an important part of the forecast. The mean repeat time between successive $M \geq 7.7$ earthquakes in the Kuril–Kamchatka arc as a whole is close to 5 years, the mean interevent interval was equal to 5.6 ± 4.4 years. The estimates for the probabilities of the next $M \geq 7.7$ earthquakes in different portions of the seismogenic zone were calculated assuming such quakes to be mutually exclusive events the sum of whose probabilities is one. These estimates are relevant to the next 5-year interval. Taking 11 five-year intervals between $M \geq 7.7$ earthquakes in 1952–2006, one or two $M \geq 7.7$ quakes occurred in nine cases of the eleven, and the assumed condition was satisfied in more than 0.8 of the cases (Sections 1, 2, 4, and 5).

The forecasts made during the period 1965–2000 have been successful in 0.8–0.9 of the cases [12 and elsewhere]. If the recent 12-year interval is considered, the forecasts were successful for the locations of the October 13, 1994, magnitude 8.1 Shikotan earthquake [20] and the December 5, 1997, magnitude 7.9 Kronotskii earthquake [17, 23]. A new success came with the November 15, 2006, $M_w = 8.3$, $M_S = 8.2$ Middle Kuril earthquake (Section 3).

(3) Ever since the beginning (in the year 1965) of seismological research using the long-term method here considered, the major seismic gap in the Middle Kuril Is. area has been regarded as a likely location of future $M \geq 7.7$ earthquakes to be expected along the Kuril–Kamchatka arc [9, 12 and elsewhere]. Several investigators believed that no earthquakes larger than 7.5 ± 0.2 could occur there. Also later, we identified the area of the Middle Kuril Is. and Shiashkotan I. as one of

⁴ The present paper was submitted to the journal on December 14, 2006, so Table 6 can contain information on the 10-day aftershocks only of the November 15, 2006, Middle Kuril earthquake. The subsequent evolution of the aftershock swarm and of the seismic process is to be treated in later publications. The evolution of the seismic process is to be compared with that observed for three pairs of great Kuril–Kamchatka earthquakes: September 7, 1918, $M = 8.2$ and November 8, 1918, $M = 7.9$; February 3, 1923, $M = 8.5$ and February 24, 1923, $M = 7.7$; November 15, 2006, $M = 8.2$ and January 13, 2007, $M = 8.2$.

the most hazardous seismic gaps [12, 14, 15, 16 and elsewhere]. The last forecasts to this effect were made twice in the year 2006—in April and again in October—just before the event in question (Figs. 2 and 6, Section 3).

The November 15, 2006, earthquake rupture area is a very accurate fit to the predicted seismic gap.

(4) The long-term forecast for the Kuril–Kamchatka arc for the period April 2006 to April 2011 (Section 2) was another confirmation that the greatest earthquake hazard existed for the Petropavlovsk-Kamchatskii area where the total probability of an $M \geq 7.7$ earthquake in six contiguous portions (11a, 11b, 12a, 12b, 13a, and 13b in Fig. 2; Table 2) capable of causing shaking of intensity VII to IX at Petropavlovsk-Kamchatskii was as high as 48% (Section 2).

The area with the second highest level of earthquake hazard was that of the Middle Kuril Is. and Onkotan I. (portions 6–9 in Figs. 2 and 4) where the total probability $P(M \geq 7.7)$ reached 26.7% (Section 2).

The forecast was found to have been successful when the November 15, 2006, $M_w = 8.3$, $M_S = 8.2$ Middle Kuril earthquake occurred there (Section 3).

After that event we made an update of the long-term forecast for the period November 2006 to October 2011 (Section 4), which will be more reliable for the Middle Kuril Is. area when aftershock data for the first year following the November 15, 2006, earthquake become available. The probability of an earthquake causing ground motions of intensity VII–IX at Petropavlovsk-Kamchatskii has increased to a level as high as 53% (Section 4). The probability of an earthquake in the Avacha Bay, which can produce shaking of intensity IX at Petropavlovsk-Kamchatskii, is equal to 16.5% (Sections 4 and 5, Table 3, Fig. 6).⁵

The next most hazardous areas are the Nemuro Peninsula, portion 1 (Table 3, Fig. 6) where $P(M \geq 7.7) = 11.2\%$; the Kamchatskii Bay in Kamchatka, portion 15 (Table 3, Fig. 6) where $P(M \geq 7.7) = 9.4\%$; and lastly, the Onkotan I. area northeast of the November 15, 2006, earthquake rupture area, portion 9 (Table 3, Fig. 6) where $P(M \geq 7.7) = 9.8\%$.

At the same time, half of the portions of the Kuril–Kamchatka seismogenic zone have probabilities of great $M \geq 7.7$ earthquakes equal to the average (3.6–4.2%) or considerably (by factors of 10–15) lower.

(5) The 1986–2006 long-term earthquake forecasts for the Kuril–Kamchatka arc were a basis for six government decrees on measures to be taken to enhance the earthquake preparedness of Kamchatka Region, see

[12]. According to the April 2006 to April 2011 long-term forecast for the Kuril–Kamchatka arc, the probability of earthquakes causing ground motions of intensity VII–IX during that period at the largest town of Kamchatka, Petropavlovsk-Kamchatskii, reached 48% (Section 2). The forecast was used to substantiate new assignments and decrees of the President and the Government of the Russian Federation regarding urgent measures to enhance seismic safety, to prevent earthquake damage, and to strengthen buildings and structures in Kamchatka Region.

(6) The long-term forecast developed here is also a long-term forecast of tsunami probability in various areas of the Kuril–Kamchatka arc.

(7) The above results show that the present long-term earthquake prediction method can be used for other regions worldwide that have similar structures and extended seismogenic zones.

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