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MIGRATION AND RECURRENCE OF GREAT EARTHQUAKES IN KAMCHATKA AND THE NORTHERN KURILS

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The Benioff zone off Kamchatka and the northern Kuril Islands is divided into several blocks using the source area locations of great 20th century earthquakes. The occurrence of the great 18 to 20th century earthquakes defines three migrations. Two of them take place along the Benioff zone. One involves several blocks, or source areas of great earthquakes, and is from southwest to northeast, the duration of earthquake sequences being within 21 years. The other involves all blocks and proceeds in both directions at approximately equal velocities, 4±1 km/yr. Some evidence suggests that the source areas of great events migrate across the Benioff zone, the mean recurrence time being 100±40 years. The results obtained will be used to forecast the periods of time during which great earthquakes are likely to occur within the blocks.

INTRODUCTION[a]

Investigation of the spatio-temporal distributions of great (M≥7.9) earthquakes that occurred in the Nankai trough area during the period 684–1946 (Figure 1) has revealed the following patterns [3].

(1) The earthquake-generating volume can be divided into three zones whose boundaries remain fixed with time. The zones are about equal in length, which is l_0=270±30 km.

(2) The rupture zones of great earthquakes tend to occur in chains, migrating from one to another in the direction from northeast to southwest, the sources of great earthquakes within a migration chain involving two or all three zones. The interstices between events in a migration chain vary between around zero (in the case of the 1605 and 1707 earthquakes where two nearly simultaneous shocks occurred in adjacent zones), one day (December 23 and 24, 1854), 3–4 years (1096 and 1099), and 23 years (1923, 1944 and 1946): $0 \le \tau \le 23$ years.

[a] For lack of data many statements of the author seem to be insufficiently justified and hence disputable. Ed.

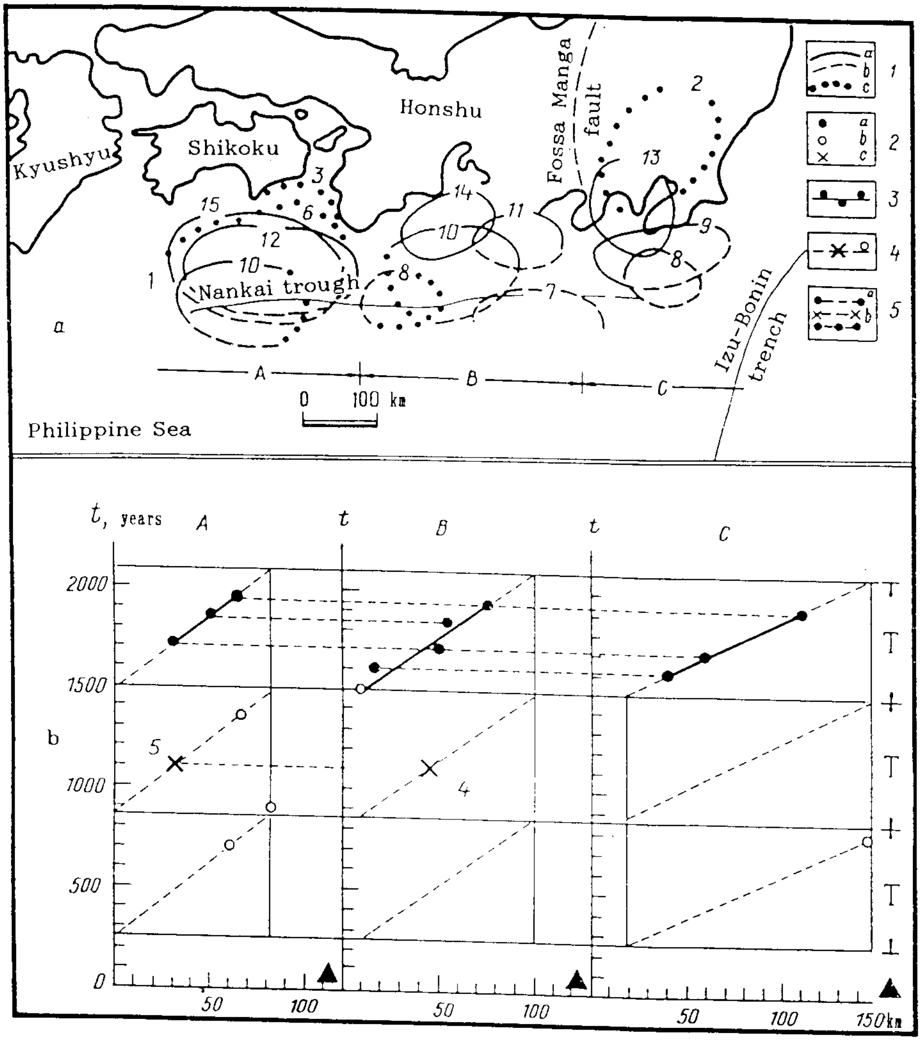

Figure 1 Distribution of M≥7.9 earthquake rupture areas for the period of 684-1946 in the Nankan trough (*a*) and a time-distance map (*b*). 1 - certain (*a*), less certain (*b*), and inferred (*c*) boundaries of rupture areas; 2 - certain (*a*), less certain (*b*), and inferred (*c*) distances from the trench axis to the rupture area boundaries nearest to the land; 3 - migration sequences calculated by least squares for each of the A, B, C zones embracing the rupture areas of the 1605-1946 earthquakes; 4 - migration sequences extrapolated into the time period of 648-1498; 5 - double (*a*) and triple (*b*) earthquakes. Figures 1 thru 15 denote the earthquakes: 1 - 11/27/684, M=8.0-8.4; 2 - 818, M=7.9; 3 - 8/26/887, M=8.6; 4 - 2/21/1099, M=8.0; 5 - 12/17/1096, M=8.4; 6 - 8/3/1361, M=8.4; 7 - 9/20/1498, M=8.6; 8 - 1/31/1605, M=7.9; 9 - 12/31/1703, M=8.2; 10 - 10/28/1707, M=8.4; 11 - 12/23/1854, M=8.4; 12 - 12/24/1854, M=8.4; 13 - 9/1/1923, M=8.2; 14 - 12/7/1944, M=8.0; 15 - 12/21/1946, M=8.0.

(3) The recurrence time of great earthquakes within each zone is roughly the same and equals T_1=128±44 years.

(4) The rupture areas within each zone migrate to the coastline, the rate of migration for all zones averaging V_1=0.17±0.04 km/yr. The typical migration time is T_0=600 years.

These patterns have enabled a prediction for the Nankai trough [3], [5], [6]: the time of expected M≥7.9 earthquakes is 2070±40 years and their macroeffect is 1.0±0.5 *MSK*-64 units greater than that produced by the last great Nankai earthquakes of 1923, 1944 and 1946.

According to the relation we previously found for the rupture length L of Japanese earthquakes as a function of magnitude M [3], the largest source dimension for a great earthquake off Japan is L_{max}=270 km for M=M_{max}=8.5. The length of all zones l_0 identified within the Nankai trough is thus identical with the source dimension for a great earthquake of maximum magnitude. Such zones are customarily termed blocks, being essentially similar to Sadovsky's blocks [17].

One also notes that $n = T_0/T_1$=5 (3 to 7) great earthquakes occur during T_0=600 years within each block in the Nankai trough area. Obviously, the time T_0 essentially controls the recurrence time of maximum shocks possible along the Nankai coast.

The patterns established for the Nankai trough may prove to be valid for other segments of the Benioff zone in this part of the Pacific. Indeed, as has been shown in [12], the Benioff zone in the Kurils can be divided into blocks with clear enough boundaries. Earthquake migration has been detected in many seismic regions of the Earth [5], [8], [9], [13], [14]. Note that the rates of the on-strike migration of great earthquakes in the northwest Pacific, derived from the same seismological material by the writer [5] and by Vilkovich and Shnirman [8], are nearly identical (250±30 and 222 km/yr, respectively). Both these values are similar to the estimate found in [14]. Different migration rates obtained by other investigators seem to be due to the fact that they were determined for groups of earthquakes comprising events of different magnitudes and occurring in different time periods.

The recurrence times of great earthquakes, 100-200 years on an average, were found for the Sanriku coast of Japan, Chile, the southern Kuril Islands [20] and other regions.

The above review shows that the locations and times of great earthquakes in some island arcs and continental margins show the same distribution pattern as that of the Nankai trough. This fact makes it possible to attempt a forecast for these island arcs and continental margins that would indicate, in addition to the seismic source zones (blocks), also the periods of time in which great earthquakes are to be expected within the blocks. Such blocks are customarily termed seismic gaps.

The aim of this paper is to examine the distribution pattern of great earthquakes off Kamchatka. Earlier [1], [3] I demonstrated that the class of large Kamchatkan earthquakes whose source areas do not

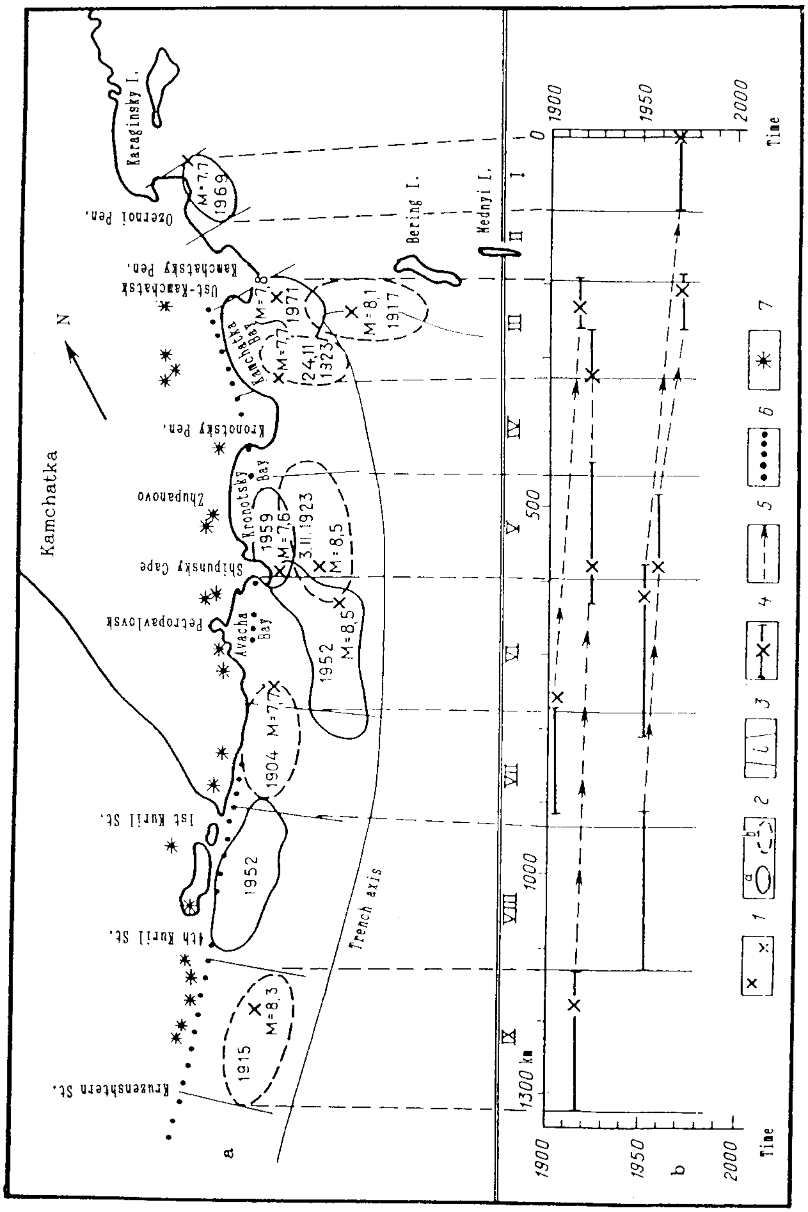

Figure 2 Distribution of the rupture areas of large northern Kuril and Kamchatkan earthquakes of the 20th century in map view (*a*) and in a time-distance plot (*b*). 1 - epicenters; 2 - certain (*a*) and less certain (*b*) boundaries of rupture areas with dates and magnitudes; 3 - block boundaries, *i* = I-IX; 4 - epicenter and rupture area in the time-distance plot; 5 - sequences of rupture areas migrating northeast (migration of type 2); 6 - western boundary of the Benioff zone; 7 - volcanoes.

overlap during a seismic cycle includes events with M≥7.6. Earthquakes of this rank have rupture areas as long as 100 km or more and are accompanied by shakings of magnitude 7-8 or larger on the Kamchatka coast. The largest magnitude of earthquakes that occurred off Kamchatka during the 20th century was M_{max}=8.5. Examples are the earthquakes of February 3, 1923, and of November 4, 1952, with fault lengths of 200-250 km [2], [7].

BLOCK STRUCTURE OF THE BENIOFF ZONE

Nine earthquakes of magnitude M≥7.6 have occurred off the North Kurils, Kamchatka and the Komandorskie Is. since the early instrumental observations of 1904. The locations of their rupture areas were determined in [2], [7], [20], [21] and are presented in Figure 2, *a*. My estimates [2], [7] of the largest 1923 and 1952 events and those offered by Fedotov [20], [21] are different.

According to my estimate [2], two great earthquakes took place in February 1923: M=8.5 on February 3 and M=7.7 on February 24, each having its own rupture area. According to Fedotov [20], [21], the later event (February 24) was an aftershock of the earlier earthquake. He offered two models for the source area of the earlier event and preferred the model in which the source area comprised the rupture areas of the February 3 and 24 events of my model and the intervening area about 100 km in length. The other version coincides with the February 3 rupture area as I determined it. One can see that the difference between my and Fedotov's determinations is significant.

We also disagreed as to the M=8.5 earthquake of November 4, 1952. According to my evidence [7] it consisted of two shocks separated by Δt = 5 s, each with its own rupture area. The source area had a length of 200-250 km for the shock in the Avacha Bay and 200 km for that off Paramushir Island, the two areas being 100-150 km apart. According to Fedotov [20], [21], the rupture area of that event extended along Kamchatka and the Kuril Islands, had a lengh of 500-600 km, and comprised both rupture areas as I determined them plus the intervening area. The source size across the Benioff zone seems to be overestimated, too.

As shown by the data presented in Figure 2, *a*, the Benioff zone off Kamchatka can be divided into nine blocks based on the positions of the large earthquakes that occurred in 1904-1971. The boundaries between them correlate with the straits between the Kuril Islands and with Kamchatkan bays and peninsulas.

The block sizes l_i are given in Table 1. They range within 100-200 km, the average being 150±40 km. Table 1 lists the magnitudes M_i of the largest earthquakes that occurred in the blocks in 1904-1971. By analogy with the data for the Nankai trough, we assume that the

Table 1 Seismic parameters of blocks in the Benioff zone of Kamchatka.

Block number	*Parameter*			
	l_i, *km*		M_i	
I	100	-	7.7	-
II	100	-	-	-
III	130	-	7.7; 7.8	-
IV	130	-	-	-
V	140	-	7.6; 8.5	-
VI	180	180	-	8.5
VII	-	160	-	7.7*
VIII	-	200	-	-
IX	-	200	-	8.3
Mean values	120±20	190±20	7.9±0.3	8.2±0.3
	$\bar{l}$ = 150±40		$\bar{M}$ = 8.0±0.4	

* Block VII had two magnitude 7.7 earthquakes on 25 and 26 June, 1904 [15]. One of them was a main shock and the other a foreshock or an aftershock.

block boundaries do not vary with time[a].

As seen in Table 1 the region consists of two zones. The northern zone includes blocks I through V with l = 120±20 km and the southern blocks VI through IX with l = 190±20 km. The zones are less different in the magnitudes of the great 20th century earthquakes.

SW TO NE MIGRATION OF EARTHQUAKES (MIGRATION OF TYPE 2)

It can be seen in Figure 2, *a* that the epicenters of great 20th century earthquakes cluster in a chain that extends along the Kamchatka coast from southwest to northeast and involves several blocks. The trend of this spatio-temporal grouping of the great earthquakes is seen better in Figure 2, *b*. Three sequences of earthquakes showing a SW-NE migration can be identified: 6/25/1904 - 1/30/1917, 5/1/1915 - 2/24/1923, and 11/4/1952 - 5/4/1959 - 12/15/1971. The sequences lasted τ=13.8 and 19 years, respectively. We see that these values do not exceed the duration of the Nankai sequences, while the direction of migration is reversed.

The Benioff zone of Kamchatka joins the Kamandorskie Is. zone around blocks II-III, which can be regarded as a continuation of the Aleutian island arc. For this reason, assuming that migration corresponds to some physical process going on in the crust and

[a] Fedotov [20] divided the Kuril-Kamchatka zone into segments on the same basis. Ed.

upper mantle within the Benioff zone, the migrating sequences must "bifurcate" into two branches in the area of blocks II and III: the Kamchatkan branch extending toward the Ozernoi Bay and the Aleutian branch toward the Komandorskie Is. The first sequence containing the 1904 and 1917 events must apparently be the Aleutian branch, since the 1917 rupture zone, as shown in [2], extends along the Aleutian trench. In that case, considering that the 1952 earthquake involved two shocks, the last sequence containing the 1952, 1959 and 1971 events can be divided into two. The Kamchatkan sequence includes the 1952_{II} - 1969 events, the other contains the 1952_{I} - 1959 - 1971 events, and after the last of these events deviates toward the Kamandorskie Is. This pattern is shown in Figure 2, *b*.

POSITIONS OF GREAT EARTHQUAKES OF THE 18-19TH CENTURIES

Consider the great Kamchatkan earthquakes of the 18 and 19th centuries which caused land shaking of intensity VII or higher and which can be classed as having magnitude M≥7.6 according to the catalog [15].

The first on the list of the Kamchatkan earthquakes whose epicentres are known with greater certainty is the earthquake of 10/17/1737, M=8.3±0.7 [15]. Its consequences are similar to those of the 1952 earthquake [18], [19]: an abnormally high tsunami that exceeded 10-20 m in both cases, a large meizoseismal area extending for about 500 km from Paramushir I. to Petropavlovsk-Kamchatskiy. These data suggest that, like the 11/4/1952 event, the 10/17/1737 earthquake involved two shocks with epicentres within blocks VII and IX (Figure 3, *b*).

According to [15], a M=7.5±0.1 event took place within block VIII on 11/18/1742. A similar occurrence was observed after the 1952 earthquake: the February 28, 1973, M=7.5 earthquake was located within its rupture area contained in block VIII [3], [15], [16]. For this reason the 1742 event may be regarded as an aftershock of the October 17, 1737 earthquake whose rupture area was in block VII.

The December 17, 1737 earthquake which, according to [15], ruptured block VIII is apparently a mistake, this opinion being also held by Soloviev [18]. If it did occur and had a magnitude of 7.5±1.0 [15], it must be treated as an aftershock of the December 17, 1737 event.

The two great southern Kamchatka earthquakes which occurred on October 17, 1737 and November 4, 1952 are different, the differences being as follows. First, the 1737 event produced an intensity of IX (VII to IX) at the site of the future city of Petropavlovsk-Kamchatskiy, the value for the 1952 event being VII. Secondly, the tsunami observed in the southern Kurils after the 1737 earthquake was larger than that due to the 1952 event. It can therefore be concluded that the October 17, 1737 shocks were somewhat differently located within the blocks indicated than was the case for the 1952

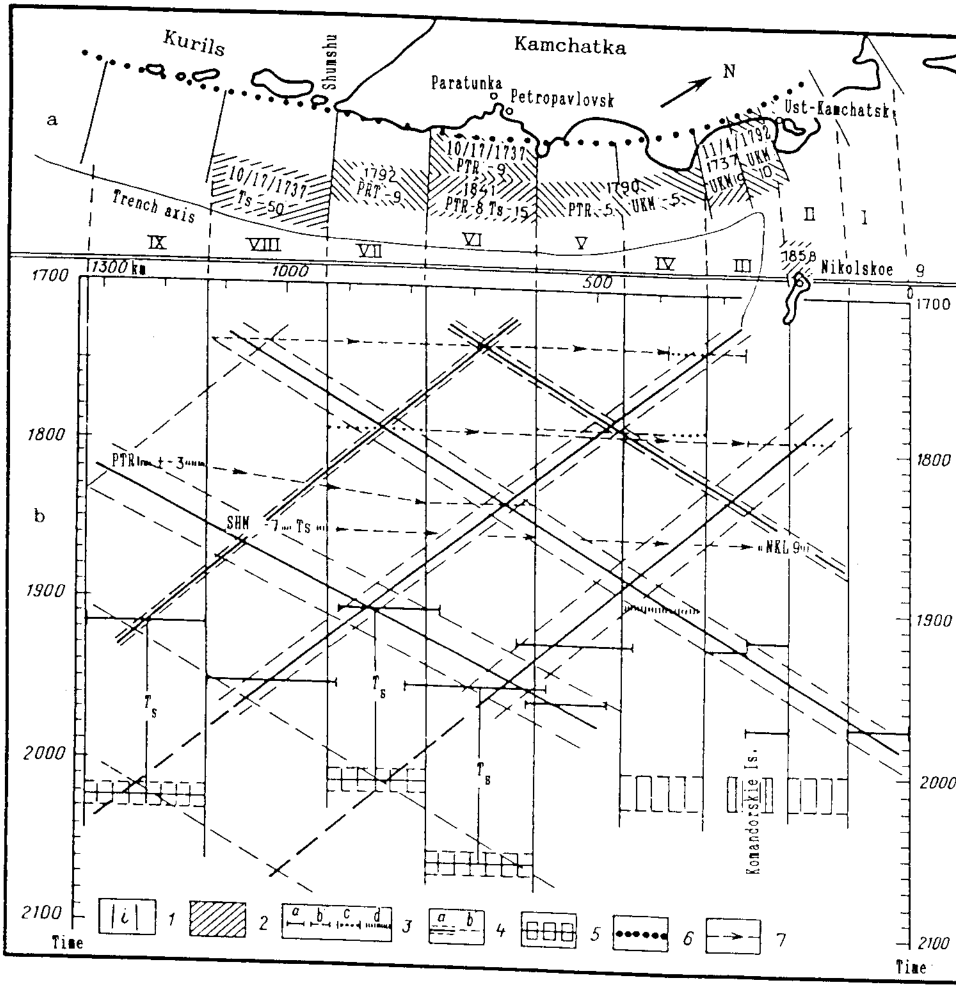

Figure 3 Distribution of the rupture areas of large northern Kuril and Kamchatkan earthquakes in the 18-19th centuries in map view (*a*) and those of the 18-20th centuries in a time-distance plot (*b*). 1 - boundaries of Benioff zone blocks; 2 - inferred rupture areas of the 18-19th century earthquakes (figures denote the year of earthquake occurrence, MSK-64 intensities in: Petropavlovsk-Kamchatskiy (PTR), Paratunka (PRT), Ust-Kamchatsk (UKM), Nikolskoe (NKL) and Shumshu (SHM), tsunami height, and t = 3, the duration of shaking, min; 3 - location of rupture areas in the time-distance plot: *a* - proved, *b* - certain, *c* - less certain, *d* - inferred; 4 - sequences of the rupture areas for the 18-20th century earthquakes migrating along the Benioff zone at a rate of 4±1 km/yr (*a*) and extrapolated into the future (*b*) (migration of type 1); 5 - time-distance regions expected to contain future earthquake rupture areas; 6 - western boundary of the Benioff zone; 7 - sequences of the rupture areas of the 18-19th century earthquakes migrating northeast; T_s - repeat time of great earthquakes in southern Kamchatka.

rupture (see Figure 3, *a*). The 1737 event seems to have occurred farther from the coastline within block VII, hence it ruptured the seafloor at greater depth, thus producing a larger tsunami in the southern Kurils, while the 1737 rupture within block VI must been closer to the coastline, giving greater macroseismic intensity on the coast.

The November 4, 1737, M=7.8±0.7 earthquake shook Nizhne-Kamchatsk with intensity up to IX [15]. The 1756 event which was felt with intensity VIII at Nizhne-Kamchatsk[a] was apparently its aftershock.

The December 2, 1790, M=7.5±0.7 earthquake occurred in the northeastern Kronotskiy Bay at the boundary of blocks IV and V [15]. It had intensity V at Petropavlovsk and Nizhne-Kamchatsk and was accompanied by foreshocks and aftershocks lasting until February 1791 [15]. The natural inference is that the rupture area of 1790 involved adjacent blocks located in the Kronotskiy Bay (block V) and off the Kronotskiy Peninsula (block IV).

The earthquake of August 22, 1792 was one of the largest events in Kamchatka as to the size of the meizoseismal area: it produced violent shaking along all of the eastern Kamchatka coast from Petropavlovsk to Nizhne-Kamchatsk. The Nankai earthquake of 1707 seems to be an analogue. According to [15], it had magnitude M=8.4±0.7 and devastated Nizhne-Kamchatsk (intensity X-XI). Considering the poor soil conditions at the site of the former village of Nizhne-Kamchatsk, the intensity should be estimated as being closer to IX-X.

It seems likely that the 1737 and 1792 rupture areas, like those of the 1923 and 1971 earthquakes, were largely located within the Kamchatka Bay (block III) but somewhat closer to the shoreline, hence the observed effects [4]. The rupture areas of the 1737 and 1792 events may have been oriented along the Benioff zone rather than across it and involved adjacent blocks.

The 1792 earthquake produced shaking of intensity VIII at Petropavlovsk and VIII-IX at Paratunka. The two sites are more than 400 km away from Nizhne-Kamchatsk. The 1792 event seems to have involved two nearly simultaneous shocks, similarly to the 1605 and 1707 Nankai events and to the Kamchatkan earthquake of 1952. The rupture area of the shock responsible for intensity VIII shaking at Petropavlovsk and Paratunka must be assigned to block VII when the positions of the October 17, 1737 and December 2, 1790 earthquakes are taken into account. The great earthquake of 1904 which ruptured that block was also accompanied by shaking of up to VIII intensity at Petropavlovsk [15].

The 1737, 1790 and 1792 events might have been three migrating sequences with the epicentres moving from SW to NE. The first

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[a] Preliminary Report on Seismic Zoning at the Construction Site of the Kronotskiy Power Station, Kamchatka. Petropavlovsk-Kamchatskiy, 1968. File No.008, KGS IFZ AN SSSR.

Table 2 Parameters of migration sequences of type 1.

Sequence number	Earthquake dates in a sequence	Parameters of sequences				
		τ, yr	V^{-1}, yr/km	t_0, yr	Δt_0, yr	V, km/yr
1	$1915—1792_I—1737_{II}$	2	0,322 ± 0,006	−219 ± 6	124	3,11
2	1952_I—1904—1841—1790—11/4/1737	9	0,30 ± 0,02	−95 ± 11	109	3,33
3	1952_{II}— 2/3/1923-1899 —1792_{II}	26	0,31 ± 0,07	14 ± 34		
1—3	Mean	12 ± 10	0,31 ± 0,03	± 17	117 ± 8	3,2 ± 0,1
4	$10/17/1737_{II}$ —1790	—	−0,25	167	81	−4,00
5	$10/17/1737_I$ —1792_{II}—1841—1899—2/24/1923 —1969	11	−0,23 ± 0,01	248 ± 9	82	−4,34
6	1904—1952_{II}—1959	18	−0,19 ± 0,09	330 ± 62		−5,26
4—6	Mean	15 ± 4	−0,22 ± 0,05	± 36	81 ± 1	−4,5 ± 0,5
1—6	Mean absolute value of V	13 ± 8	0,27 ± 0,05	± 24	99 ± 18	3,9 ± 0,8

sequence included the 1737 events and possibly continued toward the Komandorskie Is. where a large earthquake accompanied by aftershocks took place on February 18, 1742. The second sequence included the 1790 event which seems to have ruptured two blocks (IV and V). The third consisted of the two 1792 earthquakes.

The May 17, 1841, M=8.4±0.7 earthquake with a source beneath the Avacha Bay produced intensity VIII shaking at Petropavlovsk [15], [19]. Comparing the effect that was felt at the same site from the October 17, 1737 (intensity IX), 1841 (intensity VIII), and 1952 (intensity VII) events, we can say that the 1841 rupture was located in the central part of block VI.

The question of which migration sequence of the second kind contained the great 1841 earthquake will be discussed below.

According to [15], only one event can be classified as a great earthquake that occurred between the 1841 and 1904 shocks. It was an event of November 23, 1899 with magnitude M=7.9±1.0 and epicentre near the western boundary of the seismic zone, 20–30 km from Petropavlovsk. The location uncertainty for this event is 2–3°. The relevant data are quoted in [15] as doubtful, based on the 1954 Gutenberg-Richter catalog [23], in which the earthquake magnitudes before 1910 are overestimated by about 0.5 magnitude unit [22]. For this reason, even if a great earthquake did occur in 1899 off Kamchatka with a magnitude of about 7.6, the smallest value for events of this class, its most likely location was block IV, considering a possible epicentre error and a lack of macroseismic data [15]. The reasoning is as follows. The distances of blocks I, II, III and VIII, IX from the instrumental epicentre exceed 2-3°. An event of this size could not occur in block VII, because a great earthquake took place in it somewhat later, in 1904. An event of magnitude 7.6 would certainly have been reported in 1899, if it had occurred in blocks V and VII.

REVERSED MIGRATION (MIGRATION OF TYPE 1)

It is seen in Figure 3, *b* that the rupture areas of great 18-20th century earthquakes could be arranged in oppositely directed sequences with approximately equal rates of migration. The rates in these sequences are different from those described above.

Table 2 lists the parameters of migrating sequences written in the form $t_i\ (\pm\tau) = V^{-1}X_i + \Delta t_{0,i}$, where t_i and X_i are the times and coordinates of great earthquakes; V_i is a parameter having the meaning of the velocity at which great earthquakes migrate along the i-th sequence; $\Delta t_{0,i} = t_{0,i} - t_{0,i+1}$ is the interval between the ith and (i+1)th sequences. The parameters were found by least squares using the centers of gravity of the 1904-1971 rupture areas and the centers of gravity of the blocks which are hypothesized to contain the great earthquakes of 1737-1899. One can see from Figure 3, *b* that the spatio-temporal plot of great Kamchatka earthquakes may from a "cell" structure with the epicentres at the nodes. This pattern is not followed by two events in block V: February 3, 1923, M=8.5 and May 4, 1959, M=7.6.

Extrapolation of the migration lines shows that the intersections of sequences 3-4 and 1-6 do not contain great events that ought to have occurred in blocks II-III in 1840±α and in block VIII in 1865±α, respectively, where the range of possible α values must not exceed the maximum τ value, which is τ_{max} = 26 years, according to Table 2. Below each case is discussed separately.

Block VIII, 1840-1890. An earthquake of magnitude 8.0±0.4 in block VII which is off Paramushir I. and Shumshu I. at a distance of 300-400 km from Petropavlovsk must have produced shaking of intensity at least VII on the islands and V±I in the city. Several events causing shaking of intensity V or greater were felt at these locations in the mid-19th century after 1841. An analysis of these also shows an activation of block VIII off Paramushir I. and Shumshu I. against the background of the decaying aftershock activity following the great 1841 earthquake in block VI. The activation may have been associated with the earthquake of July 29, 1854 in the block. According to [15], it had magnitude 7.0±1.0, which ranks it as a large one. The relevant rupture area is shown schematically in Figure 3, *b*.

Blocks II-III, 1814-1866. A great earthquake within these blocks must have been felt in Nizhne-Kamchatsk, in case it occurred in a migration sequence of type 2, or on the Komandorskie Is., provided it belonged to an Aleutian migration sequence of the same type. The basic sources [15], [18] seem to indicate a magnitude 7.8±0.7 event in the Komandorskie Is. area on January 22, 1858. The October 28, 1849 earthquake of similar magnitude and the subsequent shocks can apparently be treated as a foreshock and aftershocks. The January 22, 1858 epicenter is shown schematically in Figure 3, *b*. The event must have occurred around the intersection of sequences 3 and 4.

The earthquakes of July 29, 1854, and January 22, 1858, consistent with migration sequences of type 1, with rupture areas within block VIII and near the Komandorskie Is., respectively, might form an Aleutian branch of a type 2 migration sequence.

MIGRATION ACROSS THE BENIOFF ZONE

Assume that the western boundary of the October 17, 1737 rupture area in the Avacha Bay block was identical with the western boundary of the Benioff zone in Kamchatka as determined in [10]. In that case the positions of the great 10/17/1737, 1841 and 1952 earthquakes suggest a seaward migration across the Benioff zone at the rate $\sim V_{\perp}$ = 60÷85 km/(1952–1737)years ≈ 0.3÷0.4 km/yr. A similar migration rate and direction under the same hypothesis as to the western boundaries of the November 4, 1737 and 1792 rupture areas can be derived from an analysis of the positions of these epicentres and the earthquakes of February 24, 1923 and 1971: $\sim V_{\perp}$ = 50÷60 km/179 ÷186 years ≈ 0.3÷0.4 km/yr.

The migration of great earthquakes across the Benioff zone based on the 1737–1971 data for blocks V and VIII has a reversed sense relative to the coastline under the same conditions. The inferred rate of migration is $V_{\perp}$ = 40 km/(1959–1923)years = 1 km/yr for the February 3, 1923 and 1959 earthquakes and $V_{\perp}$ = 0.3÷0.4 km/yr for the October 17, 1737 and 1952 events.

There is no evidence for the other blocks that could be used to estimate the rate and magnitude of transverse migration.

The possible values of the rate of transverse migration thus lie within 0.3–0.4 km/yr. The value 1 km/yr in block V is based on data for a short time period, 1923–1959. This is apparently an "instantaneous" quantity and may be regarded as the extreme value. Vilkovich and Shnirman [8] obtained a similar value for the rate of the transverse migration of Kamchatkan earthquakes with M>7.0, 1.5 km/yr.

The above considerations suggest that the rupture areas of great Kamchatkan earthquakes can migrate across the Benioff zone, like those of the Nankai earthquakes. In contrast to the Nankai trough however, where migration has the same direction in all blocks, migration in Kamchatka can occur in either of the two possible directions in different blocks. This "bidirectional transverse" migration may be indicative of obduction: the overthrusting of the continental plate on to the oceanic plate may take place in the Kamchatkan Benioff zone simultaneously with subduction. L. N. Rykunov was the first who suggested the possibility of this motion.

Table 3 Repeat times of great earthquakes in blocks.

Block number	*Date of event*	*Repeat time, years*	*Amount of data*	*Mean repeat time, years*	*Uncertainty, years*
III	11/4/1737-1792-2/24/1923-1971	55, 131, 48	3	78	38
IV	1790-1899(?)	109(?)	1	109(?)	-
V	1790-2/3/1923-1959	133, 36	2	85	49
VI	10/17/1737-1841-1952	104, 111	2	108	4
VII	1792-1904	112	1	112	-
VIII	10/17/1737-1854-1952	117, 98	2	108	10
II-VIII	Mean for Kamchatka	-	11	96	32
III-V	Mean for northern Kamchatka:		6	85	40
	including subgroup 1 ($T_{n,1}$)	131, 109, 133	3	124	11
	subgroup 2 ($T_{n,2}$)	36, 55, 48	3	46	8
VI-VIII	Mean for southern Kamchatka (T_s)	117, 98, 112, 104, 111	5	108	7

RECURRENCE OF GREAT EARTHQUAKES WITHIN A BLOCK

Table 3 lists repeat times of great earthquakes for each block. Blocks III–VIII show similar times, T_0=96±32 years. The value for the Nankai earthquakes is not much different, 128±44 years [3]. The available data suggest the same repeat time for block IX. Petropavlovsk-Kamchatskiy is the nearest site where macroseismic evidence is sufficiently complete. It would be useful therefore to analyze macroseismic data for this site around the year 1819, to determine the repeat time of great earthquakes in block IX.

Block IX is 450–650 km away from Petropavlovsk. Magnitude 8 earthquakes that occurred in that block must be felt in the city as III or IV–V at most.

About 20 shocks had been recorded in Petropavlovsk in the early 19th century before 1841. Two sets of events can be clearly identified. One includes earthquakes that preceded and accompanied the 1827 eruption of Avacha Volcano 30 km from Petropavlovsk. The other contains earthquakes which seem to be foreshocks of the great Avacha Bay earthquake of 1841.

The distinctive features of a great earthquake are a long duration of felt vibrations (1 min or longer) and a tsunami. These phenomena were observed twice in Petropavlovsk during the earlier half of the 19th century. The first occasion was on October 28, 1820: several rather strong shocks lasted as long as 3 min in Petropavlovsk. The second was on August 9, 1827. According to [11], a violent eruption of Avacha Volcano began on that date, the area of the future city of Petropavlovsk-Kamchatskiy experienced shocks of intensity up to VII and a drastic falling tide was observed in the Avacha Bay [18].

The period of time between 10/28/1820 and 5/1/1915, when a magnitude 8.3 earthquake occurred in block IX, was 95 years. That value is nearly identical with the mean repeat time of great Kamchatka earthquakes within a block (see Table 3). The inferred rupture area of a great earthquake that might occur in block IX on 10/28/1820 is shown schematically in Figure 3, *b*. Its location is not inconsistent with the requirements that can be imposed on migration sequences of types 1 and 2 (see Figure 3, *b*). In fact, the 1820-1841 sequence can be classified as a migration sequence of type 2. The duration of a migration sequence of this kind should then be increased to reach 21 years. That the location of the 1820 rupture may satisfy a migration of type 1 is indicated by the fact that the migration sequences composed of the events of 1820 - $10/17/1737_{I}$ and of 1820-1854-1904-1952_{II}-1959 have slopes that are roughly equal in absolute value and opposite in sense (V^{-1}=0.32 and -0.19 km/yr, respectively).

A more careful analysis of the data in Table 3 allows one to arrange all blocks into several groups according to the scatter of repeat times for great earthquakes. One group includes blocks VI-VIII where the repeat times range within 98-117 years (the scatter does not exceed 10 percent) and average 108±7 years. The evidence presented above places block IX into this group, its repeat time being probably close to 95 years. This value does not change the repeat time, and the overall value for the group, which includes the southern Kamchatka blocks VI-IX, is T_s=106±8 years.

The second group shows a larger scatter of repeat times (about 50 percent). It includes northern Kamchatka blocks III-V: T_n=85±40 years. The repeat times in these blocks may in turn be divided into two subgroups with similar values: $T_{n,1}$=124±11 and $T_{n,2}$=46±8 years (see Table 3).

The problem of the repeat time in blocks I and II is yet to be solved. However, as seismicity in Kamchatka decays northward toward Karaginskiy Island, great earthquakes are likely to be extremely rare events in these blocks. In that case, assuming that all great earthquakes in blocks I and II have been reported since 1737 and that the 1792 rupture involved two blocks (II and III), a likely repeat time value is 1969 - 1792 = 177 years.

CONCLUSION

The time-distance map of the rupture areas (blocks) of great Kamchatkan and northern Kuril earthquakes in the 18-20th centuries presented in this paper may provoke a lot of questions some of which can hardly be answered today. The aim of this analysis was to attempt to devise a large earthquake prediction based on three assumptions. First, seismic activity is a quasiperiodic process. Secondly, this process is accomplished by means of the longitudinal and transverse migration of large earthquakes. Thirdly, the region in which it operates consists of blocks whose boundaries remain unchanged in time. I believe that the evidence from the Nankai trough, the fact that the northwestern Pacific island arcs are similar in seismic parameters, and an attempt to describe the seismic process in the Pacific margin in terms of a unified, physically meaningful model [5] justified this study.

The results provide a basis to start work on a scheme of earthquake prediction for Kamchatka and the northern Kurils, which will help forecast the time of largest earthquakes in individual blocks and assess the expected seismic hazards.

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