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Possible Timing of Large Earthquakes by 18.6-year Lunar Cycles, Their Multiples, and Fractions

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Time series of great earthquakes were correlated with 18.6-year lunar precession periods, as well as with their fractions and multiples. Earthquake catalogs were examined for several Pacific subduction zones. After combining earthquakes into clusters the catalog data were represented as the distribution of data points on a circle for each of the studied cycle duration value. Kuiper's test was used to detect departures from uniformity for these distributions. We confirmed previously known and identified new periodicities with $T=T_0/3$, $T_0/2$, T_0, $3T_0/2$, and $3T_0$, where $T_0=18.6$ years. The best-expressed periods are $3T_0/2\approx28$ years (Alaska, Mexico, and Valparaiso, Chile) and $3T_0\approx56$ years (Kamchatka and the Kurils). We extrapolated the activity of great earthquakes to the near future for some regions.

INTRODUCTION

A relation between earthquake occurrence and lunar cycles was suggested as far back as the middle of the past century [23]. Control of the occurrence of large earthquakes by 18.6-year lunar cycles was identified for the Baikal region [3], Kamchatka and the Kurils [11], [16], and South America [10]. Kilston and Knopoff [17] detected this phenomenon for southern California with a low cutoff magnitude. Besides the cycle $T=T_0=18.613$ years, a pronounced synchronization was detected by Shirokov [13] at the period $T_0/3=6.204$ years and used to give a long-term forecast of earthquakes with magnitudes greater than or equal to 7.0 and 7.8. Shirokov [13] also examined the cycles with $T=T_0/2$

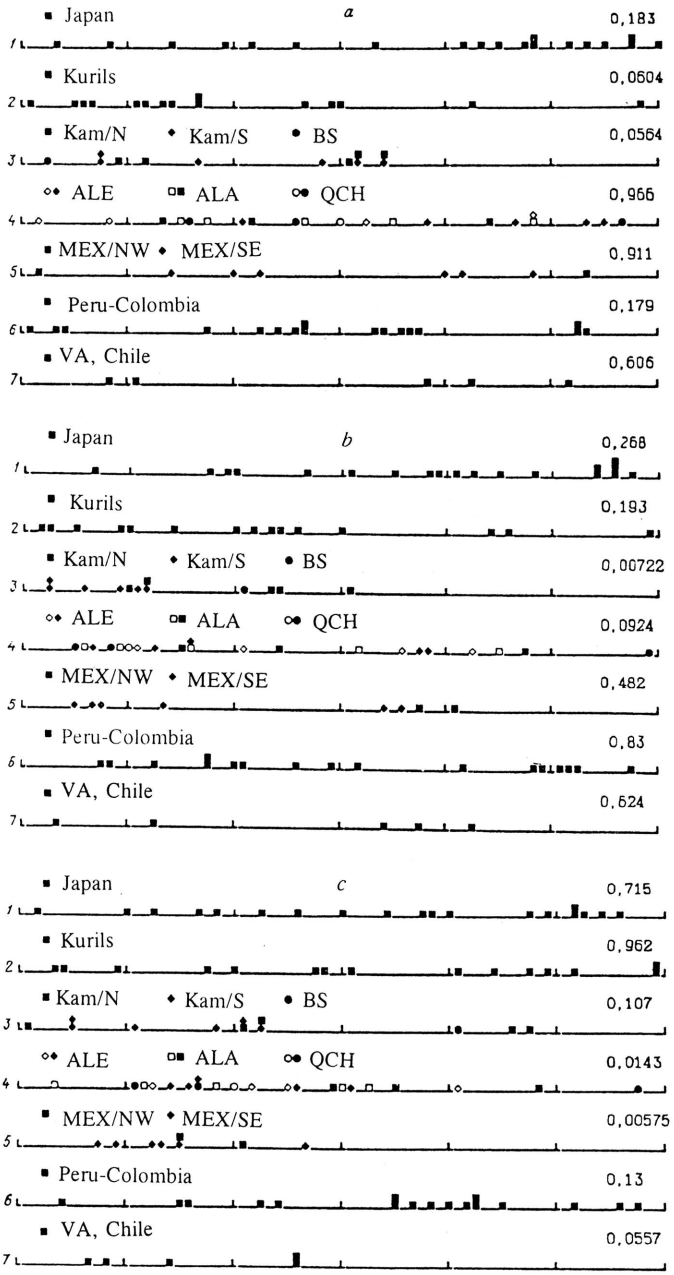
a
■ Japan 0,183
1
■ Kurils 0,0604
2
■ Kam/N ◆ Kam/S ● BS 0,0564
3
◇◆ ALE □■ ALA ○● QCH 0,966
4
■ MEX/NW ◆ MEX/SE 0,911
5
■ Peru-Colombia 0,179
6
■ VA, Chile 0,606
7
b
■ Japan 0,268
1
■ Kurils 0,193
2
■ Kam/N ◆ Kam/S ● BS 0,00722
3
◇◆ ALE □■ ALA ○● QCH 0,0924
4
■ MEX/NW ◆ MEX/SE 0,482
5
■ Peru-Colombia 0,83
6
■ VA, Chile 0,624
7
c
■ Japan 0,715
1
■ Kurils 0,962
2
■ Kam/N ◆ Kam/S ● BS 0,107
3
◇◆ ALE □■ ALA ○● QCH 0,0143
4
■ MEX/NW ◆ MEX/SE 0,00575
5
■ Peru-Colombia 0,13
6
■ VA, Chile 0,0557
7

Figure 1, *a–c*

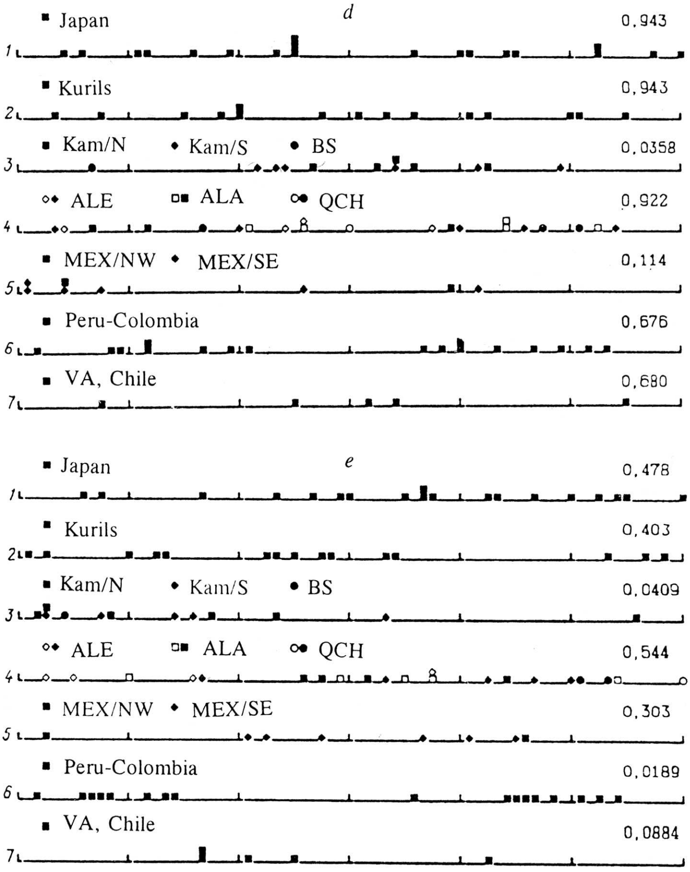

Figure 1 Summarized regional displays of clusters for the following periods (in years): *a* - T_0 = 18.613; *b* - $3T_0$; *c* - $3T_0/2$; *d* - $T_0/3$; *e* - $T_0/2$. Numerals on the right are the associated *P*-values; M=8=8+ and 7.8+ (*1* and *6*, respectively); M_{nc}=7.6+ (*2* and *3*); M_s=7.7+ (*4* and *7*); M_w=7.6+ (5). For explanations see the text.

and $T_0/3$, but did not find significant periodicities for the cutoff magnitude M=7.0. A cycle of 85 years, close to $9T_0/2=83.8$ years, was noted for great earthquakes in the Valparaiso area, Chile [18]. A period of 30 years, close to $3T_0/2=27.92$ years, was observed for Mexico [24].

The value $T_0=18.613$ years is the time of revolution for the nodes of the lunar orbit, that is, the period of revolution for the plane in which the Moon and Earth are revolving about their common center of mass (barycenter) with respect to the axis passing through the barycenter perpendicularly to the ecliptic; the plane is inclined at an angle of about 5° to the ecliptic. Because of this, the amplitude of monthly changes in the Moon's declination periodically oscillates between the extreme values 18 and 28°, producing changes in the relative and absolute amplitudes of various earth tide components [5], the semi-diurnal and the diurnal component in the first place. The relation between the 18.6-year lunar cycle and seismicity has been variously explained by invoking the hypothesis of a "trigger" effect of earth tides on earthquake occurrence or the effect of the tides in the long-continued preparation of a large earthquake. Both hypotheses are rather speculative, there being essentially no convincing explanation as yet.

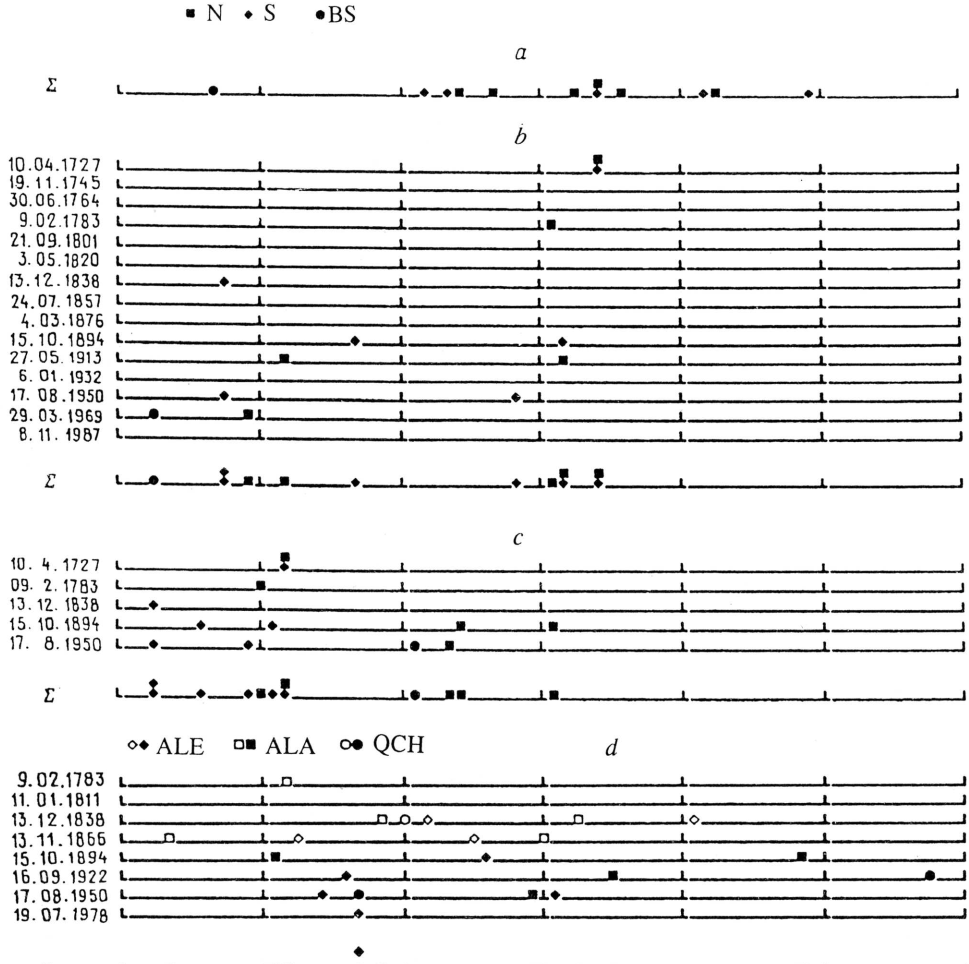

Figure 2 Detailed and summarized time displays of clusters of large earthquakes for periods $T_0/3$, T_0, and $3T_0$ for Kamchatka (*a*, *b*, and *c*, respectively) and for period $3T_0/2$ for Alaska (*d*). M_{nc}=7.6+ (*a*–*c*); M_S=7.7+. *P*-values: *a* - 0.0358, *b* - 0.0564, *c* - 0.00682, *d* - 0.0143.

In this study we continued to work on identifying empirical cyclicities like those referred to above using data for several regions of the circum-Pacific ring. We focused on a parallel analysis of a number of periods for several selected regions applying the same significance analysis procedure to earthquake catalogs for long observation periods.

METHOD AND PRINCIPLES OF DATA SELECTION

Our method consists in mapping a catalog onto a circle and in examining the nonuniformity in the distribution of data points (events) on it. Whenever there is a pronounced, statistically significant nonuniformity, we conclude that there is a cyclicity. For any concrete cycle under study having a period T, the position of a mapped point on the circle is defined by a phase of the cycle $\Phi (0 \leq \Phi < 1)$ at the date of the respective earthquake. This last was calculated from

$$\Phi = (t - t_0)/T_{mn} - \text{Entier}\,((t - t_0)/T_{mn}),$$

where t is the Julian date of the earthquake; t_0 the Julian date of a certain definite passage of the ascending node of the Moon's orbit through the point of the vernal equinox; Entier means "the integer part of". The date April 10, 1727, was used as t_0, obtained by application of the Brown formula [11]. The periods under consideration were $T = T_{mn}T_0$, where $T_0 = 18.613$ Julian years [5]; m and n are the largest natural numbers. The value of Φ varies by one during T_{mn}. The occurrence time of an earthquake is thus mapped as a point on a circle, that is, on the half-open interval $[0,1)$ with ends coinciding.

Having represented earthquakes by these points, we made a statistical analysis by testing what would be the probability of obtaining the actual distribution of points on the circle under the null hypothesis, i.e., under the uniform distribution law. The law must hold, if the period of time analyzed is equal to a multiple of the cycle, and if the earthquake occurrence is a Poissonian distribution. As a matter of fact, both of these assumptions were not strictly true. In particular, the time period of study was chosen independently of the assigned cycle length and of the time the cycles began to be counted. A possible distortions of the results due to this cause were evaluated and turned out to be small.

A much more dangerous source of distortion consists in departures of the earthquake occurrence from the Poisson law. The best-pronounced type of departure observed in earthquake catalogs consists in the clustering of events (aftershocks, swarms, groups, etc.). This tendency can easily simulate the effects of a desired periodicity by producing a nonuniform distribution of points on the circle. Consequently, we performed two kinds of data processing: for the original catalog and for a catalog of clusters. Clusters were formed by keeping to the following informal rule: events with interevent time not exceeding one year and interevent distance of the order of the rupture length (based on

Table 1 *P*-values resulting from application of the Kuiper test under the null hypothesis of a uniform distribution.

Catalog	*Restraints*	*Number of events*	*P*				
			18,6	6	9	28	56
Kamchatka, 1937–1991; $M_{nc}=7.6+$	–	14	0,020	0,0081	0,0068	0,078	0,0047
	c	12	0,056	0,036	0,041	0,25	0,0068
	B69	11	0,014	0,0099	0,090	0,11	0,0072
Kurils, 1737–1991 $M_{nc}=7.6+$	–	18	0,031	0,76	0,36	0,52	0,061
	c	15	0,060	0,94	0,40	0,96	0,19
Japan, 684–1968; $M=8+$	–	20	0,10	0,98	0,35	0,61	0,41
	c	19	0,18	0,94	0,48	0,72	0,27
Alaska, 1786–1991; $M_S=7.7+$	–	24	0,61	0,71	0,22	0,0030	0,0081
	c	21	0,97	0,92	0,54	0,014	0,092
Alaska, 1898–1991; $M_S=7.7+$	–	14	0,23	0,39	0,028	0,033	0,026
	c	11	0,88	0,66	0,12	0,20	0,36
Mexico, 1808–1985; $M_w=7.7+$	–	9	0,80	0,033	0,64	0,0025	0,24
	c	8	0,91	0,11	0,30	0,0058	0,48
Peru, 1586–1974; $M=7.8+$	–	17	0,18	0,68	0,019	0,13	0,83
Valparaiso, Chile, 1647–1985; $M_S=7.7+$	–	5	0,61	0,68	0,088	0,056	0,62

Note. Restraints: "–" all events are entered individually; "c" a cluster of events is treated as a single event; "B69" the 1969 earthquake is not included in the analysis.

their magnitudes) are taken to make up a cluster; the occurrence time for this cluster is assumed to be the time of its largest component. In most of the cases this informal rule yields an unambiguous result. Below we simply list all clusters we chose in order to anticipate questions that may arise.

It is convenient to use the Kolmogorov statistic in order to test whether data points are distributed uniformly over given interval. In the case under discussion, however, the points actually lie on a circle rather than in an interval, because 0 and 1 constitute a single point. Kuiper [4] modified the Kolmogorov test to adapt it to this situation. The method we used to calculate the probability (significance level P) can be in error for the Kuiper distribution by the following amounts: $\leq 1\%$ with sample size 10 or larger, and $\leq 2.5\%$ with sample size 5-10. This accuracy was thought to be acceptable.

The Kuiper test has inadequate power when the departure from uniformity is of the type of periodicity, so it was occasionally supplemented with a binomial test. The latter uses an explicit division of the interval into "denser" and "sparser" segments with subsequent counting of events in the two segments and calculating the probability of this outcome on the assumption of a uniform distribution. For the probability to be correct it is necessary to allow for the choice of the division [12, V.1, Ch.2, Problem 13]. One advantage of the Kuiper test is that the user need not choose a division.

Data selection involves two steps, the selection of a region and a depth range and the selection of a cutoff magnitude. We chose the following regions: Kamchatka, the Kurils, Alaska and the Aleutians, Japan, Mexico, and Valparaiso, Chile (periods close to $T_0/3$, $2T_0$, $3T_0$, and $9T_0/2$ were reported), as well as Peru and Colombia. We studied great shallow earthquakes with cutoff magnitudes of 7.6-7.9. Subregions were chosen within regions and specially marked in the plots to show the timing of departures from the uniform distribution in different subregions of a region.

We tried to use published earthquake catalogs whenever possible. Analysis was carried out for the following cycles: $T_0 = 18.613$ years, $3T_0 = 55.84$ years, $3T_0/2 = 27.92$ years, $T_0/2 = 9.306$ years, and $T_0/3 = 6.204$ years. We also tested some other values, for instance, $2T_0$, $T_0/4$, and $T_0/5$, but these did not produce results of interest. The results were displayed as the positions of representative cycle points (Fig. 1); detailed time displays are presented in Fig. 2 as examples.

ANALYSIS FOR INDIVIDUAL REGIONS

Kamchatka. Data for large Kamchatkan earthquakes were derived from *Novyi Katalog...* [6]. We selected events with depths $H = 0–80$ km and $M_{nc} \geq 7.6$ (M_{nc} is the New Catalog magnitude) for the area north of 50°N from the Kurils catalog, and all events from the Kamchatka catalog, 1737 to 1974. No events with $M \geq 7.6$ occurred there in 1974-1993. All events were divided into three subregions: "S" south of Cape Shipunskiy (53°N), "N" (northern) between Cape Shipunskiy and Cape Kamchatskiy (56.5°N), "B" Bering Sea north of Cape Kamchatskiy. The last group of events included one earthquake of November 22, 1969. The next step was to identify clusters. Below we list the catalog with the following notation: clusters are enclosed in brackets; "m" means the main shock in a cluster; "N", "S", and "B" are the subregions; month and day are indicated (after a slash) only in cases where ambiguity may arise:

1737/10-S; 1737/11-N; 1792-N; 1841-S; 1899-S; (1904/06/25-S-m, 1904/06/25-S); 1947-N; (1923/02/03-N-m; 1923/02/24-N); 1952-S; 1959-N; 1969-B; 1971/12-N.

The total of 14 events made up 12 clusters (a single event was treated as a cluster). The 1792 event was included in region "N" on a formal basis: its rupture must have involved part of subregion "S".

Figure 2 shows the distribution of clusters: along the time axis for the cycles T_0 and $3T_0$ and in summary form for T_0, $3T_0$, and $T_0/3$. These plots are supposed to be examined together with Table 1 where the P-values for the Kuiper test are given as resulting from two versions of the catalog: 1 - complete catalog, 2 - clusters alone (the main version). For Kamchatka we quote Variant 3 involving clusters only, without the 1969 earthquake. The plots in Fig. 2 for T_0 and $T_0/3$ display Shirokov's result [16]: the first, second and sixth year of the 6-year cycle ($T_0/3$) and the third six-year interval of the 18.6-year cycle are devoid of large earthquakes in subregions "N" and "S". The P-values for T_0 and $T_0/3$ are close to 5%. The result for the 56-year cycle ($P<1\%$) is a new result obtained because there were no events in the entire later half of the cycle. The $T_0/2$ cycle too proved to be significant ($P<5\%$). The 1969 Bering Sea earthquake situated outside the island arc Benioff zone departed from the pattern for the six-year cycle; when it was eliminated, the result was $P<1\%$.

We also tested the significance so far obtained for the 56-year cycle by applying the binomial test to the data. As a matter of fact, four hazardous $T_0/6$ intervals were identified in the $3T_0$ cycle. The total relative length of the hazardous intervals was $4(T_0/6)/3T_0 = 0.222$. They contained 11 clusters of the total of 12. The probability of this distribution was found from the binomial law

$$P = C_m^n p^n (1-p)^{m-n}$$

to be 6.1×10^{-7} with $p=0.222$, $m=12$, $n=11$. The arbitrary choice of these four intervals from a total of eighteen under the null hypothesis demanded a correction factor, $C^4_{18}=3060$, making the significance level equal to 0.0019 (see the discussion of this approach in [12]). As was expected, the binomial test had a greater power in this case, confirming the high significance of the departures from the uniform distribution given by the Kuiper statistic. When the 1969 event which had occurred outside the Benioff zone was disregarded, the P-value became as low as 6.7×10^{-8}, the significance level being 0.00021.

We carried out an informal test of this pattern using additional data. Below we list important seismic events in Kamchatka that did not satisfy the original selection criterion ($M_{nc} \geq 7.6$) and are quoted from [1], [2], [6]; the events that fit within the 4/18 interval of the 56-year cycle were marked with (+), and the others with (-):

(+) 1756-N, I=VIII at the Nizhne-Kamchatsk fortress;

(+) 1971/04/5-N, tsunami (5m?) in the mouth of the Kamchatka River;

(-) 1827/08/09-S, tsunami (2-5m?) in the Avacha Bay and I=VII-VIII at Petropavlovsk-Kamchatskiy (not mentioned in NC);

(+) 1848/06-S, tsunami (5-10 m?) in the Avacha Bay (not mentioned in NC);

(+) 1866/09/06-S, $I>$VII at Petropavlovsk-Kamchatskiy;

(+) 1923/04/13, $M_{nc}=7.3$, tsunami 11 m high in the mouth of the Kamchatka River;

(-) 1927/12/28-N, $M_{nc}=7.1$, tsunami 0.3-0.6 m high in the Hawaiian Is.;

(+) 1971/11/24-S, $M_{nc}=7.2$, $h=100$ km, $M_w=7.65$.

Our additional data corroborated this pattern (six cases against two).

Kuril Is. and Hokkaido. Our catalog of shallow Kuril earthquakes was compiled from NC using the same criteria as for Kamchatka; the 1978 cluster was added:

1843; 1894; 1896; 1904; 1915; 1916; (1918/9-m, 1918/11); 1935; 1937; 1952; 1958; 1963; 1969; 1973; (1978/3/22, 1978/3/22, 1978/3/24-m).

In all, there were 18 events grouped into 15 clusters for the period of 1742-1991.

The results of using a Kuiper test are given in Fig. 1 and Table 1. It is only for the 18.6-year cycle that a significant (6%) departure from the uniform law has been detected. The earlier half of the cycle was active, similarly to Kamchatka.

Japan. The "Japan" region includes the events of the Japan arc that occurred on the Pacific side of Honshu and Shikoku islands. Our catalog of great events (M=7.9+) is based on a tsunami catalog [8] and a macroseismic catalog [25]; it includes the following events (the letters in brackets "S" denote the tsunami catalog [*S*] and the macroseismic catalog [*M*]):

684/11/27-[S]; 869/7/13-[S]; 887/8/26-[S]; 1096/12/17-[S]; 1099-[M]; 1361/8/3-[S]; 1498/9/20-[S]; 1605/1/31-[S]; 1611/12/02-[S]; 1677/4/13-[S]; 1677/4/13-[S]; 1703/12/31-[S]; 1707/10/28-[S]; (1854/12/23-[S]-m, 1854/12/24-[S]); 1891-[M]; 1891-[M]; 1923/9/1-[S]; 1933/3/3-[S]; 1944/12/7-[S]; 1968/5/16-[S].

In all, there were 20 events and 19 clusters. No clearly defined cyclicity was apparent. Low significance ($P=18\%$) was obtained for the 18.6-year cycle. In contrast to Kamchatka, most of the events occurred in the last third of the cycle.

Alaska. The "Alaska" region includes several subregions, namely, the Aleutian Islands (ALE) between 170°E and 165°W (Unimak I.), Alaska proper (ALA) (165°W - 147°W) (as far as Prince William Sound), and the Queen Charlotte Islands (QCH) (147°W - 130°W). The catalog of great preinstrumental earthquakes (prior to 1898) is based on [8], [21]; it includes the following events (references in brackets are [N] for Nishenko and Jacob [21] and [S] for Soloviev and Go [9]):

1788-ALA-[S]; 1847-ALA-[N]; 1848-QCH-[N]; 1849-ALE-[N]; 1854-ALA-[S];

1858-ALE-[N]; 1868-ALA-[S]; 1872-ALE--[N]; 1878-ALE-[S]; 1880-ALA-[N].

In all, there were 10 events.

The catalog for the instrumental period was based on the catalogs of Abe *et al.* summarized in [22]; the cutoff magnitude was $M_S=7.7$:

(1899/7/4, 1899/9/4, 1899/9/10-m, 1900); 1906; 1917; 1929; 1938; 1949; 1957; 1958; 1974; 1986.

In all, there were 14 events and 11 clusters. The results are displayed in Figs. 1 and 2 and listed in Table 1. The 18.6-year cyclicity found by Shirokov [11] from $M \geq 7$ seismicity is not apparent, but the cycle $3T_0/2=27.92$ years is obvious ($P=1.5\%$). It might be improved ($P=0.3\%$) by eliminating the earthquakes of 1949, 1858, and 1849 that occurred along the peripheries of the Queen Charlotte and Komandorskie islands. To check the reliability of this period we carried out analysis for the reliable 1898-1992 data. The significance became worse, 20%, which may be regarded as satisfactory, considering that the sample size was twice as small. The plots demonstrate a general consistency in the nonuniformity of earthquake distributions within the cycle for the data subsets of 1787-1896 and 1897-1992, and for the ALA and ALE subregions. The situation is not quite clear with the USA region.

Mexico. The catalog was based on the data of Anderson *et al.* [15] for 1806-1985 and for depths of 0-80 km. The M_0 magnitudes were converted to M_w using the cutoff value $M_w=7.7$. The events that had occurred southeast of the Isthmus of Tehuantepec were eliminated; the remaining quasi-homogeneous zone was divided into the NW and the SE subregion, the boundary between the two passing along the Orozco Fracture Zone (18°N, 102°W). The resulting catalog contained nine events and eight clusters:

1845/4/7; 1870/5/11; 1899/1/24; 1907/4/15; 1928/6/17; (1932/6/3, 1932/6/18); 1957/7/28; 1985/9/19.

The $3T_0/2$ cyclicity was well pronounced, as in the case of Alaska. Additional evidence for it was provided by the fact that the active period of the 28-year cycle contained a cluster consisting of two intermediate-depth ($h \approx 100$ km) earthquakes of 1928, each with $M_w > 7.7$.

Peru, Ecuador, and Colombia. The catalog of shallow $M \geq 7.8$ earthquakes for this region is based on the data of [9], [19], [22] and includes the following events (S refers to Soloviev and Go [9], N to Nishenko [19], and A to the Abe catalog [22]):

1586-[S]; 1604-[S]; 1664-[N]; 1678-[S]; 1687-[S]; 1725-[N]; 1746-[S]; 1821-[N]; 1868-[S]; 1906-[A]; 1913-[A]; 1940-[A]; 1942/5/14-[A]; 1942/8/24-[A]; 1958-[N]; 1966-[A]; 1974-[N].

In all, there were 17 events. According to [22], the 1958 and 1974 events had magnitudes $M_S=7.3$ and 7.6, respectively. This is below the cutoff value $M=7.8$, but Nishenko [19] treated them as great earthquakes, and we included them in our working catalog.

A large earthquake is mentioned in [9] and [19] as occurring in 1590 in southern Peru, but no date or magnitude are given; this event was not included in our working catalog.

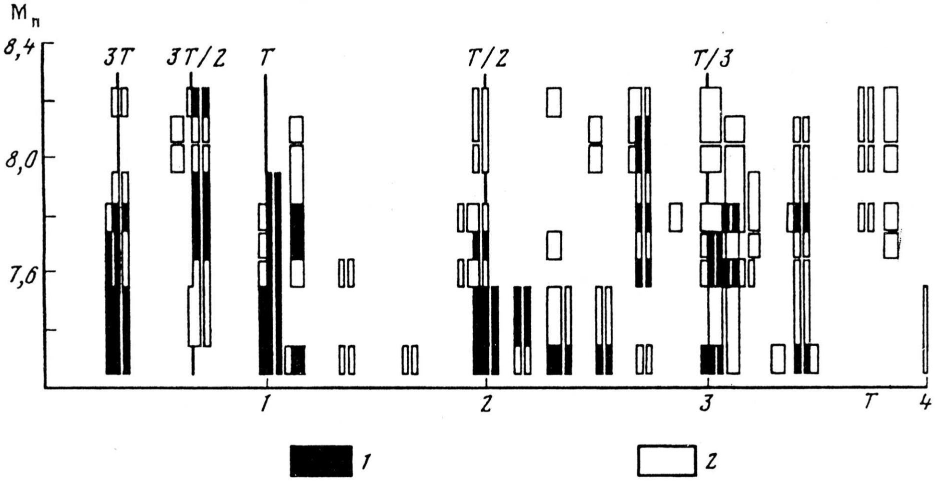

Figure 3 Results of a "spectral" analysis applied to the Kamchatka catalog of clusters; *1, 2* - significance level of the Kuiper statistic, <2.5% and <10%, respectively, for a certain combination of cutoff magnitude M_{cut} (ordinate) and cycle period T. The horizontal coordinate is frequency $F=1/T$ in units of $1/T_0=1/18.613$ years. The width of rectangles is $1/12\ T_0$, approximately corresponding to the frequency resolution attainable with a 250-years catalog. The number of events varies along the vertical: 21 events for the lowest cutoff value $M_{cut}=7.3$ and five events for the highest $M_{cut}=8.3$. Note that the previously identified cycles are well pronounced.

A significant cycle for this region was found to be $T_0/2=9.306$ years ($P=2\%$), the active periods being the first and last quarters of the cycle (Fig. 1*e*). Discarding the 1958 and 1974 events and adding the 1590 earthquake, ascribing to it the "worst" date for the $T_0/2$ cycle, namely, December 31, 1590, one gets $P=3\%$.

Valparaiso, Chile. This region (denoted C-5 in [19]) was used as a well-known example of cyclicity. It includes the following events

1647/5/13; 1730/7/8; 1822/11/19; 1906/8/16; 1985/3/3.

As was expected, this region yielded a significant ($P=6\%$) result for the period $3T_0/2=27.92$ years. The actual cycle length is close to $9T_0/2=83.7$ years.

ANALYSIS OF RESULTS

A joint analysis of the data for all regions revealed the following facts.

1. The lunar cycle proper (18.613 years) was found for Kamchatka and the Kurils alone. Shirokov [11] reported this cycle for Alaska and the Aleutians for $M \geq 7$. However,

this cycle was not confirmed by our analysis (for a different cutoff magnitude).

2. The cycle $T_0/3=6.204$ years was not identified anywhere except Kamchatka (and may be hypothesized for Mexico).

3. The cycle $3T_0/2$ was found ($P<6\%$) for the Aleutians, Mexico, and Chile and inferred ($P<15\%$) for Kamchatka and Peru, that is, in five out of the seven regions of study. The active phase was approximately the same in four cases (except Peru): the earlier half of the cycle (or since 1727/4/10 in the method of phase measurement adopted here).

4. The cycle $3T_0$ is well pronounced in Kamchatka ($P<1\%$) and has low significance ($P=20\%$) for the Kurils, but has the same phase in the two regions. It is also noticeable ($P=10\%$) for the Aleutians where it does not seem to be independent, but simply is a reflection of nonuniformity in the distribution of two successive 28-year cycles.

5. An important fact is the coincidence of cycles between different regions. With the small samples sizes and low significance levels, these coincidences provide important additional confirmation that the cyclicities are real. Coincidences are obvious between Kamchatka and the Kurils, as well as between Alaska and the Aleutians.

SPECTRAL ANALYSIS

One methodological weakness of our approach is that a rather restricted list of possible periods is analyzed, in addition to a certain arbitrary choice of a cutoff magnitude. For this reason we carried out an additional check by examining the Kamchatka catalog over continuous ranges of cycle durations and cutoff magnitudes. To be more specific, we tried all frequencies in the range between $1/5T_0$ and $4T_0$ at intervals of $1/12T_0$. This frequency interval agreed with the length of the available catalog, whose inverse determined the spectral resolution attainable. The results (Fig. 3) demonstrated convincingly that our conclusion as to significant periodicity was actually independent of the choice of a cutoff magnitude. Inspection of Fig. 3 suggests that the periodicities unrelated to the 18.6-year lunar cycle that can be seen there are either not so well expressed or simply do not exist, the apparent coincidences being merely accidental fluctuations.

DISCUSSION OF RESULTS

1. **Cutoff magnitude choice.** The cutoff magnitude we used, M=7.6-7.7, was a formally arbitrary choice. As a matter of fact, it cannot be made higher, because then the amount of data would be drastically reduced and the conclusions would be unreliable. Lower values are possible: this leads to a gradual deterioration of the clearness and hence significance of the results for all regions except Alaska, where the 28-year period is well

pronounced even with a cutoff magnitude as low as $M_S=6.7$.

2. **Additional corroboration** that the phenomenon under study is real is the identification of cycles that are multiples of 18.6 years based on the study of different catalogs compiled by different authors. For example, Table 1 in [20] for the Concepcion subregion, Chile, gives an average period for five intervals as 92.3 ± 8 years ($5T_0\approx93$ years). Similar results were reported for Mexico [24]: Table 5 in that paper contains the following values of average periods for individual subregions: 54 years ($\approx3T_0$) for Oaxaca II, 38 years ($\approx2T_0$) for Oaxaca III, 56 years ($\approx3T_0$) for San Marcos, and 36 years ($\approx2T_0$) for Petatlan. We wish to stress that these additional results for Mexico largely rest on earthquakes with a lower cutoff magnitude than that adopted for the above regions here, hence provide nearly independent information.

3. **Hypothetical mechanism of cyclicity**. Very stringent requirements are to be placed on this mechanism to explain the presence of very diverse cycles ($T_0/3$, $T_0/2$, T_0, $3T_0/2$, $3T_0$, and $9T_0/2$) along with the absence of their greatest common divisor $T_0/6$ and the fact that the main cycle T_0 is not well pronounced. Moreover, cyclicity itself is manifested variously as a general tendency with about half of a cycle being active or as a rather rigorous periodicity; in the latter case earthquakes may repeat themselves in every cycle (Chile) or may sometimes be missing (Kamchatka). We shall restrict our discussion to some general considerations. There is the well-known phenomenon of synchronization exerted on a nonlinear oscillator by an external periodic force. The oscillator is a seismic zone. The synchronization is easily achieved during the main period of its action and its multiples, e.g., $3T_0$. The other periods are less understandable. It should also be taken into account that the period of 18.613 years is the period of tide amplitude variation (modulation period). Another nonlinear element is necessary for long-period excitation to develop, namely, a demodulator. Vibrational acceleration of asthenospheric flow due to earth tides may be suggested as a demodulator. A change in tide amplitude affects the flow velocity, and hence, the instantaneous tectonic load. Note that the simplest, quadratic nonlinearity generates the period $T_0/2$ (9 years), while all of the periods identified, except $T_0/3$, are multiples of $T_0/2$.

4. **Multiple frequencies** (fractional periods) were reliably identified in [7], [14] for the 11-year solar cycle, along with the fundamental frequency/period of the external excitation, for the Kuril seismicity of 1946-1974. Also present were the periods 5.5 and 2.75 years. In this study we identified a very well-pronounced 5.5-year period ($P=0.00598$) for the Kuril earthquakes with $H=80$-600 km and $M_{nc}=7.4+$.

5. **The elimination of clusters** in several regions reduced considerably the level of significance reached, thus certainly diminishing a likelihood of self-deception.

6. **Possibility of extrapolation**. An attractive procedure is to extrapolate the above patterns to the future. However, because the patterns are purely empirical in character, the reliability of extrapolation cannot be assessed rigorously. Because these patterns were observed during several cycles, this holds some promise of a success, but gives no

guarantee. It is a notorious fact that a nonlinear oscillator may behave in a quasi-periodic manner during several cycles (or even tens of cycles), but this does not prevent it from changing the phase or the period, or becoming altogether chaotic. This state of affairs is not improved by an external synchronization. However, one can still try to extrapolate using the highly significant cycles.

7. **Extrapolation for several regions.** *Kamchatka.* The 56-year cycle suggests an increase of activity in 2006-2043 (for M=7.6+); the 18.6-year and the 6-year cycles provide additional evidence supporting this conclusion. Considering the high significance of cyclicity for Kamchatka, the results were put into the shape of a long-term forecast (see the Appendix).

Kurils and Hokkaido. The 18.6-year cycle suggests increased activity from now till 1997 and in 2006-2015 (with M=7.6+).

Aleutian Is., Alaska, and Mexico. The 28-year period gives the following intervals of increased activity for these two regions (with M=7.7+): 1983-1996 and 2010-2024.

Peru, Ecuador, and Colombia. The $T_0/2$ cycle gives a period of increased activity (with M=7.8+) for 1994-1999.

8. ***Post factum* testing.** To demonstrate how large earthquakes can be predicted using lunar cycles, we tested an earlier forecast offered by Shirokov [13] in 1972 for the period following January 1, 1974. We compared the 1974-1995 seismicity with the alarm intervals declared in that paper (based on the 18.6-year cycle) for $M \geq 7.8$ earthquakes in Kamchatka, the Kurils, and northwestern Japan: January 1974 to February 1981 and March 1988 to September 1999. These intervals contain four events of the four $M \geq 7.8$ ones that occurred before the end of 1995: March 23-24, 1978 (cluster of three events); July 12, 1993; October 4, 1994; and December 3, 1995 (a cluster of three events totaling M=7.8). With a total alarm time being 15 of 22 years and assuming a uniform distribution, the probability of this forecast is 22%. The result is thus sufficiently successful, though the associated significance is low (22 years is not a sufficient time for reliable testing). The December 8, 1978, magnitude 8 earthquake that occurred in the South Kurils at a depth of 160 km fits the forecast declared for a depth range of 0-100 km.

CONCLUSION

We corroborated the known and identified some new types of cyclicity for large earthquakes that occurred in several regions of the Pacific Rim whose periods were related to the lunar cycle $T_0=18.613$ years. The best-expressed periods are $3T_0/2 \approx 28$ years and $3T_0 \approx 56$ years. The 28-year period was found in four of the seven regions studied, the effect being best seen for the Alaska-Aleutians region and Mexico, as well as for Valparaiso, Chile, where it is a harmonic of the well-known cycle 85 years ($\approx 9T_0/2$) and for Kamchatka. The active phase of this cycle is the same for all of these regions. The 56-year period was also found in four regions of the seven, but in two cases that was a twice repeated 28-year cycle. The 56-year cycles in Kamchatka and the Kurils have a common active phase. These results were used to prepare a long-term forecast of large earthquakes and tsunamis in Kamchatka for 1993-2062.

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Appendix

LONG-TERM FORECAST OF EARTHQUAKES AND TSUNAMIS FOR KAMCHATKA (PETROPAVLOVSK-KAMCHATSKIY AND UST-KAMCHATSK)

This long-term forecast was made in 1991 for two areas in Kamchatka: the Gulf of Avacha coast with Petropavlovsk-Kamchatskiy City and the Elizovo town (subregion "S") and the Gulf of Kamchatka coast with the Ust-Kamchatsk town (subregion "N") (Tables 2 and 3). The forecast was based on the assumption that the cyclicities identified (having the periods $T_0/3$, T_0 and $3T_0$) would hold for the future too, as well as their non-active fractions: 0.0000–0.3333 and 0.8333–1.000 for the period $T_0/3$; 0.6666–1.000 for T_0; and 0.6666–1.000 for $3T_0$. The other four intervals within a 56-year cycle, each $T_0/6=3.1$ years, were supposed to be hazardous.

Tables 2 and 3 display the situation for the nearest four hazardous intervals; all of these belong to the next 56-year cycle starting in 2006. For each interval we indicate "analogous events" which occurred 56, 112,... years before that interval, the intensities observed in Petropavlovsk-Kamchatskiy and Ust-Kamchatsk, and the tsunami heights for the coasts of the Gulf of Avacha and Gulf of Kamchatka.

Table 4 summarizes the number of predicted events and excessive magnitudes (≥ 7.6), intensities ($\geq$VIII), and tsunami heights (≥ 5 m) for each of the four intervals when summed over 256 years. The 1792 earthquake was counted twice, for the N and S subregions using a description from [6]. These data were used to find the mathematical expectation ν of the number of such events in each of the four hazardous intervals. The expectations were estimated by finding the mean of two estimates based on two hypotheses, A and B. According to hypothesis A, the expected number of events in each of the four hazardous intervals were supposed to be equal: for instance, for the $M_{nc}=7.6+$ events and subregion S, we got seven events during five cycles, 1.4 events per cycle, and 0.35 events per hazardous interval. According to hypothesis B, events were counted separately for each hazardous interval: for the same events, we got 3, 4, 0, and 0 events in the four periods during five cycles, or the means 0.6, 0.8, 0.0, and 0.0. These ν estimates were then used to find the probability P that at least one event is likely to

Table 2 Hazardous periods during 1991–2060 for the Petropavlovsk-Kamchatskiy area based on a long-term forecast using a 56-year cycle.

Period number	*Period, yrs.*	*Events known in analogous periods*[*]					p_M	p_I	p_h
		Year	M_{nc}	M_s	*Intensity I*	h_{ts}, m	%		
1	2008,6–2011,7	1841	8,4	–	8–9	15	37	22	26
		1899	7,9	7,4	–	–			
		1952	8,5	–	7	15			
2	2014,8–2017,9	1737	8,3	–	8–9	30	43	42	26
		1792	8,4	–	8–9	2–5?			
		1848	–	–	–	5–10?			
		1904	7,7	7,2	8	–			
		1904	7,7	7,4	8	2–5?			
		1959	7,9	–	7–8				
3	2027,1–2030,2	–	–	–	–	–	16	14	09
4	2033,3–2036,4	1866	–	–	8–9?	–	16	22	09
		1923	8,5	–	6–7	2–5			
Outside of analogous periods		1827	–	–	7–8	2–5?			

Note. For each period we estimated the probability that at least one earthquake with magnitude $M_{nc} \geq 7.6$ is likely to occur in subregion S (southern Kamchatka): p_I, which is for at least one earthquake with intensity $I \geq$ VIII to occur in Petropavlovsk-Kamchatskiy and Elizovo; p_h, for at least one tsunami of height $h_{ts} \geq 5$ m to occur on the coast of the Gulf of Avacha. The probabilities for these events to occur outside of these hazardous periods, in particular, from 1991 to 2007, are small.

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[*] Notable earthquakes near Petropavlovsk-Kamchatskiy and tsunamis at the Gulf of Avacha coast that occurred 55.84, and $2 \times 55.84 = 111.68$ years before the hazardous periods discussed.

Table 3 Hazardous periods in 1993–2060 for the Ust-Kamchatsk area given by a long-term forecast based on the 56-year cycle.

Period number	*Period, yrs.*	*Events known in analogous periods*[*]					p_M	p_I	p_h
		Year	M_{nc}	M	*Intensity I*	h_{ts}, m	%		
1	2008,5–2011,7	–	–	–	–	–	11	09	03
2	2014,8–2017,9	1737	7,8	–	8–9	–	27	26	03
		1791	6,8	–	8	2–5?			
		1792	8,4	–	10	2–5?			
3	2027,1–2030,2	1915	7,3	7,6[**]	–	–	27	09	03
		1917	8,1	–	5–6	–			
		1971	7,8	–	7	0,5			
4	2033,3–2036,4	1756	–	–	8	–	20	26	12
		1923	8,5	–	7	–			
		1923	7,3	8,2[***]	8–9	11			
Outside of analogous periods		1936	5,7	–	8–9	–			

Note. The probabilities p_M, p_I, and p_h refer to subregion S, Ust-Kamchatsk, and the Gulf of Kamchatka, respectively.

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[*] Notable earthquakes near Ust-Kamchatsk and tsunamis at the Gulf of Kamchatka coast that occurred 55.84 and $2 \times 55.84 = 111.68$ years before the hazardous periods under discussion.

[**] Value of M_S.

[***] Value of M_t (tsunami magnitude after Abe).

Table 4 Estimation of the number and probability of earthquakes and tsunamis that are likely to occur in 1993-2062 around Petropavlovsk-Kamchatskiy and Ust-Kamchatsk during four hazardous periods (see Tables 2 and 3).

Location	*Event*	*Numbers of events for 256 years (1737–1992)*						*Predicted for 1993–2062*	
		In hazardous periods				*Total*	*in quiet periods*	*N, summed over hazardous periods*	*P* ($N > 0$)
		1	2	3	4				
Subregion S	$M_{\text{нк}} \geq 7{,}6$	3	4	0	0	7	0	1,4(0–3)	0,75
Subregion N	$M_{\text{нк}} \geq 7{,}6$	0	2	2	1	5	0	1,0(0–2)	0,63
S + N	$M_{\text{нк}} \geq 7{,}6$	3	6	2	1	12	0	2,4(1–4)	0,91
Petropavlovsk-Kamchatskiy	$I \geq 8^{*}$	1	4	0	1	6	0	1,2(0–2)	0,70
Ust-Kamchatsk	$I \geq 8$	0	2	0	2	4	1	0,8(0–2)	0,55
Gulf of Avacha	$h_{\text{ц}} \geq 5^{**}$	2	2	0	0	4	0	0,8(0–2)	0,55
Gulf of Kamchatka	$h_{\text{ц}} \geq 5$	0	0	0	1	1	0	0,2(0–1)	0,18

Note. The figures in the parentheses are expected ranges of N for 2008–2036.

* Intensity of shaking.

** Tsunami height (m).

occur during a specified hazardous interval using the following formula that holds for a segment of a Poisson process:

$$P = 1 - \exp(-\lambda t_0),$$

where λt_0 is the mathematical expectation of the number of events for the time $t_0 = 3.102$ years. The resulting P values are listed in Tables 2 and 3.

The forecast proper was formulated as follows.

1. The events described in Table 4 ($M \geq 7.6$; $I \geq$ VIII; and $h_{ts} \geq 5$ m) are likely to occur in 1992-2062 mostly during the periods indicated in Tables 2 and 3. Considering the overall uncertainty, it is expected that at least 80% of such events will take place during 1992-2062.

2. The total number of such events in 2008-2036 will be close to the values of N given in Table 4. We estimated the probability of at least one event to occur during the total forecast period. The probabilities P for each hazardous period, given in Tables 2 and 3, are merely indicative of the trend, the values themselves being rather unreliable.

The above forecast does not apply to the Bering Sea and the Kommandorskie Islands, to smaller events ($I <$ VII–VIII), smaller tsunamis ($h_{ts} < 5$ m), or to intermediate-depth earthquakes. During a period of 1991-2008 large earthquakes and tsunamis are unlikely at the Pacific coast of Kamchatka.

REFERENCES

1. *Katalog tsunami na Kamchatke* (A tsunami catalog for Kamchatka)(Obninsk: VNIIGMI-MPD, 1987).
2. F. A. Kirillov, *Katalog zemletryaseniy Kurilo-Kamchatskoy zony. Otchet* (An earthquake catalog for the Kuril-Kamchatka zone. A report)(Moscow: Fondy IFZ AN SSSR, 1962).
3. V. V. Lamakin, *Dokl. Akad. Nauk SSSR* **170**, N2: 410–413 (1966).
4. K. Mardia, *Statistics of Directional Data* (London - New York: Academic Press, 1972).
5. P. Melchior, *The Earth Tides* (Oxford, etc.: Pergamon Press, 1966).
6. *Novyi katalog silnykh zemletryaseniy na territorii SSSR* (A new catalog of large earthquakes for the USSR area)(Moscow: Nauka, 1977).
7. M. G. Odinets, *Izv. Akad. Nauk SSSR. Fizika Zemli* N8: 20-29 (1983).
8. S. L. Soloviev and Ts. N. Go, *Katalog tsunami na zapadnom poberezhie Tikhogo okeana* (A catalog of tsunamis for the western Pacific coast)(Moscow: Nauka, 1974).
9. S. L. Soloviev and Ts. N. Go, *Katalog tsunami na vostochnom poberezhie Tikhogo okeana* (A catalog of tsunamis for the eastern Pacific coast)(Moscow: Nauka, 1975).
10. T. P. Tamrazyan, *Priroda* N12: 96-99 (1975).
11. S. A. Fedotov and G. A. Sobolev, in: *Poiski predvestnikov zemletryaseniy* (Search for earthquake precursors)(Tashkent: FAN, 1976): 49-61.
12. W. Feller, *An Introduction to Probability Theory and Its Applications*, vol. 1, 2nd ed. (New York: John Wiley and Sons; London: Chapman and Hall, 1957).

13. V. A. Shirokov, in: *Vulkanizm i geodinamika* (Volcanism and geodynamics)(Moscow: Nauka, 1977): 103-115.

14. A. M. Shurygin and M. G. Odinets, *Volcanol. Seismol.* N6 (1984)(cover-to-cover translation of the Russian journal *Vulkanol. Seismol.* 1984, N6: 92-102).

15. J. G. Anderson, S. K. Singh, J. V. Espindola, and J. Yamamoto, *Phys. Earth Planet. Inter.* **58**: 307-322 (1989).

16. S. A. Fedotov, G. A. Sobolev, S. A. Boldyrev, *et al., Tectonophysics* **37**: 305-321 (1977).

17. S. Kilston and L. Knopoff, *Nature* **304**, N5921: 21-25 (1983).

18. S. P. Nishenko, *J. Geophys. Res.* **90**: 3589-3615 (1985).

19. S. P. Nishenko, *PAGEOPH* **35**, N2: 169-259 (1991).

20. S. P. Nishenko and R. Buland, *Bull. Seismol. Soc. Amer.* **77**: 1382-1399 (1987).

21. S. P. Nishenko and K. H. Jacob, *J. Geophys. Res.* **95**, NB3: 2511-2532 (1990).

22. J. F. Pacheco and L. R. Sykes, *Bull. Seismol. Soc. Amer.* **82**, N3: 1306-1349 (1992).

23. A. C. Perrey, *Compt. Rend. Acad. Sci.* **36**: 537-540 (1853).

24. S. K. Singh, L. Astiz, and J. Havskov, *Bull. Seismol. Soc. Amer.* **71**, N3: 827-844 (1981).

25. T. Usami, *Descriptive Catalogue of Destructive Earthquakes in Japan* (Tokyo: Univ. Tokyo Press, 1975).