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Recurrence of Kamchatka Strong Earthquakes on a Scale of Moment Magnitudes

A. A. Gusev* and L. S. Shumilina**

* *Institute of Volcanic Geology and Geochemistry, Far East Division, Russian Academy of Sciences,*
Petropavlovsk-Kamchatski, Russia
** *Schmidt United Institute of Physics of the Earth, Russian Academy of Sciences,*
Bol'shaya Gruzinskaya ul. 10,
Moscow, 123995 Russia

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Abstract—A catalog of moment magnitudes M_W is constructed for the strongest earthquakes on Kamchatka over the period from 1737 through 2000. Macroseismic evidence and tsunami data were used for historical earthquakes, and the M_W value for earthquakes of the 20th century was estimated through other magnitudes either with the use of nonlinear intermagnitude relations or directly from M_0. Recurrence plots were constructed on an M_W scale for the time periods 1923–1952, 1952–1962, and 1963–1988. Year-averaged estimates of numbers n_6 of shocks with $M_W \geq M_{W0} = 6.0$ obtained for various time intervals differ appreciably. The function $\log n_M(M_W)$ is approximately linear in the range $M_W = 5.5$–7, where the recurrence plot slope is $b = 0.95$–1.1. Several variants of the recurrence "prediction" of the strongest earthquakes ($M_W = 9$) are constructed from n_6 and b data assuming that the recurrence plot is linear. Comparison of these predictions with the actual data over 264 years showed that the observed recurrence rate significantly (by a factor of up to 5) exceeds any predicted variants obtained by a linear extrapolation of the $M_W = 5.5$–7 recurrence plot. Thus, the hypothesis on the linearity of the recurrence plot is at variance with our data, and the recurrence of moderate shocks appreciably fluctuates with time. The deviation of the recurrence plot from linearity has a pattern consistent with the model of a characteristic earthquake. Methodologically, the results presented in this paper imply that empirical estimates of the recurrence of moderate events made for various time intervals can differ substantially, and the application of the hypothesis on the recurrence plot linearity tends to significantly underestimate the recurrence of the strongest events.

INTRODUCTION

The estimation of the long-term average seismicity level is vital to the assessment of seismic hazard. This problem has two aspects: recurrence rate estimation for a magnitude level supported by experimental data and extrapolation of the observed recurrence rate to the highest magnitudes. Notwithstanding long-term investigations, the problem is far from being fully solved. The following main difficulties are encountered.

(1) Long-term variations in the seismicity level due to the strongest earthquakes exist, and this raises the question of within which limits the estimation of long-term averages is meaningful.

(2) Fluctuations in the seismicity level due to moderate shocks are observed. In particular, difficulties related to the aftershock periods of strong earthquakes are well known. Fluctuations in the background (basic) seismicity involve even more serious and poorly studied difficulties.

(3) A unified magnitude classification of strong and weak earthquakes is often absent, and differences between magnitude scales of different time periods are unknown. Any reliable estimates are particularly difficult to obtain for magnitudes of historical earthquakes.

(4) The actual seismicity does not comply with the Gutenberg–Richter law (the recurrence plot is nonlinear within a wide range of magnitudes).

The scale of moment magnitudes M_W provides a good basis for the unification of source intensity estimates that are available for various time periods and various magnitude intervals and are obtained in terms of various scales. Preliminary systematic determinations of global and regional intermagnitude relations could be advantageous for such a unification. Relations of this type were proposed in [Gusev and Melnikova, 1990], which enabled the study of the above problems of seismicity on Kamchatka. This work was performed in three stages. First, a Kamchatka catalog of the strongest earthquakes on the M_W scale was constructed. The recurrence of moderate earthquakes in terms of the same scale was then estimated for various periods of instrumental observations and by various means. Finally, all these data were jointly analyzed.

CATALOG OF THE STRONGEST EARTHQUAKES ON THE M_W SCALE

A few methods are applicable to the M_W estimation for Kamchatka earthquakes over the period from 1899 through 1990. Below, they are characterized in the order of their trustworthiness.

(1) Scale of the seismic moment M_0 directly connected with M_W through the formula [Hanks and Kanamori, 1979]

$$M_W = (2/3)\log M_0\ [\text{dyn cm}] - 10.7.$$

An authoritative world catalog of M_0 values developed at Harvard University has existed since 1976 [http:\\www.seismology.harvard.edu]. Earlier determinations are only available for the event of 1952 (a reliable estimate) and for the events of 1923, 1959, and November 24 and December 15, 1971 (relatively reliable estimates) [Purcaru and Berckhemer, 1982; Zobin *et al.*, 1988; Okal, 1992a, 1992b].

(2) Scale of the magnitude M_t estimated from data on far-field tsunami heights (actually, in the Hawaiian Islands) [Abe, 1979]. This scale is calibrated against the M_0 scale (in the ideal case, $M_t = M_0$). The M_t scale proved fairly reliable for estimating M_0 and M_W in the case of shallow reversed faults in subduction zones.

(3) Scale of the surface wave magnitude M_S. The connection between M_S and M_0 is correlative and less reliable compared to M_t. In dealing with M_S, the following facts should be taken into account.

(a) Abe [1981, 1984] and Abe and Noguchi [1983a, 1983b] published original estimates of M_S and m_B ($=m_{PV}$ for P waves recorded by medium-period instruments) based on data of Gutenberg. They also revised the systematically overestimated values of M_S and m_B obtained by Gutenberg for 1898–1912 (these overestimates are due to the fact that Gutenberg did not take into account the resonance property of the transfer function inherent in the instruments of that period). The resulting set of M_S and m_B values appreciably changes the relative weights of various events of the 18th–20th centuries on Kamchatka (and in the world). After these revisions, the magnitudes reported in [Gutenberg and Richter, 1954; Duda, 1965] should be regarded as obsolete. We denote the Gutenberg–Abe values of M_S by M_S^{GR}.

(b) Magnitudes M_S (determined from 20-s surface waves and denoted below as M_S^{US}) published by seismological services of the United States [*Earthquake* ..., 1973–1988] are not equivalent to the Gutenberg–Abe magnitudes, because different formulas are applied for the calculation of M_S [Abe, 1981, 1984]. The following relation between M_S^{GR} and M_S^{US} should be used: $M_S^{US} = M_S^{GR} + 0.18$ [Abe, 1981, 1984].

Table 1. Comparison of the magnitudes M_S^{US} and M_{LH}

M_{LH}	4.5	5.5	6.5	7.5	8.5
M_S^{US}	4.4	5.35	6.2	7.3	8.5

(c) The magnitude M_{LH} (M_{LV}), determined from surface wave data recorded by the General Network of Seismological Observations of the USSR (Obninsk), can be regarded, on average, as equivalent to M_S^{US} (note that M_{LH} also diverges from M_S^{GR} by about 0.18). However, this is not true of the Kurile–Kamchatka zone (and Japan) [Gusev and Melnikova, 1990]: M_{LH} and M_S^{US} differ and their distinctions are magnitude-dependent (Table 1). Clear examples of these distinctions are the Kamchatka events of November 22, 1969 ($M_S^{US} = 7.3$ and $M_{LH} = 7.7$), and December 28, 1984 ($M_S^{US} = 7.0$ and $M_{LH} = 7.5$).

(d) Magnitudes M_{Atl} reported in [Savarensky *et al.*, 1962] can be regarded as being of the same type as M_{LH}, but their numerical values are lower than M_{LH} by 0.2–0.25.

(e) Judging from actual numerical values, magnitudes M_{NC} reported in *New Catalog* ... [1977] (NC) were estimated from data given in [Gutenberg and Richter, 1954; Duda, 1965] for earthquakes of 1899–1953 and from M_{LH} values for earthquakes of 1953–1973. According to points (a)–(c), this means an inhomogeneity of magnitude determinations (the magnitudes have greater weights until 1954 and are distorted until 1912). Moreover, one should keep in mind that, according to Abe [1984], Gutenberg used m_B, rather than M_S, values in his catalog at depths of 40–60 km (as well as at great depths). All this does not allow one to consider the NC data as final.

In view of the above facts, we tried to reduce all of the surface wave magnitudes to M_S^{GR}, after which values of M_W were estimated from M_S^{GR} on the basis of the nonlinear correlation formula between these magnitudes [Gusev and Melnikova, 1990].

(4) The scale of medium-period P-wave values m_B (m_{PV}) incorporating corrections in accordance with point 3a is the most important source of M_W estimates for shocks at depths greater than 70 km before 1977. Such estimates appear to be more reliable than the NC estimates M_{LH}^* obtained from M_{LH} and corrected for depth, because the individual scatter in these corrections is large. The M_W values were estimated from m_B on the basis of the nonlinear relation proposed in [Gusev and Melnikova, 1990].

Table 2. Data on earthquakes of 1737–1896

Date	Description	Accepted value of M_W
Oct. 17, 1737	A stronger analogue of the 1952 event. An intensity of 8–9 in Petropavlovsk-Kamchatski (cf. 7 in 1952), a tsunami height of 60 m (!?) (20 m in 1952), $M_{NC} = 8.3$	9.2
Nov. 4, 1737	An intensity of 9–10 in Nizhne-Kamchatsk, aftershocks over a few months, $M_{NC} = 7.8$	7.8^+
Dec. 17, 1737	Tsunami is nearly of the same height as in 1952 but is more local. $M_{NC} = 7.5$, which does not comply with the tsunami scale. The reality of the event raises doubts: the description might relate to the event of October 17, 1737	8
Dec. 2, 1790	The shock was felt in Nizhne-Kamchatsk and Petropavlovsk. $M_{NC} = 7.5$; the epicenter in the Kronotski Bay. A great depth of the shock is probable	Not included in the M_W list, being regarded as an unreliable estimate
Apr. 15, 1791	An intensity of 8 in Nizhne-Kamchatsk. According to [*Catalog* ..., 1987], tsunami took place, but its description is ambiguous. $M_{NC} = 6.8$ (a minimal estimate)	The value $M_W = 7.5$, obtained with regard for the tsunami, is doubtful
Aug. 22, 1792	The earthquake was felt from Nizhne-Kamchatsk to Petropavlovsk-Kamchatski. The NC epicenter is in the Kronotski Bay. Descriptions of ground motions in Paratunka and Nizhne-Kamchatsk imply that both towns were close to the epicentral zone. The assumption that the epicenter was in the Kronotski Bay suggests an unusually high macroseismic magnitude. Possibly, two events with $M_W \approx 8$–8.5 took place in the Avachinskii and Kamchatka bays, or a source with $M_W \approx 8.5$–9.2 was about 600 km long. The tsunami data are vague; $M_{NC} = 8.4$	8.8
Aug. 9 and 10, 1827	The eruption of the Avachinskii Volcano was accompanied by strong earthquakes. Tsunami (away from the shore) was noted. In addition, a tectonic earthquake with $M_W \geq 7.0$ may have taken place. The event is not listed in the NC	7.0^+
May 18, 1841	An intensity of 8–9 in Petropavlovsk-Kamchatski and a tsunami that had a height of 4.6 m in Hilo, Hawaii; $M_t = 9$; $M_{NC} = 8.4$	$M_W = M_t = 9$ (relatively reliable)
June 1848	Sea level fluctuations in the Petropavlovsk harbor: "The sea alternately rose, encroaching on the shore, and dropped, exposing the sea floor." (A concurrent earthquake was also noted.) With the given configuration of the bay, this suggests a wave no less than 5–10 m in height or very intense seiche events, so that a value of $M_W \geq 7.5$ may be accepted. Not listed in the NC	7.5^+
Oct. 28, 1849	An earthquake near Mednyi and Bering Islands. An intensity of 9 on Mednyi Island; tsunami. $M_{NC} = 7.5$ is a minimum estimate	7.5^+
June 27, 1854	This NC date most likely relates to the Julian calendar. Devastating tsunami on Shumshu Island. $M_{NC} = 7.0$	7.5^+
Sept. 6, 1866	An intensity of no less than 7 in Petropavlovsk. $M_{NC} = 7.0$ is a minimum estimate	7.0^+

Note: The superscript "+" at an M_W value means "and more."

The determination of M_W in the preinstrumental period, 1737–1896, is a very difficult problem, and proposed solutions are often of a conjectural nature. Several NC magnitude estimates are based on the length of the period of perceptible aftershocks. We tried to reject data of this type, because such an approach is hardly reliable under Kamchatka conditions. It is known that the events of October 4, 1952; December 15, 1971; and August 17, 1983, gave rise to numerous aftershock series, whereas much less numerous aftershocks followed earthquakes of similar magnitude and depth that occurred on February 3, 1923; May 4, 1959; and November 24, 1971. The NC magnitudes were included in our analysis, but their underlying data were revised on the basis of the macroseismic catalog of Kirillov [1962] and the tsunami catalog [*Catalog* ..., 1987]. Results of the analysis that needed comment are summarized in Table 2.

Results of the M_W determinations are summarized in Table 3. Below, we present some explanations to this table. We believe that the catalog includes all events with $M_W \geq 7.5$ since 1899. The catalog covers the rectangle (50.0°–59.9°N, 153.0°–169.9°E). The enlargement of the "Kamchatka" region (compared to the NC area) is related to the position of the earthquake source of 1952 (and probably of 1737), which lies beyond the conditional boundaries of the Kamchatka region. The index R refers to the catalog of Rothe [1969], and the index d refers to magnitudes estimated from NC record lengths. For the period 1898–1912, the latter can give overestimated magnitudes for the same reasons as in the case of M_S. The values M_S^{GR} are given according to the Gutenberg–Abe data. Blanks in the M_S^{GR} column of the table mean that the given event is absent in the Abe catalog and its value of M_S^{GR} (or m_B) is 6.8 or less. Columns 10–13 present the determinations of M_W from correlation formulas with the magnitude indicated in parentheses. The $M_W(M_0)$ values (column 12) are determinations from the Harvard University catalog [http:\\www.seismology.harvard.edu]. The M_W values in the last column are our final estimates.

RECURRENCE ESTIMATES OF MODERATE SHOCKS AND THEIR EXTRAPOLATION TO HIGHER MAGNITUDES

Data on the strongest ($M \geq 7.5$) earthquakes on Kamchatka over the past 100–105 years can be regarded as complete, but this period is obviously insufficient for reliable estimation of recurrence intervals of such earthquakes. Recurrence estimates are more reliable for the magnitudes 6–7. However, the validity of the extrapolation of such estimates into the range of the highest magnitudes is a special problem, discussed below. The data for 1737–1898 are both noninstrumental and obviously incomplete. Gaps are expected to be particularly numerous in the period from 1855 through 1898, after a Russian naval base was moved from the town of Petropavlovsk-Kamchatski to Primorye and the naval port was closed in this city. Actually, the NC contains only 3 shocks for the period 1855–1900, whereas their number is 11 for 1810–1855, 8 for 1765–1810, and 8 for 1720–1764. Thus, the recurrence rates for the period 1737–1898 are obviously underestimated, and the data may be regarded as more or less complete only for the strongest shocks, such as the event of October 17, 1737.

We start with the analysis of the 20th century data. These are data of comprehensive instrumental observations (we address the area (50.0°–60.0°N, 156.0°–165.9°E) and the depths $H = 0$–69 km). For each of the literature sources used, these data were treated and analyzed in accordance with the following general scheme.

(1) A certain time interval was fixed during which no abrupt evident changes in the average recurrence rate of earthquakes were observed.

(2) The type of magnitude most suitable for conversion into M_W was chosen, and the conversion was performed using correlation formulas [Gusev and Melnikova, 1990].

(3) A cumulative recurrence plot was constructed for earthquakes on the M_W scale in the range $M_W = 5.5$–7 (or in a range close to this one) and its parameters were estimated (the yearly recurrence rate n_6 of $M_W \geq 6$ events and the slope b).

(4) The n_6 and b estimates were linearly extrapolated to determine the yearly recurrence rate of $M_W \geq 9$ events (n_9). This predictive estimate for the ultimate magnitude was compared with the observed number of events in 1737–2000.

The resulting estimates are summarized in Table 4.

Now, we consider separately the catalogs studied.

(1) Vikulin and Kim [1983a] believe that their catalog *Kurile–Kamchatka Earthquakes: Observations of 1911–1952* (henceforth referred to as KKE) is complete in relation to events with $M > 5.5$ since 1923. The KKE magnitudes (M_{GC}) being correlated with the NC, the above note on the possible inhomogeneity of the NC magnitude estimates is valid here as well.

This catalog was used for the analysis of the period 1923–November 3, 1952 (without November and December 1952, including the event of November 4, 1952, and the beginning of its aftershock sequence) under the assumption that the KKE magnitudes M_{GC} of this period are nearly equivalent to M_S^{GR}. Results of this analysis are given in Fig. 1a and Table 4.

(2) Magnitude estimates reported in [Rothe, 1969; Savarensky *et al.*, 1962] and M_{LH} values from [*Bulletin* ..., 1954–1964] can be used for the period from November 4, 1952, through 1961. The compatibility of these magnitude estimates raises doubts. We decided to use the magnitudes M_{Atl} from [Savarensky *et al.*, 1962] for November 4, 1952 through 1961, assuming that M_{Atl} is inhomogeneous in this time interval and is equivalent to $M_{LH} - 0.25$. Results of this analysis are shown in Fig. 1b and Table 4.

(3) The period 1962–1974 was studied directly from the NC data, and results of this analysis are shown in Fig. 3c and Table 4. The plot is far from being linear due to the obvious deficiency in shocks with $M = 6.5$–7.0, and b could not be reliably estimated.

(4) Since the late 1960s, seismological services of the United States have systematically determined the

Table 3. Catalog of Kamchatka earthquakes

Date	Epicentral coordinates		Depth H, km	Magnitudes									
	deg N	deg E		M_{NC} (M_{LH})	M_{GR} (M_{Rothe})	M_S^{GR}	M_S^{US} (M_{m})	m_B	M_W (M_S)	M_W (m_B)	M_W (M_0)	M_W (M_t)	M_W
October 17, 1737	50.5	158.0	(40)	8.3								9.2	9.2
November 4, 1737	55.5	163.0	(20)	7.8									(7.8+)
December 17, 1737	50.0	157.0	(50)	7.5									(8)
November 18, 1742	50.5	157.0	(40)	7.5									(7.5)
December 2, 1790	54.0	162.0	(20)	7.5									(7.5)
April 15, 1791	56.0	163.0	(20)	6.8									(7.5)
August 22, 1792	54.0	162.0	(20)	8.4									(8.8)
1827	53.1	158.5											(7.0+)
May 17, 1841	52.5	159.5	(30)	8.4								9.0	9.0
1848	52.5	159.5											(7.5+)
October 28, 1849	55.0	166.0	(20)	7.5									(7.5+)
June 27, 1854	51.0	158.0	(40)	7.0									(7.5+)
January 22, 1858	55.0	166.0	(20)	7.5									(7.5+)
September 6, 1866	52.5	159.5	(30)	7.0									(7.0+)
November 23, 1899	53.0	159.0	(20)	7.9	7.9	7.4			7.55				7.6
June 25, 1904, 14:00	52.0	159.0	(30)	7.7d	8.0	7.2		7.3	7.35	7.5			7.4
June 25, 1904, 21:00	52.0	159.0	(30)	7.7d	8.1	7.4		7.2	7.55	7.35			7.5
June 27, 1904	52.0	159.0	(30)	7.3d	7.9	7.2		7.0	7.35	7.15			7.3
July 24, 1904	52.0	159.0	(30)	6.9	7.5	(6.7)		7.1	(6.9)	7.25			7.0
September 15, 1905	53.0	164.0	(30)	7.0d	7.6	7.4		7.1	7.55	7.25			7.5
October 8, 1906	53.5	154.5	(200)	7.0	7.0			6.2		(6.2)			
August 17, 1907	52.0	157.0	(120)	7.2	7.25			7.0		(7.0)			7.2
March 6, 1914	52.0	159.4	(50)	6.7	7.0	6.3		7.1	6.6	7.25			6.6
July 31, 1915	53.5	163.3	(20)	7.3	7.75	7.6		7.5	7.75	7.8			7.8
January 30, 1917	55.2	164.5	(20)	8.1	7.75	7.8		7.7	8.0	8.1			8.0
March 4, 1922	53.1	158.3	220	7.4	7.0			7.1		7.25			7.3
February 2, 1923	52.5	160.5	(20)	7.0	7.25	7.2		7.3	7.35	7.5			7.4
February 3, 1923	53.0	161.0	(20)	8.5	8.3	8.3	(8.4)	7.7	8.7	8.2		8.8	8.5
February 24, 1923	55.0	162.4	(20)	7.7	7.4	7.3		7.4	7.45	7.7			7.5
April 13, 1923	55.4	162.8	(20)	7.3	7.25	7.2			7.35			8.2	8.2
August 19, 1925	54.4	168.6	(20)	6.9	7.2	7.0		7.3	7.2	7.5			7.2
December 28, 1927	53.8	161.4	(20)	7.1	7.3	7.3		7.0	7.45	7.7		7.5	7.5
January 13, 1929	50.6	154.7	135	7.8	7.7			7.4		7.7			7.7
March 17, 1933	54.4	162.5	20	6.6	6.9	7.0		7.1	7.2	7.25			7.2
June 30, 1936	55.0	165.0	(20)	7.2	7.4	7.4		7.4	7.55	7.7			7.6
November 13, 1936	56.2	163.3	(20)	7.3	7.2	7.1		7.3	7.3	7.6			7.3
September 24, 1941	50.0	157.8	70		7.0			6.8		6.9			6.9
August 23, 1942	53.0	163.8	(20)	6.9	7.0	6.4		7.0		7.1			7.1
September 23, 1944	53.0	162.5	(20)	6.9	7.4	7.2		7.3	7.4	7.5			7.4
April 15, 1945	57.0	164.0	(20)	7.0	7.0	7.2		7.0	7.35	7.1			7.3
September 13, 1946	52.4	158.2	80	7.0									

Table 3. (Contd.)

Date	Epicentral coordinates		Depth H, km	Magnitudes									
	deg N	deg E		M_{NC} (M_{LH})	M_{GR} (M_{Rothe})	M_S^{GR}	M_S^{US} (M_m)	m_B	M_W (M_S)	M_W (m_B)	M_W (M_0)	M_W (M_t)	M_W
October 2, 1946	52.0	159.0	50	7.2	6.75								
November 4, 1952	52.3	161.0	(20)	8.5	8.25	8.2		7.9	8.6	8.7	9.0	9.0	9.0
November 29, 1952	52.8	159.2	40	7.3									
September 4, 1953	50.4	157.0	60	7.3									
November 10, 1953	50.9	157.6	60	7.0	(6.9)			7.0		7.1			7.1
March 18, 1955	54.0	161.0	70	7.1	(7.4)	7.3		7.2	7.45	7.35			7.4
November 23, 1955	50.4	157.3	60	7.3		6.8		6.9			7.1		7.1
June 26, 1958	54.0	160.1	120	7.0*									
May 4, 1959	53.1	160.3	20	7.6		7. 7	(7.9)	7.8	7.9			8.2	8.0
June 18, 1959	53.9	160.5	15	7.0									
July 25, 1960	53.5	158.9	120	7.2*				7.2		7.35			7.4
October 28, 1960	51.8	157.8	110	7.4*				6.9		7.05			7.1
November 22, 1969	57.8	163.6	20	7.7			7.3	7.4	7.3	7.7		7.75	7.7
August 30, 1970	52.3	151.7	640	7.0*				7.2		7.35			7.4
November 24, 1971	52.67	159.5	125	7.3*			(7.4)	7.4		7.7	7.65		7.5
December 15, 1971	55.91	163.37	30	7.8			7.8	7.5	7.8	7.8	7.7	7.8	7.8
February 28, 1973	50.36	156.70	70	7.5			7.2	7.2			7.35		7.4
February 19, 1977	53.53	169.92	33	(7.1)			6.7	7.0					6.8
August 17, 1983	55.64	161.52	98	(7.5)			6.7	6.9			7.0		7.1
December 28, 1984	56.29	163.49	13	(7.5)			7.0	7.0			6.7		6.7
February 29, 1988	55.02	167.38	30	(7.1)			6.8	7.0			6.9		6.9
November 6, 1990	53.42	169.82	27	(7.6)			7.0				7.1		7.1
March 2, 1992	52.92	159.89	41	(7.1)			6.8				6.8		6.8
June 8, 1993	51.25	157.77	54	(7.4)			7.3				7.5		7.5
November 13, 1993	51.95	158.67	52	(7.1)			7.1				7.0		7.0
January 1, 1996	54.00	159.65	33	(7.0)							(6.3)		6.4
June 21, 1996	51.79	158.98	36	(7.3)			6.6				6.7		6.7
December 5, 1997	54.88	161.95	33	(7.9)			7.6				7.9		7.9
March 8, 1999	51.75	159.87	15								6.9		6.9

Note: Data in columns 1–5 are taken from [*New Catalog* …, 1977] for 1737–1974 and from [Kondorskaya and Ulomov, 2000] for 1975–1999. The mantle wave magnitude M_m in column 8 is given after [Okal, 1992a, 1992b].

20-s magnitude M_S [*Earthquake* …, 1973–1988], which correlates well with M_W. We used data of 1973–1988, and results of their analysis are shown in Fig. 1d and Table 4. A deficiency in shocks with $M = 6.5–7$ is also evident.

(5) Events of 1964–1973 are summarized in [*Seismic* …, 1980], where the numbers of events of different energy classes K^{F68} [Fedotov, 1972] are given. In particular, this summary includes zones of reliable recording of shocks with $K^{F68} = 9$ (i.e., 8.5 and more) and 11 (10.5 and more); the former is somewhat smaller and the latter is somewhat larger than the region studied in our paper. We used these data directly, and results of their treatment are shown in Fig. 1e. Table 4 presents geometric means of two values of n_6. Variously estimated values of b coincide.

(6) Direct determinations of M_0 (i.e., M_W) are available for 1976–2000 [http:\\www.seismology.harvard.edu; Dziewonski *et al.*, 1981; Dziewonski and Woodhouse, 1983]. As distinct from the preceding five cases, these data are direct determinations of moment

Table 4. Parameters of recurrence plots

Time period	Original magnitude	M_{W1}–M_{W2}	n_6	$n_9 \times 10^3$	b	C
1923–November 3, 1952	M_{GC}	6.1–7.0	3.26	4.9	0.93	2.4
November 4, 1952–1961	M_{Atl}	5.6–6.8	11.90	6.1	1.10	1.9
1962–1974	M_{NC}	5.8–6.5	1.26	–	[1.69]	–
1973–1988	M_S^{US}	5.5–6.4	1.43	0.15	1.32	–
1964–1973	K^{F68}	4.3–6.1	1.16	1.2	1.00	–
1976–2000	M_W	5.5–7	1.74	2.5	0.95	4.8
1962–2000	M_W^*	(5.5–7)	1.55	2.2	0.95	5.4
1923–2000	M_W^*	(5.5–7)	3.50	3.5	1.00	3.3
1900–2000	M_W^*	–	–	**10(1)**	–	–
1737–2000	M_W^*	–	–	**11.8(3)**	–	–

Note: M_{W1}–M_{W2}, range of magnitudes used for estimating n_6 and b; n_6, yearly average number of $M_W \geq 6$ events obtained by a linear approximation; $n_9 \times 10^3$, extrapolated or actual (boldfaced) yearly average number of $M_W \geq 9$ events (the number of events used for obtaining an actual estimate is shown in parentheses); b, estimated slope of the recurrence plot; C, ratio of the actual estimate of n_9 over 1737–2000 to the extrapolated value shown in the same row.
* Moment magnitude estimated partially or mainly by an indirect method.

magnitudes, rather than estimates based on correlation formulas. The pertinent results are shown in Fig. 1f.

Analysis of the results given in Table 4 indicates that the recurrence of moderate shocks in 1962–2000 varies within limited bounds and can be regarded as approximately constant. The related weighted average of n_6 is also presented in Table 4. For extrapolation purposes, it can be combined with the value $b = 0.95$, obtained from the Harvard catalog. Other estimates of b yield even smaller extrapolated values of n_9.

The estimate of n_6 for the period 1923–November 3, 1952, appears to be less reliable. However, a more than twofold divergence from the yearly recurrence of 1962–2000, observable at both $M = 6$ and 7, seems to be quite real. The even higher estimate of n_6 for November 4, 1952, through 1961 raises no doubts: it is evidently associated with the intense aftershock process in the source zone of the November 4, 1952, earthquake. We also derived a weighted average estimate of n_6 for the period 1923–2000 (Table 4). For extrapolation purposes, it can be combined with the value $b = 1.00$, close to the weighted average over these years.

Now, we can compare the actual data on strong shocks (Table 3) with the predicted values obtained in terms of the hypothesis on the recurrence plot linearity (the Gutenberg–Richter law). The actual recurrence of events of various magnitudes in the periods 1901–2000 (100 years, $M_W \geq 7.5$) and 1737–2000 (264 years, $M_W \geq 8.5$) is plotted in Fig. 2. The lower thresholds are chosen in such a way that the catalog can be regarded, to an extent, as complete for a given threshold. Comparison of the actual data with the extrapolated values for moderate events of 1923–November 3, 1952, or 1962–2000 shows that the extrapolation systematically underestimates the real recurrence rate of strong events. This is reflected in the numerical values of the last column of Table 4, which shows the factor by which the observed 264-year recurrence n_9 exceeds the n_9 value linearly extrapolated from various datasets. The underestimation reaches a factor of 5 for the most reliable data, recorded after 1962. Note that any attempt at accounting for possible gaps in the data on strong earthquakes of 1737–1899 will only reinforce our inferences on the underestimation effect of linear extrapolation.

DISCUSSION

We believe that Fig. 2 reflects, at a qualitative level, the real structure of the dependence $N(M_W)$ in the island arc segment: a nearly linear trend at moderate magnitudes and an upward deflection as magnitudes tend toward ultimately high values. Similar effects heave been repeatedly observed, first in the North Anatolian fault zone [Båth, 1981] and later in subduction zones, in particular, the Mexican [Singh *et al.*, 1983] and Aleutian [Davidson and Scholz, 1985] zones. The universal nature of this tendency was noted by Wesnousky *et al.* [1984], who related it to the so-called model of a characteristic earthquake. This problem was studied in more detail by Stirling *et al.* [1996]. Thus, we may reject with certainty the idea of automatic application

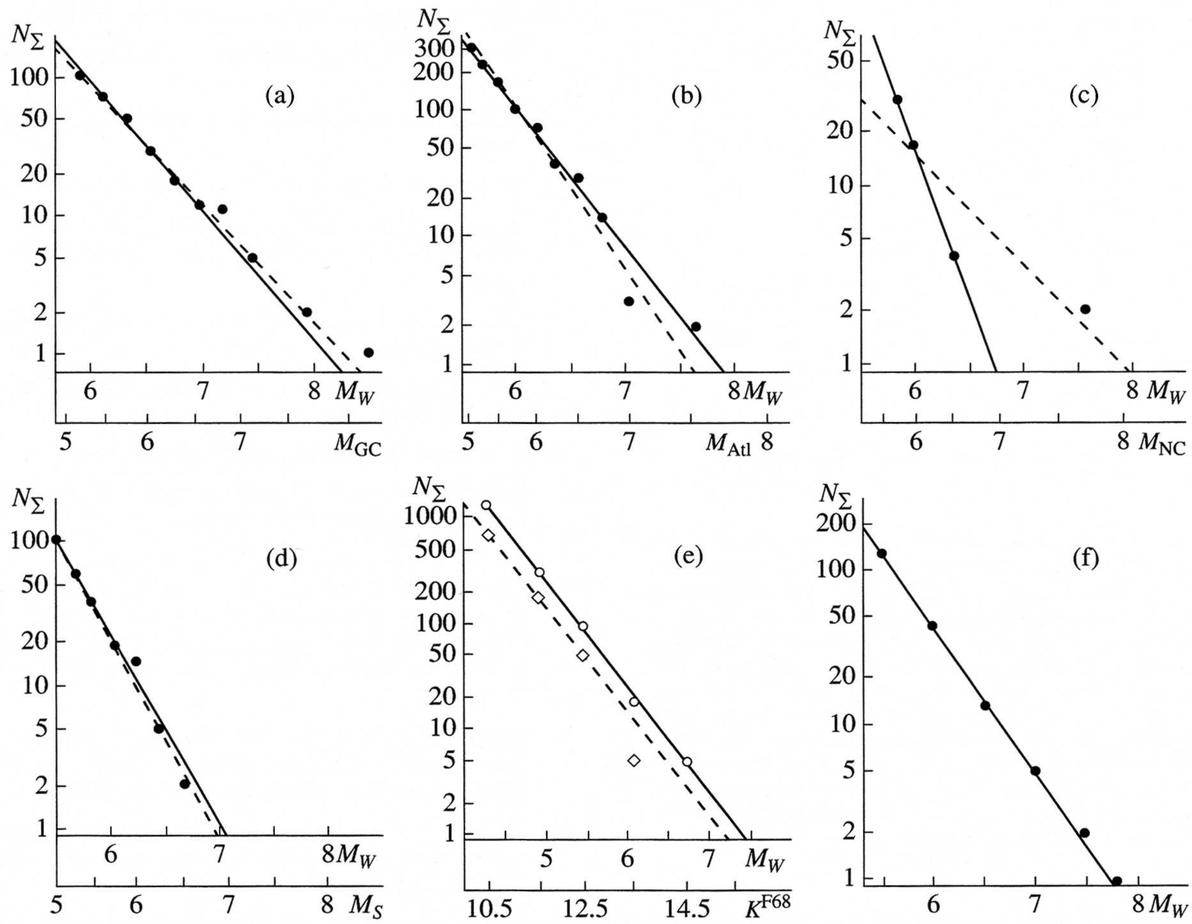

Fig. 1. Cumulative recurrence plots for moment magnitudes (the number of earthquakes $N_\Sigma(M_W)$ of a magnitude $M'_W \geq M_W$) for several periods of the 20th century (plots (a–e) are constructed from other magnitude scales laid off on an additional abscissa axis). (a) 1923–November 3, 1952, magnitude M_{GC} [Vikulin and Kim, 1983a]. The solid and broken lines are approximations in the ranges M_{GC} = 5.5–7.0 and 5.7–8.5, respectively. (b) November 4, 1952 through 1961, magnitude M_{Atl} [Savarensky *et al.*, 1962]. The solid and broken lines are approximations in the ranges M_{Atl} = 5.5–8 and 5.5–7.0, respectively. (c) 1962–1974, magnitude M_{NC} [*New Catalog ...*, 1977]. The solid and broken lines are formal approximations in the ranges M_{NC} = 5.5–7 and 5.5–8.0, respectively. (d) 1973–1988, NEIC US magnitude M_S [*Earthquake ...*, 1973–1988]. The solid and broken lines are approximations in the ranges M_S = 5.5–7 and 5.5–6.5, respectively. (e) 1964–1973, the magnitude parameter is the energy class K^{F68} [*Seismic ...*, 1980]. The circles and the solid line are the numbers of reliably recorded $K^{F68} \geq 11$ events with hypocentral depths H = 0–50 km; the diamonds and the broken line are the same for $K^{F68} \geq 9$ and H = 0–100 km. In both cases, the range K^{F68} = 10.0–13.0 was used. (f) 1976–2000, moment magnitude M_W from the Harvard University catalog [http:\\www.seismology.harvard.edu]. The solid line is the approximation in the range M_W = 5.5–7.

of the Gutenberg–Richter law to recurrence extrapolation from moderate to high magnitudes. Such an extrapolation typically leads to underestimated values (in our case, an underestimation by a factor of 2 to 5 is also fairly typical). However, one may not rule out cases when the Gutenberg–Richter law can be effectively applied.

It is interesting to note that the nonlinearity of the plot $\log N(M_W)$ is only evident on the scale M_W, whereas the superposition of the bends in the curves $\log N(M_W)$ and $M_{LH}(M_W)$ nearly eliminates the nonlinearity of the plot $\log N(M_{LH})$. Thus, if the scale M_{LH} is regarded as a reference scale, the problem in question can be considered as artificial. However, such a view is questionable, considering that the seismological literature reveals an obvious tendency toward using the scale M_W as a reference scale.

The significant fluctuations in the seismicity level discovered in this work are of great interest. The variations in n_6 obtained in our study may well reflect the real behavior of the seismicity level for moderate shocks. The higher recurrence rate in the aftershock period of the 1952 event has long been known, but the more than twofold distinction between the levels of 1923–November 3, 1952, and 1962–1988 has not been noted previously. Fluctuations of such a size can addi-

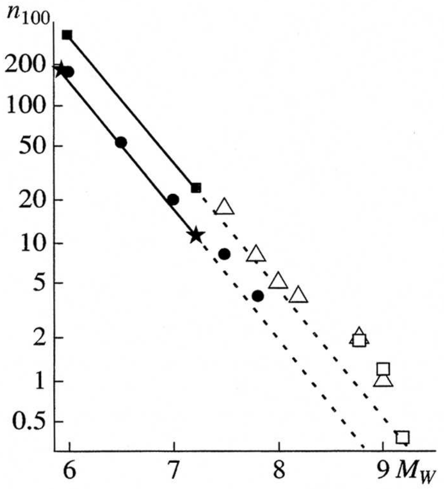

Fig. 2. Summary of cumulative recurrence plots of Kamchatka earthquakes on the scale of moment magnitudes. All plots are reduced to a period of 100 years. The solid squares and their connecting line are estimates from data of 1923–November 4, 1952 (see Table 4); the broken line continuing the solid one is an extrapolation to higher magnitudes. The stars are estimates from data of 1962–2000 (see Table 4). The solid circles are M_W data from the Harvard catalog for 1976–2000. The triangles and open squares are actual data for 1900–2000 and 1737–2000, respectively. The variants of linear extrapolation of data on average magnitudes are seen to underestimate, more or less significantly, the recurrence rates at higher magnitudes.

tionally distort recurrence estimates for the strongest earthquakes obtained from data on the recurrence of moderate shocks.

CONCLUSIONS

(1) A catalog of the strongest earthquakes of Kamchatka is compiled for the first time on the moment magnitude scale. The use of this scale enabled the study of earthquake statistics on a reliable methodological basis.

(2) The recurrence of moderate shocks on Kamchatka in the period 1923–2000 is studied and its temporal variations are discovered.

(3) The actual recurrence of the strongest earthquakes of 1737–2000 was compared with predicted estimates obtained by the application of the hypothesis of recurrence plot linearity to the statistics of moderate shocks of 1923–2000. All of the predicted variants underestimate the recurrence of shocks having ultimate magnitudes. According to the most reliable data of recent years, the inferred values are smaller by a factor of about 5.

REFERENCES

1. K. Abe, J. Geophys. Res. **84** (B4), 1561 (1979).
2. K. Abe, Phys. Earth Planet. Inter. **27**, 72 (1981).
3. K. Abe, Phys. Earth Planet. Inter. **34**, 13 (1984).
4. K. Abe and S. Noguchi, Phys. Earth Planet. Inter. **32**, 45 (1983a).
5. K. Abe and S. Noguchi, Phys. Earth Planet. Inter. **33**, 1 (1983b).
6. M. Båth, Pure Appl. Geophys. **119**, 1063 (1981).
7. *Bulletin of the Seismic Network of the USSR (1952–1961 gg.)* (AN SSSR, Moscow, 1954–1964) [in Russian].
8. *Catalog of Kamchatka Tsunamis* (VNIIGMI MCD, Obninsk, 1987) [in Russian].
9. F. C. Davidson and C. H. Scholz, Bull. Seismol. Soc. Am. **75**, 1349 (1985).
10. S. J. Duda, Tectonophysics **2** (5), 409 (1965).
11. A. M. Dziewonski, T. -A. Chou, and J. H. Woodhouse, J. Geophys. Res. **86**, 2825 (1981).
12. A. M. Dziewonski and J. H. Woodhouse, in *Earthquakes: Observation, Theory, and Interpretation: Notes from the International School of Physics "Enrico Fermi" (1982: Varenna, Italy)*, Ed. by H. Kanamori and E. Boschi (North-Holland, Amsterdam, 1983), pp. 45–137.
13. *Earthquake Data Report* (US National Earthquake Information Service. US Dept. of Commerce Washington Science Center, Rockville, 1973–1988).
14. S. A. Fedotov, *Energy Classification of Kurile–Kamchatka Earthquakes and the Problem of Magnitudes* (Nauka, Moscow, 1972) [in Russian].
15. A. A. Gusev and V. N. Melnikova, Vulkanol. Seismol., No. 6, 55 (1990).
16. B. Gutenberg and C.F. Richter, *Seismicity of the Earth and Associated Phenomena*, 2nd ed. (Univ. Press, Princeton, 1954).
17. T. C. Hanks and H. Kanamori, J. Geophys. Res. **84**, 2348 (1979).
18. F. A. Kirillov, *Catalog of Earthquakes in the Kurile–Kamchatka Zone* (IFZ AN SSSR, Moscow, 1962) [in Russian].
19. N. V. Kondorskaya and V. I. Ulomov, Eds., *Catalog of Earthquakes of North Eurasia* (IFZ RAN, Moscow, 2000) [in Russian].
20. *New Catalog of Strong Earthquakes in the USSR from Ancient Times through 1975* (Nauka, Moscow, 1977) [in Russian].
21. E. Okal, Pure Appl. Geophys. **136**, 17 (1992a).
22. E. Okal, Pure Appl. Geophys. **136**, 59 (1992b).
23. G. Purcaru and H. Berckhemer, Tectonophysics **84**, 57 (1982).
24. J. P. Rothe, *The Seismicity of the Earth, 1953–1965 (*UNESCO, 1969).
25. E. F. Savarensky *et al.*, Eds., *Atlas of Earthquakes in the USSR* (AN SSSR, Moscow, 1962) [in Russian].
26. *Seismic Regionalization of the USSR: Basic Methods and Regional Description of the Map of 1978* (Nauka, Moscow, 1980) [in Russian].

27. *Seismological Bulletin of the USSR Seismic Network* (AN SSSR, Moscow, 1962–1963) [in Russian].

28. *Seismological Bulletin of the USSR Network of Reference Seismic Stations* (AN SSSR, Moscow, 1965–1977) [in Russian].

29. S. K. Singh, M. Rodriquez, and L. Esteva, Bull. Seismol. Soc. Am. **73** (6), 1779 (1983).

30. M. W. Stirling, S. G. Wesnousky, and K. Shimazaki, Geophys. J. Int. **124**, 833 (1996).

31. A. V. Vikulin and Ch. U. Kim, *Kurile–Kamchatka Earthquakes: Observations of 1911–1952. Materials of the World Data Center B* (MGK AN SSSR, Moscow, 1983a) [in Russian].

32. A. V. Vikulin, and Ch. U. Kim, *Kurile–Kamchatka Earthquakes: Observations of 1953–1961. Materials of the World Data Center B* (MGK AN SSSR, Moscow, 1983b) [in Russian].

33. S. G. Wesnousky, C. H. Sholz, K. Shimazaki, and T. Matsuda, Bull. Seismol. Soc. Am. **74** (2) 687 (1984).

34. V. M. Zobin, S. A. Fedotov, E. I. Gordeev, *et al.*, Vulkanol. Seismol., No. 1, 3 (1988).