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PROGRESS OF EARTHQUAKE PREDICTION IN KAMCHATKA

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ABSTRACT

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The results of studying earthquakes prediction in Kamchatka by seismological methods, obtained during 1969–1971, are described.

(1) Long-term (1965–1970) seismic prediction for the Kurile–Kamchatka arc is proved to be accurate. Predictions are given for 1971–1975. (2) While analyzing the catalogue of Kamchatka earthquakes for 1965–1970, seismo-statistical predictors were found for earthquakes with $M \geqslant 5$. These predictors allow one to establish the increased probability of such an earthquake 5–10 days prior to its actual occurrence. (3) A stable decrease of *P*- and *S*-wave frequencies was observed, for earthquakes with M = 3–3.5, previous to earthquakes with $M \geqslant 6$.

INTRODUCTION

Earthquakes prediction studies in Kamchatka started with the work of S.A. Fedotov (Fedotov, 1965), in which the idea of "seismic cycle" was introduced and long-term seismic predictions were compiled for the Kurile–Kamchatka arc (Fedotov, 1968). Then, on the basis of the data of detailed observations by means of which nearly all the earthquakes with $K_{\mathrm{S}\,1.2}^{\mathrm{F}\,68} \geqslant 8.5$ (or $M \geqslant 2.6$) were measured a study was made of the earthquake spectra and seismostatistics in order to make the long-term prediction more precise and to search for earthquake forerunners. With the aim of prediction, observations of the electrotelluric field were carried out by G.A. Sobolev, V.N. Morozov and others, repeated observations of seismic waves at constant shot and receiver points were conducted by V.I. Mjachkin, V.B. Preobrazhensky and others, and precise geodetic levelling was carried out by A.K. Pevnev and others.

Results obtained by 1969 were published (Fedotov et al., 1970). The present paper describes the results of further studies, obtained in the period 1969–1970 during detailed seismic observations.★

★ Results of other works will be published elsewhere.

LONG-TERM SEISMIC PREDICTION*

Early in 1965 long-term predictions were compiled for the Kurile–Kamchatka zone for 1965–1970, 1971–1975 and subsequent years. Methods of its construction was described in detail in a paper by Fedotov (Fedotov, 1968). In 1971 the forecast efficiency was checked and more precise predictions were able to be made for the next 5 years. In Table I the forecast for 1965–1970 is compared with the actual seismicity for 13 areas of the band marked on Fig.1. The distance Δ is shown along the zone axis (see Fig.1). The expected stages of the seismic cycle (I, II, III) are to be interpreted as follows: (a) an aftershock stage of an earthquake with $M \geqslant 7.75$ (about 15 years); (2) stabilization stage; (3) foreshock stage (up to 15–20 years). For the areas where the data are unreliable the cycle stage prediction was given in two versions and/or noted with a question mark. In the $A_{10} \pm \sigma$ column the seismic activity levels and the limits of their standard deviations are given (within the brackets). Seismic activity A_{10} is the number of earthquakes with $\log E$ (Joules) $= K^{F68}_{S1.2} = 10 \mp 0.5$ in the area of 1000 km^2, per year. Placed further are lower limits of maximal magnitudes to be overcome with probabilities $p = 0.8$; $p = 0.5$ and an upper limit of M_{max}. The right part of Table I gives the actual values of A_{10} and the magnitudes of two strongest earthquakes of the area for 1965–1970. In the column Comparison forecast success (+) or failure (–) is marked for reliable cases. The value of seismic activity A_{10} in 6 cases out of 7 appeared to be within the limits which were predicted with the probability of 0.7. The lower limits of maximal magnitudes are overcome for $p = 0.8$ in 6 cases out of 7 and for $p = 0.5$ in 3 cases out of 7. Both earth-

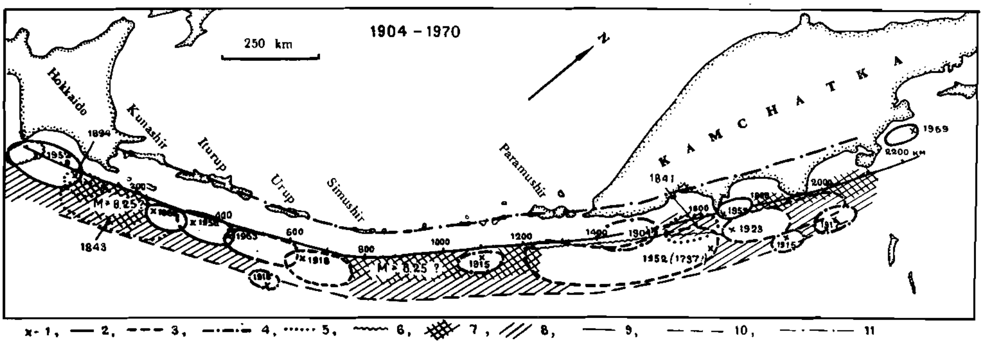

Fig.1. Map of foci of Kurile–Kamchatka earthquakes during 1904–1970 with $M \geqslant 7.75$, $h < 80$ km and probable places of the following earthquakes. *1* = Point epicenters of earthquakes with $M \geqslant 7.75$; *2* = boundaries of the epicentral areas of earthquakes with $M \geqslant 7.75$; *3* = uncertain areas with earthquakes of the same magnitude; *4* = probable epicentral areas of earthquakes in 1904–1918 with $M \geqslant 7.75$; *5* = supposed epicentral areas of the strongest known earthquakes of the nineteenth century; *6* = boundaries of tsunami "sources"; *7* = most probable areas of earthquakes with $M \geqslant 7.75$ to occur after 1971; *8* = less certain areas of the same earthquakes; *9* = the line of outcrop of the Pacific inclined focal plane on the ocean floor; distances along the arc are also shown; *10* = the axis of the deep-sea trench; *11* = the axis of the volcanic belt of the Kurile–Kamchatka arc.

*This investigation was carried out by S.A. Fedotov.

TABLE I

Comparison of the long-term seismic prediction for 1965–1970 for the Kurile–Kamchatka arc with the seismicity observed in reality

Section	Δ (km)	Prediction for 1965–1970					Reality (1965–1970)		Comparison			
		Stage	$A_{10} \pm \sigma$	M ($p \approx 0.8$)	M ($p \approx 0.5$)	M max	A_{10}	M	A_{10} ($p \approx 0.8$)	M ($p \approx 0.8$)	M ($p \approx 0.5$)	M max
1. Lesser Kurile Islands	100–300	III?	1.5–3.5?		6.75?	8.25–8.5	~7.8	8, 7.5				++
2. Iturup	300–450	I	2.3(1.2–4.6)	6–6.25	6.75	7.25	~5.9	7.25, 7	–	+	+	
		I	2.7 → 1.8									
3. Friz strait–Urup	450–600	I	5.3(2.7–10.6)	6.25–6.5	7	7.25	~4.7	7, 6.5	+	+	+	
			15 → 1.3									
4. Urup–Simushir	600–750	I–II	1.5–5.0	6–6.25	6.5–6.75	7.5	~3.5	7, 6.5	+	+	+	
5. Simushir–Kruzenstern strait	750–1000	III?	1.5–3.5?		6.75?	8.25–8.5	~1.6	6, 6				
6. Shiashkotan	1000–1100	II	1.5(0.7–3.0)	6	6.5–6.75	7.5	~0.9	6, 5	+	+	–	
7. Onekotan the Third Kurile strait	1100–1200	III?	1.5–3.5?		6.75?	>7.75	~2.8	6.5, 6.5				
8. Paramushir–Lopatka	1200–1350	II	1.5(0.7–3.0)	6–6.25	6.75	7.5	2.3	5.75, 5	+	–	–	
9. South of Kamchatka	1350–1550	II	1.5(0.7–3.0)	5.75–6	6.5	7.5–7.75	0.9	6, 6	+	+	–	
10. Avachinsky Bay–Shipunsky peninsula	1550–1700	II?	2.0(1–4)	6.25	6.75–7	7.5	2.0	6, 6	+	+	–	
			2.2 → 1.7									
		III?	1.5–3.5?		6.75?	8?						
11. Kronotsky Bay	1700–1850	I–II	1.5(0.7–3.0)	6–6.25	6.5–6.75	7.25–7.5	2.7	6, 5.75	+	+	–	
12. Kronotsky peninsula	1850–1950	II?	1.5(0.7–3.0)	6–6.25	6.5–6.75	7.25–7.5	3.2	6, 5.5				
		III?	1.5–3.5		6.75?	8?						
13. Kamchatsky Bay	1950–2150	III?	1.5–3.5		6.75?	8–8.25	2.8	6.5, 6				

quakes with $M \geqslant 7.5$ occurred in that section where such earthquakes were considered to be possible. The strongest of them (on August 12, 1969 near the Shikotan island (see Fig.1) with $M = 8 \geqslant 7.75$) took place in one of the 6 sections where such earthquakes were considered to be possible, and in one of those three where they were believed to be the most probable. Thus, the prediction for 1965–1970 appeared to be quite successful, and even more precise than had been expected.

The forecast given in 1965 for the next 5-year period can now be improved. As a consequence of the Shikotan earthquake the northern part of area *1* is now at aftershock stage, though the southern part is still dangerous, being the possible place for an earthquake with M up to 8.25 according to the dimensions of the gap in epicenter areas (Fig.1). The most dangerous places are areas = *3*, *7* and *12*. There the seismicity levels, being somewhat higher than the average value for the stabilization stage may indicate the foreshock stage. Other possible places for future large earthquakes are areas *1*, *5* and *10*(?). In the complete version of the forecast probabilities of shocks with intensity $I = 9$ onshore are also given. On the whole, the long-term seismic prediction gives an idea of the probable distribution of both weak and strong shallow earthquakes of 1971–1975 near the coasts of Kamchatka and the Kurile Islands.

SEISMOSTATISTICAL EARTHQUAKE PREDICTORS★

During the search of seismostatistical methods of earthquake prediction the catalogue of small earthquakes of Kamchatka was studied. The quite complete catalogue for the period 1965–1970 includes about 3000 earthquakes of the energetic classes $K_{S1.2}^{F68} \geqslant 8.5$ ($M \geqslant 2.6$ by the correlation function $K_{S1.2}^{F68} = 4.6 + 1.5\,M$). In this work earthquakes with $K \geqslant K_1 = 12.0$ ($M \geqslant 5$) were assumed to be large. Such a choice was caused by the necessity of obtaining sufficient material for statistical conclusions. Earthquakes within a radius of 100 km that occurred within a month after the event, with $K \geqslant K_1$, were considered to be aftershocks and were excluded.

As initial information catalogue data were used for the time and energy of earthquakes. The limits of the region under consideration are 50°–58°N and 155°–165°E. The data for the analysis were presented as sets of numbers of earthquakes of each energy class for successive five-day intervals. The learning-set consisted of 343 intervals, and the remaining 92 were used as the test set. The average number of events in an interval is about 8.

Let us call the intervals Type I and Type 0. Type I are those which contain large earthquakes, and Type 0 are quiet. In the learning set there are 43 intervals of Type I, while in the test set there are 18. After a preliminary analysis three parameters relevant to the prediction were selected, those being: (1) exponent γ of $N(E) \sim E^{\gamma}$ distribution estimated by the maximum probability method for grouped sample; (2) the range d of numbers of earthquakes in three successive intervals; (3) maximal class $\bar{K}$. We shall call the values of the mentioned parameters in the intervals with relative numbers –1 and –2 predictors and use them for prediction of the interval-type 0. We shall denote

★This investigation was carried out by A.A. Gusev.

these six values as:

$$\gamma_{-1}, \gamma_{-2}, d_{-1}, d_{-2}, \bar{K}_{-1}, \bar{K}_{-2}$$

We have estimated the likelyhood ratios λ for each predictor on the basis of the learning material. Fig.2 presents predictor γ_{-1} distribution densities in the intervals preceding the intervals of Type 0 and Type I; their ratio (curve difference) is the probability ratio λ. Rounded-off values of λ's are brought together in a Table II.

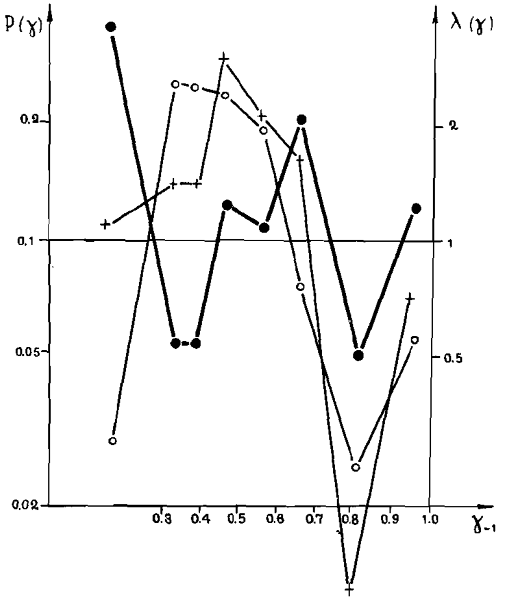

Fig.2. Distributions of the predictor γ_{-1} before the intervals Type I (crosses) and Type 0 (circles) (those containing and not containing large earthquakes, respectively) (scale on left); black circles indicate the probability ratio $\lambda = P(\mathrm{I})/P(0)$ (scale on right). Intervals of averaging are the same as in Table II (column 1).

TABLE II

Values of probability ratios for predictors γ_{-1} and γ_{-2}, d_{-1} and d_{-2}, and $\bar{K}_{-1}$ and $\bar{K}_{-2}$

Predictor value	Probability ratios		Predictor value	Probability ratios		Predictor value	Probability ratios	
$-\gamma$	$\lambda(\gamma_{-1})$		d	$\lambda(d_{-1})$	$\lambda(d_{-2})$	$\bar{K}$	$\lambda(\bar{K}_{-1})$	$\lambda(\bar{K}_{-2})$
−0.3	4	1.5	0–2	0.5	1.0	9–11	1	1
−0.35	0.5	1.5	3–10	1.0	1.0	12	2	2
−0.4	0.5	1.0	11–12	2	2	13	1	1
−0.5	1.0	1.0	>13	1	2			
−0.6	1.0	1.5						
−0.7	2.0	2.0						
−0.8	0.5	0.5						
<0.81	1.0	1.0						

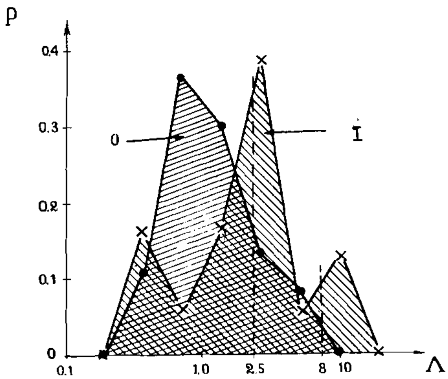

Fig.3. Distributions of the product of probability ratios for intervals containing Type I but not Type 0 large earthquakes, for the test set.

For each interval of the test set we have computed the product Λ of λ values for all 6 predictors. Λ distribution for both types of intervals is given in Fig.3; the separation is obvious. The 0.5% significance level is exceeded for threshold value $\Lambda_t = 2.5$.

Let us introduce an efficiency measure: $I = P(\text{earthquake-forcast})/P_{\text{a priori}}$, which is the ratio of strong-earthquake density in the predicted time-interval to its mean value. In the test set $I = 2.1$ with $\Lambda_t = 2.5$, and $I = 2.9$ with $\Lambda_t = 8$. These hopeful results were obtained during stable seismic activity. The next task was prediction in a non-stationary case.

ON VARIATION OF SMALL EARTHQUAKES SPECTRA BEFORE LARGE EARTHQUAKES*

During a great outbreak of seismic activity in the southern Kurile Islands during 1958–1967 small earthquakes were permanently recorded by a frequency-band seismic station of the "ChISS" type at Gorny, Iturup Island (Fedotov and Boldyrev, 1969). Velocity spectra of vertical component of P and S waves were studied using 5 octave filters covering the frequency range of 0.8–30 c.p.s. For ten years the spectra of more than 2000 earthquakes of classes 10–12 ($M = 3.5$–5.0) were obtained with focal depth of 0–150 km, recorded at the distances of up to 450 km. 13 dimensionless spectral parameters were computed for each earthquake, namely logarithms of ratios of P and S amplitudes at adjacent frequency bands and ratios of P-wave amplitude to S-wave amplitude in the same channel.

It was found that in volumes containing large ($M \geqslant 6$) earthquakes these parameters vary in time. Variations of parameters for a 2-year period are presented on the plot in Fig.4. At three activisation periods average values of parameters were stable, and for quiet periods an obvious trend was observed, namely, a relative decrease of higher frequency amplitude for both P and S waves and of P-wave amplitude in relation to that of S. Average spectra of P and S waves and their ratio can be seen on Fig.5, both before and just after

*This investigation was carried out by S.A. Boldyrev.

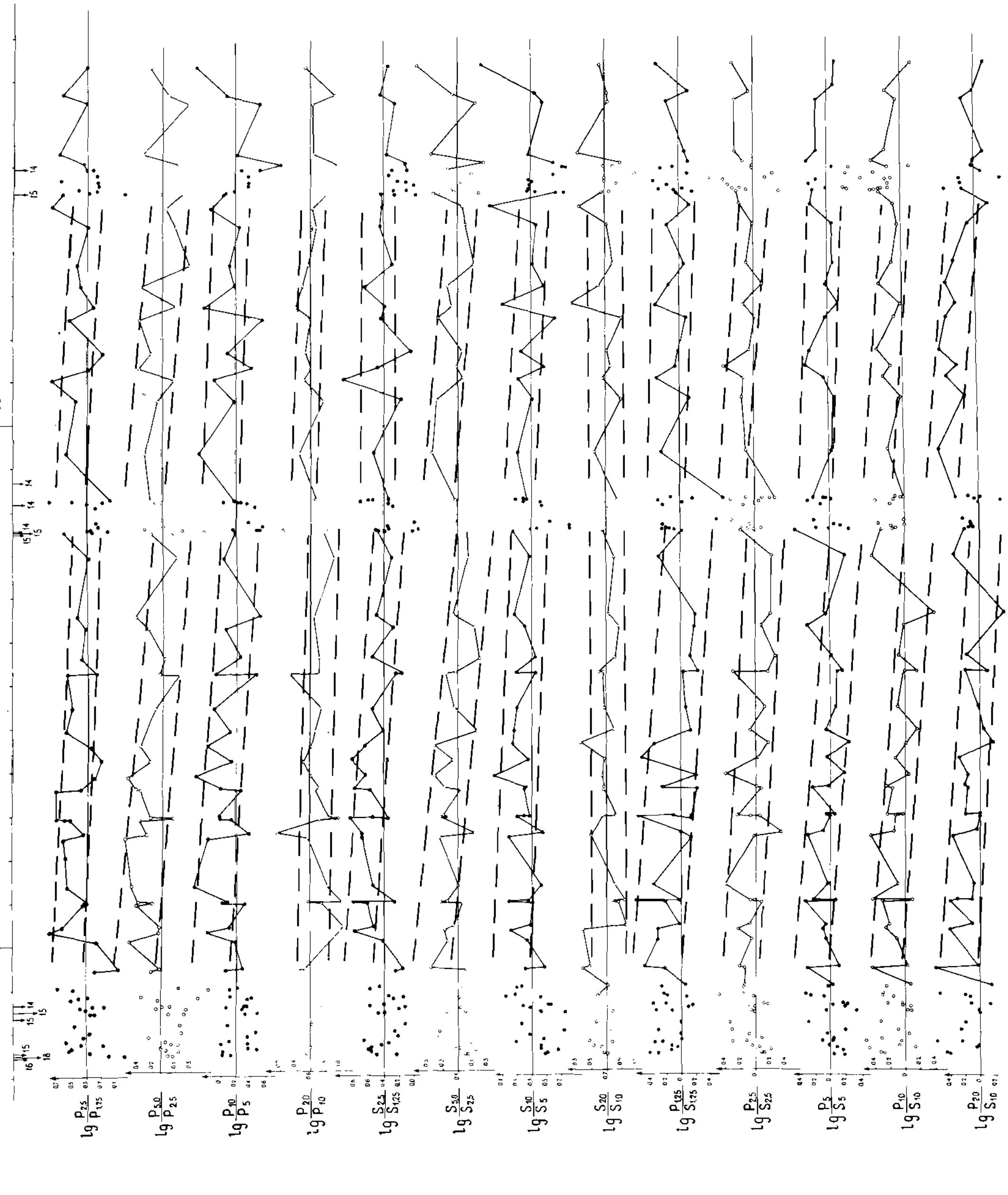

Fig.4. Variation of spectral parameters of earthquakes of the energy class $K = 10$ with time. Letters P and S denote the amplitudes of these waves in the band of central frequency marked in the subscript.

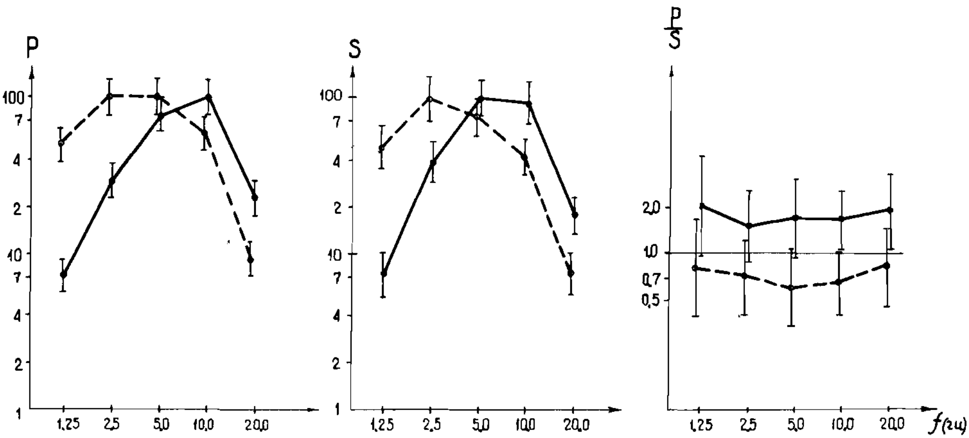

Fig.5. Averaged values of standardised spectra of P and S waves of the earthquakes, K = 10 (M = 3.5) before a large earthquake (dotted line) and directly after the aftershock series (continuous line).

an activization period. The shift of spectral maximums to lower frequencies and a relative decrease of P-wave amplitude are obvious. Measured variations of spectral parameters have been qualitatively confirmed in other regions.

CONCLUSION

During detailed seismological observations in 1968–1971 in Kamchatka further progress was made in the studies of earthquakes prediction. If work continues successfully it may be possible to make attempts to predict the place and time of Kamchatka earthquakes of $M \geqslant 6$ with an accuracy of about 10 days.

REFERENCES

Fedotov, S.A., 1965. On regularities in distribution of strong earthquakes of Kamchatka, Kurile islands and northeastern Japan. *Tr. Inst. Phys. Zemli Akad. Nauk S.S.S.R.*, 36(203): 66–93.

Fedotov, S.A., 1968. On seismic cycle, possibility of quantitative seismic regionalization and long-term seismic prediction. In: *Seismicheskoje Rajonirovanie S.S.S.R.* Nauka, Moscow, pp.121–150.

Fedotov, S.A. and Boldyrev, S.A., 1969. On frequency dependence of body wave attenuation in the crust and the upper mantle of the Kurile island arc. *Izv. Akad. Nauk S.S.S.R. Phys. Zemli*, N9: 17–33.

Fedotov, S.A., Dolbilkina, N.A., Morozov, V.N., Myachkin, V.I., Preobrazhensky, V.B. and Sobolev, G.A., 1970. Investigation on earthquake prediction in Kamchatka. *Tectonophysics*, 9: 249–258.