

# On Applicability of the RTL Prognostic Algorithms and Energy Estimation to Sakhalin Seismicity

G. A. Sobolev

*Institute of Physics of the Earth, Russian Academy of Sciences,  
Bol'shaya Gruzinskaya ul. 10, Moscow, 123995 Russia*

Received August 21, 2006

**Abstract**—Premonitory phases (seismic quiescence and foreshock activity) have been retrospectively identified before the Neftegorsk and Ulegorsk earthquakes using the RTL technique. The probabilities that these phases were accidental are less than 1 and 2%, respectively. This allows an optimistic assessment of the possibility of applying this technique to seismicity at Sakhalin. The estimates of the time and energy class for the two earthquakes, using a model of self-organized seismic criticality, proved to be unconvincing because obvious acceleration of the seismic process prior to these seismic events did not occur. The applicability of this approach to the seismicity at Sakhalin should be tested for future large earthquakes. The regional Sakhalin catalog for 1980–2000, with a lowest completely reported energy class of  $K = 8$  (lent by the Geophysical Service, Russian Academy of Sciences) was used as the database for this study.

**DOI:** 10.1134/S0742046307030050

## INTRODUCTION

Intermediate-term prediction techniques, which make it possible to estimate the time at which a future earthquake will occur within a range of several years as well as its location to within 50–100 km, can be of practical significance for planning earthquake-prevention measures to be taken before the event. The most popular techniques of this sort are based on an analysis of low-magnitude seismicity with the identification of seismic quiescence anomalies, seismic increases, changes in the  $b$ -value, and other characteristics of seismicity, including a simultaneous analysis of several parameters [1, 2, 7, 8, 14, 15, 19].

One algorithm that has been tested is the RTL technique [9–11, 16]. Physical justification for this algorithm has been found in the results of laboratory experiments which demonstrated successive phases of seismic quiescence and foreshock activity [13]. We will describe the most important properties of this algorithm. The prediction parameter is the product of three functions:  $RTL = R \times T \times L$ , where

$$\begin{aligned} R(x, y, z, t) &= \left[ \sum_i \exp\left(-\frac{r_i}{r_0}\right) \right] - R_s, \\ T(x, y, z, t) &= \left[ \sum_i \exp\left(-\frac{t_i}{t_0}\right) \right] - T_s, \end{aligned} \quad (1)$$

$$T(x, y, z, t) = \left[ \sum_i \exp\left(-\frac{l_i}{l_0}\right) \right] - L_s.$$

Here,  $x, y, z$ , and  $t$  are the coordinates and time of a large earthquake under consideration;  $r_i$  and  $t_i$  are the epicentral distance and origin time of a current earthquake of energy class  $K$  relative to the epicenter and time of the large earthquake;  $l_i$  is the source dimension of the current earthquake,  $r_0$  is a coefficient that characterizes the influence function of the current earthquake depending on its distance from the large earthquake epicenter;  $t_0$  is a coefficient that characterizes the influence function of the current earthquake depending on its difference from the time of the large earthquake;  $p$  is a coefficient that takes on the values 1, 2, or 3, thus characterizing the dependence of  $L$  on the first, second, or third power of the source dimension; and  $R_s, T_s$ , and  $L_s$  are linear trends. The source dimension (rupture length) is calculated from the empirical relationships connecting it to energy class or magnitude. When working with Russian catalogs, we used the formula [4]:

$$\log l_i = 0.244 \log K_i - 2.266. \quad (2)$$

One of the advantages of the RTL algorithm for detecting the anomalies of seismic quiescence and foreshock activity is its high sensitivity to long-term background variations. Decrease of the RTL values from the long-term zero background level corresponds to a stage of seismic quiescence, while a subsequent recovery

toward the zero level characterizes the foreshock phase. Previously, the RTL algorithm was mainly used to search for premonitory seismicity anomalies in Kamchatka as well as in episodic studies in Kazakhstan, Japan, China, Greece, USA, and several other seismic regions for which representative earthquake catalogs covering long spans of time are available.

The energy of a future large earthquake is estimated by the RTL algorithm based on the assumption [18] that the seismic process acceleration prior to a future large earthquake is described by the power law equation

$$Q(t) = A - B(t_f - t_i)^m \quad (3)$$

where  $Q(t)$  is the Benioff strain;  $t_f$  is the time of the large earthquake;  $t_i$  the current time; and  $A$ ,  $B$ , and  $m$  are free parameters. This formula was developed in agreement with the concept of self-organized criticality (SOC). Taking into account seismicity self-similarity on different earthquake energy scales and the technique of group renormalization, we included log periodic components [17] in the equation of type (3):

$$Q(t) = Q(t_i) + Q(t_f) - B(t_f - t_i)^m \times [1 + c \cos(2\pi \log(t_f - t_i)/p - \varphi)] \quad (4)$$

with three more free parameters  $c$ ,  $p$ , and  $\varphi$ . Here,  $Q(t_i)$  is the strain stored by the prediction time, and  $Q(t_f)$  is the strain released during a large earthquake predicted to occur at time  $t_f$ .

Sobolev and Tyupkin [12] found that Eq. (4) can be used to predict the time and energy of impending Kamchatka earthquakes. In this case the value of one of the key free parameters (specifically, the exponent  $m = 0.12$ ) was found from experimental laboratory measurements and a standard Kamchatka earthquake (March 2, 1992, of energy class 14.6). Moreover, it was established that variations in the multiplier in square brackets in Eq. (4) are so close to unity that they have almost no effect on the determination of the time and energy of a future earthquake.

The goal of the present study is to investigate how the RTL techniques and energy estimation of earthquakes can be used to analyze seismicity at Sakhalin.

#### DATA AND TECHNIQUE

Two large earthquakes, commonly referred to as the Neftegorsk and Ulegorsk events, occurred on May 27, 1995, and on August 4, 2000, on Sakhalin. Our analysis of seismicity was based on the regional Sakhalin catalog for 1974–2001, which was lent by the Geophysical Service (GS), Russian Academy of Sciences. The RTL algorithm must use a catalog that contains completely reported events beginning from a certain minimum energy class  $K_{\min}$ . The statistical

procedures for determining  $K_{\min}$  are described in [5]. The estimates are based on histograms showing the energy distribution of earthquakes in the range between  $K_{\min}$  and  $K_{\max}$  which are used to test the hypothesis that the data fit a straight recurrence plot for low magnitudes. The appropriate algorithm has been implemented in a computer program that can determine the reporting of events in moving time windows and for assigned spatial cells. Smirnov [6] tested the statistical estimation algorithm to assess the completeness of reporting for several regional catalogs and determined the algorithm efficiency. It was found that aftershock sequences are responsible for considerable local increases in the lowest class of complete reporting. These increases are superposed on the background level to produce a “break” in the recurrence plot, which is interpreted by the algorithm as the lowest class of complete reporting. Therefore, when the lowest class of complete reporting was assessed, aftershocks were eliminated from the catalog by the algorithm described in [3]. The principle underlying the identification of aftershocks from other events, usually called background seismicity, is based on comparison of their distribution functions in space and time. In the regional Sakhalin catalog, the lowest class of complete reporting was never lower than  $K \geq 8.0$  during the period 1974–1995. However, it was found that no decimals were present in the pre-1980 catalog for earthquakes with  $K < 9.0$ . Since the RTL algorithm is sensitive to such a change in parameters, the results to be described below are based on an analysis of the 1980–2001 catalog.

#### THE RTL VARIATIONS PRIOR TO THE NEFTEGORSK AND UGLEGORSK EARTHQUAKES

Plot 1 in Fig. 1 shows the variations in the RTL parameter at the center of the Neftegorsk aftershock area (52.85°N, 142.9°E). We used seismic events around this point that satisfied the following criteria:  $K_{\min} \geq 8.0$ , depth of focus  $H \leq 80$  km, epicentral distance  $r_i \leq R_{\max} = 2r_0 = 400$  km, and a time window of  $(t - t_i) \leq T = 2t_0 = 2$  years. The plot demonstrates the phases of seismic quiescence and subsequent aftershock activity. Quiescence (a plot decrease as interpreted by the RTL method) started in September 1994, and the lowest values of amplitude (14.1 units) were reached in December 1994. The functions  $R$ ,  $T$ , and  $L$  were equal to  $-0.4$ ,  $-2.45$ , and  $-2.4\sigma$  during that period. Plot 2 in Fig. 1 shows the variation in the number of the events used to calculate plot 1 in a moving window of  $T = 2$  years at intervals of 10 days.

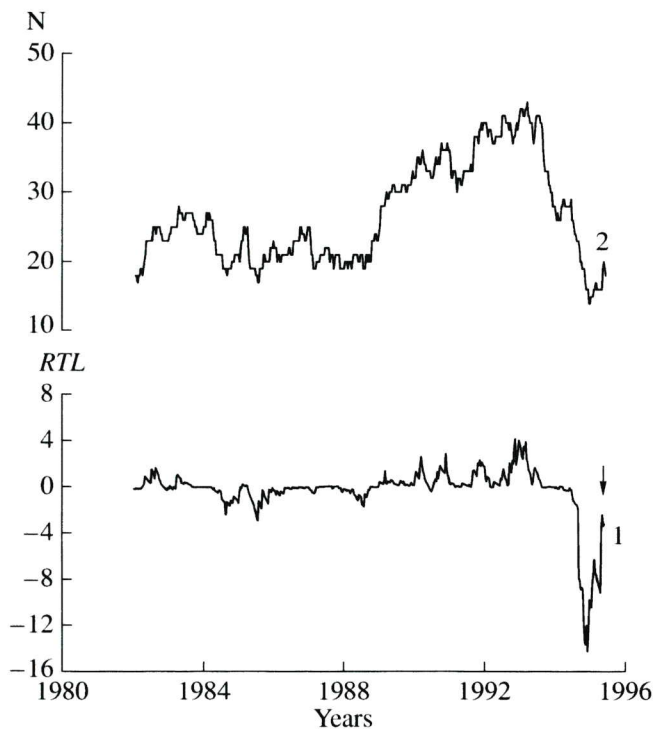


**Fig. 1.** The RTL prognostic parameter (1) and number of earthquakes  $N$  (2) before the Neftegorsk earthquake, the occurrence time of which is marked by an arrow. Calculation parameters:  $K_{\min} \geq 8.0$ ,  $r_i \leq R_{\max} = 2r_0 = 400$  km,  $(t - t_i) \leq T = 2t_0 = 2$  years.

We tested the RTL anomaly for stability by varying  $K_{\min}$  and the free parameters  $r_0$  and  $t_0$ . An increase in  $K_{\min}$  to 8.5 (plot 1, Fig. 2) or a decrease in  $R_{\max}$  to 200 km (plot 2) somewhat reduced the anomaly amplitude, because fewer events were involved in the calculations: 113 and 130, respectively, as against the number of events (283) used to calculate plot 1 in Fig. 1. An increase in  $R_{\max}$  to 600 km (plot 3) insignificantly affected the anomaly structure and magnitude. Plots 1 and 2 in Fig. 3 show some slight changes due to a decrease in  $T_{\max}$  to 1 year or an increase to 4 years. The result was that the variations in the free parameters within the above ranges confirmed that the successive phases of seismic quiescence and aftershock activity are stable.

We investigated the geographic distribution of the anomalies by constructing a map of the lowest RTL values on the  $15 \times 15$  km grid for the time interval May 26, 1994–May 26, 1995 (i.e., for the last year before the Neftegorsk earthquake) with the same parameter values as were used in Fig. 1. It was found (Fig. 4) that the anomalous quiescent area was about 100 km across, with the lowest values (the center of the 1994 anomaly) being displaced northwestward

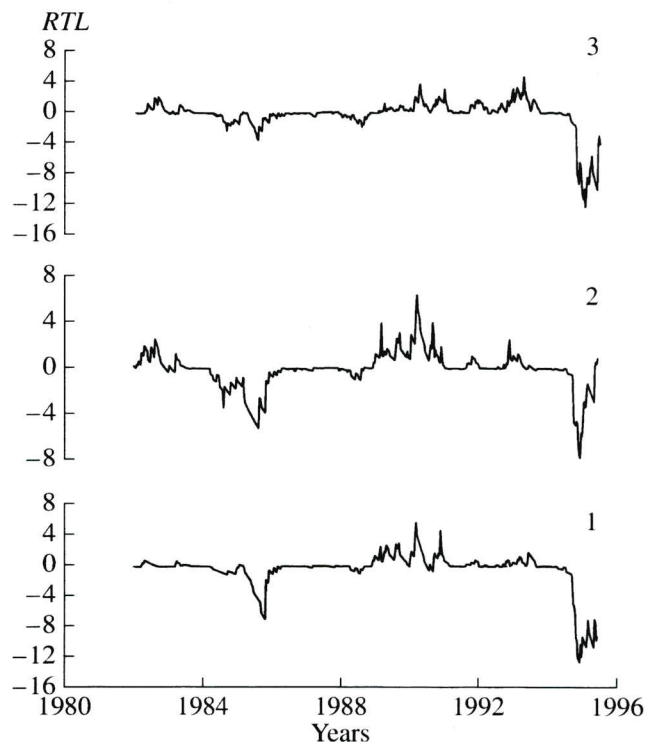


**Fig. 2.** The RTL prognostic parameter before the Neftegorsk earthquake. The calculation parameters: (1)  $K_{\min} \geq 8.5$ ,  $r_i \leq R_{\max} = 2r_0 = 400$  km,  $(t - t_i) \leq T = 2t_0 = 2$  years; (2)  $K_{\min} \geq 8.0$ ,  $r_i \leq R_{\max} = 2r_0 = 200$  km,  $(t - t_i) \leq T = 2t_0 = 2$  years; (3)  $K_{\min} \geq 8.0$ ,  $r_i \leq R_{\max} = 2r_0 = 600$  km,  $(t - t_i) \leq T = 2t_0 = 2$  years.

relative to the Neftegorsk earthquake epicenter. However, the determined boundaries of the anomalous zone are uncertain owing to the comparatively low number of events used.

The same analysis procedure was applied to the Uglegorsk earthquake using formula (1). Plot 1 in Fig. 5 shows the RTL variations at the mainshock epicenter ( $48.80^\circ$  N,  $142.30^\circ$  E) with the following parameter values:  $K_{\min} \geq 8.0$ , hypocenter depth  $H \leq 80$  km, epicentral distance  $r_i \leq R_{\max} = 2r_0 = 400$  km, and a time window of  $(t - t_i) \leq T = 2t_0 = 2$  years. Seismic quiescence started in May 1999 and the lowest RTL values were recorded in November. The anomaly amplitude was  $-10.2$  units, and  $R$ ,  $T$ , and  $L$  were equal to  $-1.9$ ,  $-2.5$ , and  $-2.1$  of the rms deviations from the long-term background, respectively. Plot 2 shows how the number of earthquakes (231 events for the time interval January 1, 1980–August 3, 2000) varied in a moving window of  $T_{\max} = 2$  years. Two more anomalies are shown in Fig. 1. The earlier anomaly is apparently related to the catalog changes mentioned above, while the later anomaly (in 1995) reflects the seismicity variations following the Neftegorsk earthquake.

The pre-Neftegorsk anomaly was examined for stability by calculating the RTL with varied input parameters. An increase in  $K_{\min}$  to 8.5 (plot 1 in Fig. 6) or a decrease in  $R_{\max}$  to 200 km (plot 2) somewhat reduced the anomaly amplitude, because fewer events were taken into account (128 and 108, respectively, as compared to 231 events used to calculate plot 1 in Fig. 5). Increasing  $R_{\max}$  to 600 km (plot 3) resulted in the growth of anomalous values in 1999. The anomaly was also clearly defined at time windows of  $T_{\max} = 1$  or 4 years (see Fig. 7, plots 1 and 2).

The map of anomalously low RTL values (seismic quiescence) for the time interval August 3, 1999–August 3, 2000 (the last year before the Uglegorsk earthquake) suggests that, in 1999, the anomalous zone was about 200 km across and the area of the lowest values was situated southwest of the mainshock epicenter (Fig. 8).

**Assessing the significance of the anomalies identified.** Statistical significance was assessed by generating many random catalogs with the same parameters as in the actual Sakhalin catalog and by counting the number of cases where the random catalog gives an anomaly of the same significance as the observed anomaly.

For the case of the Neftegorsk earthquake, we determined the characteristics of the actual Sakhalin catalog for the period from January 1, 1980 to May 26, 1995, in an area of  $49.30^{\circ}$ – $55.23^{\circ}$  latitude and  $140.17^{\circ}$ – $145.00^{\circ}$  longitude with hypocenter depths of  $H \leq 80$  km. We found 210 events of energy class 8–11.7. The annual average number of events was  $N_0 = 13$  at an rms deviation of  $D = 5$ . These data were used to compute the experimental probability  $P$  for the occurrence of earthquakes given in Table 1:

$$P = n(K_i)/N, \quad (5)$$

where  $n(K_i)$  is the number of events of different energy classes, and  $N$  is the total number of events.

The subsequent procedure included three steps: (a) generation of random catalogs for the area indicated above; (b) counting the annual number of events in the range  $[N_0 - D, N_0 + D]$ ; and (c), randomizing the earthquakes of different energy classes over time and coordinates with the same probability of occurrence as in the actual catalog according to Table 1. The time, latitude, and longitude of each event were sampled from a uniform distribution on 1 year intervals in the range  $49.30^{\circ}$ – $55.23^{\circ}$  latitude and  $140.17^{\circ}$ – $145.00^{\circ}$  longitude.

Next, we calculated the RTL values from the random catalog at the same point and with the same input parameters as for the actual case shown for the Neftegorsk earthquake in plot 1, Fig. 1. The probability of

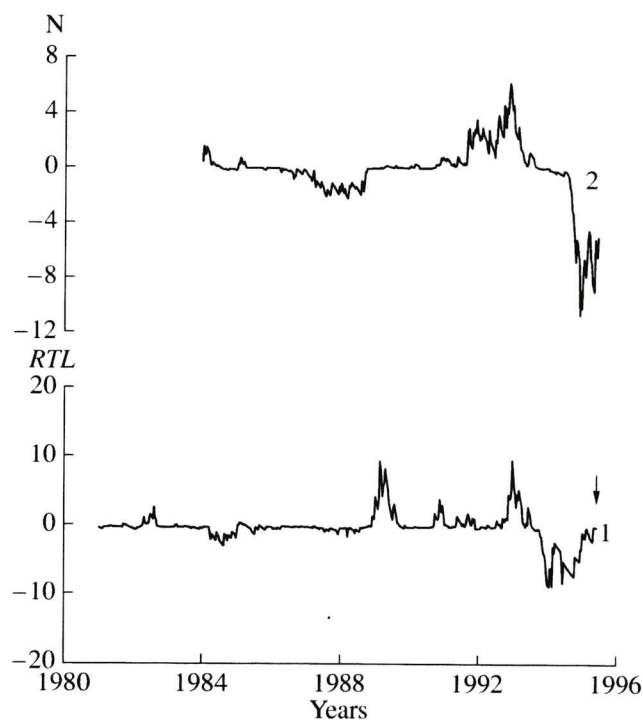


**Fig. 3.** The RTL prognostic parameter before the Neftegorsk earthquake. The calculation parameters: (1)  $K_{\min} \geq 8.0$ ,  $r_i \leq R_{\max} = 2r_0 = 400$  km,  $(t - t_i) \leq T = 2t_0 = 1$  year; (2)  $K_{\min} \geq 8.0$ ,  $r_i \geq R_{\max} = 2r_0 = 400$  km,  $(t - t_i) \leq T = 2t_0 = 4$  years.

identifying an anomaly in a random catalog was found from the following criterion: the amplitude of negative values at the anomaly minimum for different durations (widths) of the anomaly  $W$  had to exceed 10 RTL units, where  $W$  is the time interval during which the RTL values differ from the minimum by less than two standard deviations. We analyzed 4000 random catalogs (see Table 2).

The magnitude of the actual anomaly (Fig. 1, plot 1) was  $-14.1$  units, and its duration was 0.7 years. Thus, based on Table 2, we conclude that the probability of accidental identification of seismic quiescence (in the RTL interpretation) before the Neftegorsk earthquake was less than 1%.

In the case of the Uglegorsk earthquake, we similarly analyzed the catalog for the period from January 1, 1980 to August 3, 2000, in an area with coordinates  $45.50^{\circ}$ – $52.37^{\circ}$  latitude and  $140.17^{\circ}$ – $144.61^{\circ}$  longitude with hypocenter depths of  $H \leq 80$  km. We found 231 events of energy classes 8 to 11.7. The annual average number of events was  $N_0 = 11$  at an rms deviation of  $D = 4$ . Table 3 shows the occurrence probabilities of different-class earthquakes.

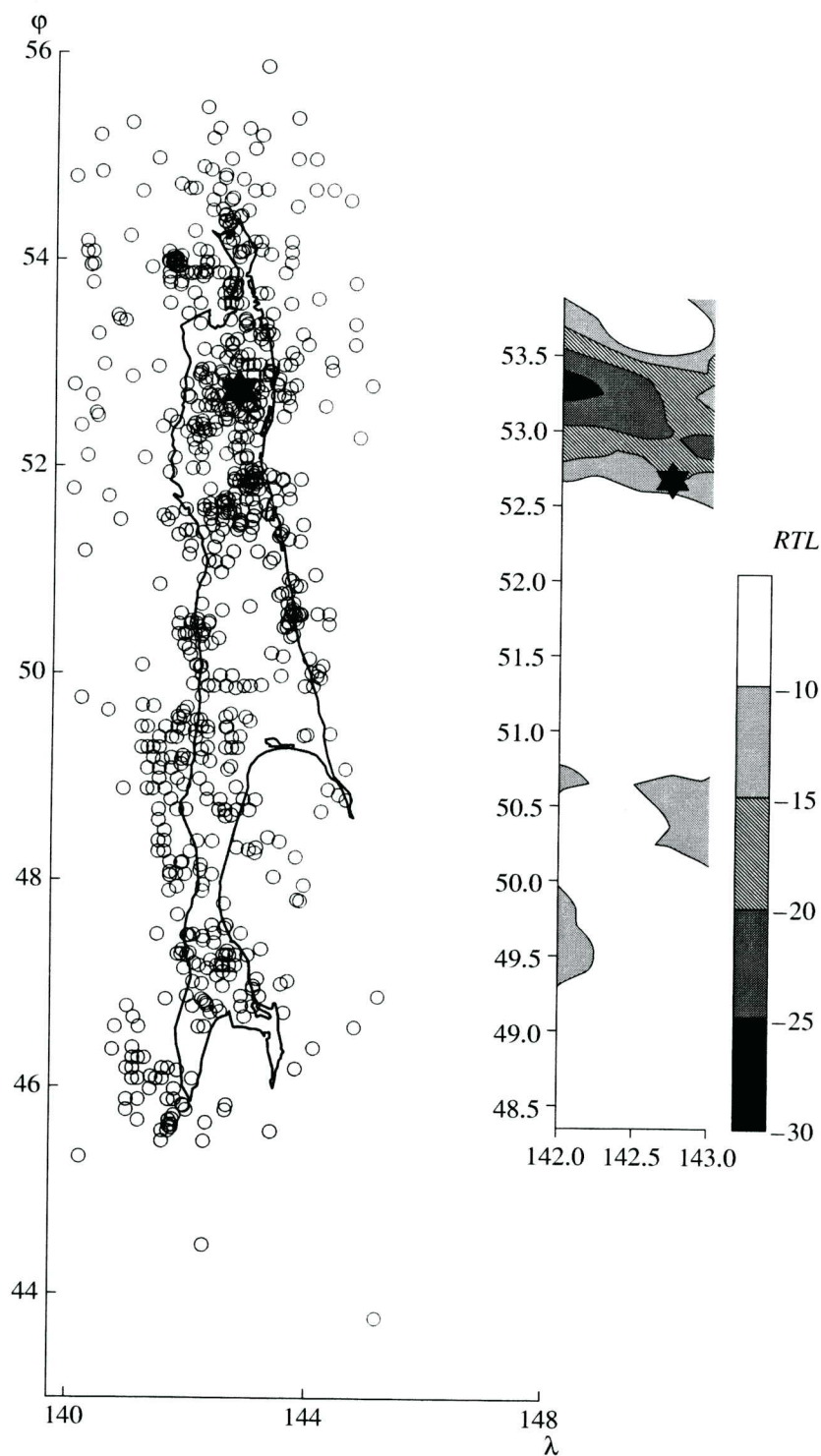


**Fig. 4.** The spatial distribution of the RTL anomaly (dark shading in the columns on the right) before the Neftegorsk earthquake (marked by the asterisk). The earthquake epicenter and seismicity ( $K_{\min} \geq 8.0$ ) are shown on the left.

The probabilities of seismic quiescence originating before the Ulegorsk earthquake, calculated using the above criteria based on 4000 random catalogs, are presented in Table 4.

The actual anomaly (Fig. 5, plot 1) had a magnitude of  $-10.23$  RTL units and lasted 0.5 years. Hence, the probability of accidental occurrence is below 2%.

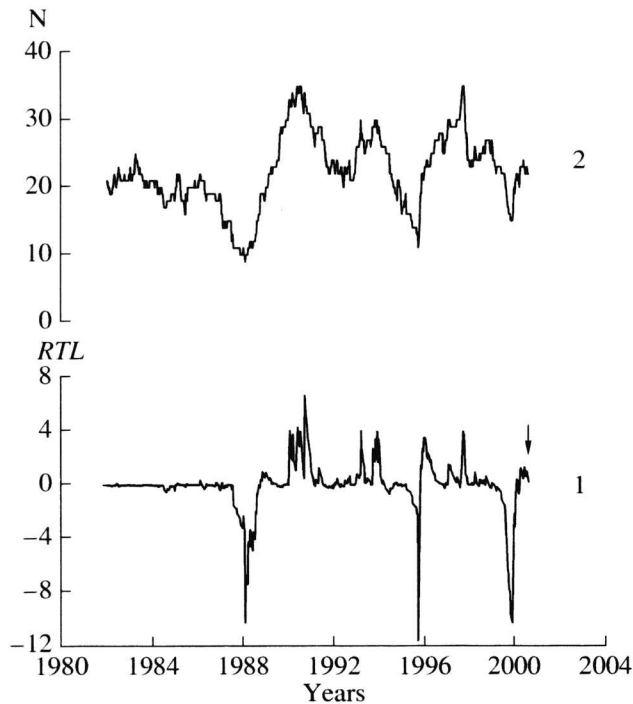


**Fig. 5.** The RTL prognostic parameter (1) and number of earthquakes  $N$  (2) before the Uglegorsk earthquake, the occurrence time of which is marked by an arrow. The calculation parameters:  $K_{\min} \geq 8.0$ ,  $r_i \leq R_{\max} = 2r_0 = 400$  km,  $(t - t_i) \leq T = 2t_0 = 2$  years.

#### MODEL ENERGY ESTIMATION FOR NEFTEGORSK AND UGLEGORSK EARTHQUAKES

The area of observation centered at the epicenter of a future large earthquake should be kept as small as possible for a more accurate determination of the earthquake location, but at the same time a sufficient number of events should be sampled.

The sampling radii in previous calculations for Kamchatka earthquakes [12] were  $R_{\text{eff}} = 1.5l_i$ , where  $l_i$  is the rupture length according to (2). Pilot calculations performed using (4) for the Sakhalin catalog under consideration showed that the shortest radius  $R_{\text{eff}}$  for the area of accelerated seismicity around the Neftegorsk and Uglegorsk earthquake epicenters should be not less than  $3l_i$  because only a few pre-mainshock events correspond to a shorter  $R_{\text{eff}}$ .

For the May 27, 1995 Neftegorsk earthquake (energy class  $K = 15.2$ ) this gives  $R_{\text{eff}} = 3l_i = 83$  km. The beginning of the acceleration (1988) was selected based on the data in plot 2 from Fig. 1. The calculations were carried out using the formula

$$Q = Q_m - B(T_m - t_i)^m, \quad (6)$$

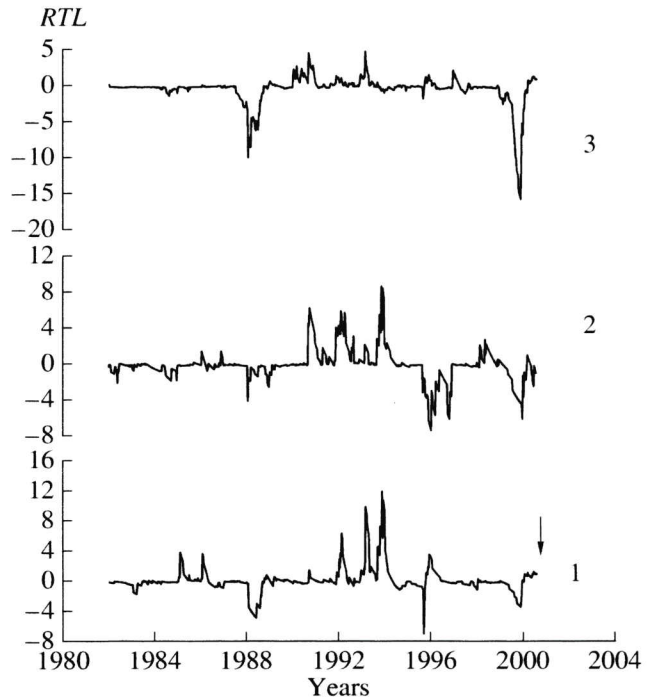


**Fig. 6.** The RTL prognostic parameter before the Uglegorsk earthquake. The calculation parameters: (1)  $K_{\min} \geq 8.5$ ,  $r_i \leq R_{\max} = 2r_0 = 400$  km,  $(t - t_i) \leq T = 2t_0 = 2$  years; (2)  $K_{\min} \geq 8.0$ ,  $r_i \leq R_{\max} = 2r_0 = 200$  km,  $(t - t_i) \leq T = 2t_0 = 2$  years; (3)  $K_{\min} \geq 8.0$ ,  $r_i \leq R_{\max} = 2r_0 = 600$  km,  $(t - t_i) \leq T = 2t_0 = 2$  years.

where  $Q$  is the total strain,  $Q_m$  is the strain found from our model with a future earthquake taken into account,  $T_m$  is the time of a future earthquake,  $t_i$  is the current time of the events covered by  $R_{\text{eff}}$ , while the exponent  $m$  and the constant  $B$  are free parameters. The strain released by a future earthquake is given by the difference between  $Q_m$  and  $Q_i$ , where  $Q_i$  is the strain stored by the instant of prediction (the square root of the energy of events covered by  $R_{\text{eff}}$ , a known quantity). We call Eq. (6) the model of critical seismicity acceleration (CSA model).

Our calculation of the occurrence time and energy class for the Neftegorsk earthquake, carried out using the CSA model, involved 16 events listed in Table 5. The theoretical curve (6) was constructed using values of parameters  $Q_m$ ,  $B$ , and  $m$  such that the sum of the squares of the deviation from the experimental data for the curve was minimal.

The solid line in Fig. 9 shows the prediction curve. This curve yields  $T_m = 1995.39$  as the predicted occurrence time, which differs from the actual time of occurrence by 0.01 years (about 4 days). The stored seismic strain found as the square root of the energy for the earthquakes involved in the calculation (Table 5) is  $Q_i =$

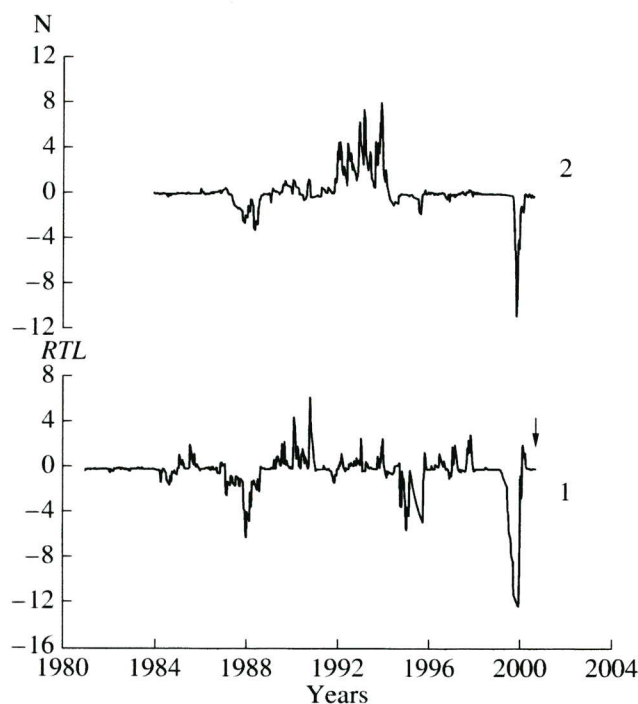


Fig. 7. The RTL prognostic parameter before the Uglegorsk earthquake. The calculation parameters: (1)  $K_{\min} \geq 8.0$ ,  $r_i \leq R_{\max} = 2r_0 = 400$  km,  $(t - t_i) \leq T = 2t_0 = 1$  year; (2)  $K_{\min} \geq 8.0$ ,  $r_i \leq R_{\max} = 2r_0 = 400$  km,  $(t - t_i) \leq T = 2t_0 = 4$  years.

$1.1628 \times 10^{11}$ ; parameters  $B$  and  $m$  were equal to 90 and 0.012, respectively.

The difference between the predicted model strain  $Q_m$  and the strain  $Q(i)$  can be used to find the energy class of a future earthquake from the relationship

$$K_m = \log(Q_m - Q_i)^2 + 11 = 14.9171. \quad (7)$$

This energy class was calculated to be 0.3 units smaller than the energy class  $K = 15.2$  of the Neftegorsk earthquake in the Sakhalin catalog.

It follows from Table 5 that the seismic process slightly accelerated in 1992 when five events of energy class 8.2–9.6 occurred. These events were followed by a 2-year gap, and the last event ( $K = 8.3$ ) before the Neftegorsk earthquake only occurred on October 1, 1994. This data contradicts the hypothesis that seismicity accelerates immediately before a large earthquake. The question arises of what result would be obtained from (6) if the prediction was made for October 1992, immediately after the  $K = 8.7$  event. That case is illustrated by the dashed line in Fig. 9. The predicted time given by the model ( $T_m = 1992.8$  years) is very far from the actual occurrence time, while the predicted energy class  $K_m = 14.9041$  is almost the same as the value predicted in the previous case. Our analysis also indicates that, if prediction calculations were repeated from October 1992 to October 1994, the predicted time

would have been displaced in a regularly shifted manner with an almost constant energy estimate.

For the Uglegorsk earthquake ( $K = 14.0$ ), the sampling radius was 42.4 km. From 1988 to August 4, 2000, only six events (listed in Table 6) occurred in the circle of such a radius centered at the Uglegorsk epicenter. The last event occurred four months before the mainshock. The results of the calculations performed using formula (6) are shown in Fig. 10. The predicted model time is  $T_m = 2000.87$ , which is three months later than the actual occurrence time. The energy estimate is  $K_m = 14.9109$ . The deviation of the theoretical curve (6) from the actual stored strain was minimized by assigning the values 90 and 0.004 to the free parameters  $B$  and  $m$ , respectively.

## DISCUSSION OF RESULTS

We now compare the results of the application of the RTL algorithm to Sakhalin with a typical (standard) earthquake of energy class  $K = 14.6$ , which occurred on Kamchatka ( $52.92^\circ$  N,  $159.83^\circ$  E) on March 2, 1992. Figure 11 shows the variations in the number of events  $N$  and in the RTL parameter for that earthquake. We took into account the events around the epicenter satisfying the following criteria:  $K_{\min} \geq 8.5$ , hypocentral depth  $H \leq 100$  km, epicentral distance  $r_i \leq R_{\max} = 2r_0 = 100$  km, and a time window of  $(t - t_i) \leq T = t_0 = 2$  years. Plot 1 displays the stages of seismic quiescence and subsequent foreshock activity. Quiescence (in the RTL interpretation) began in January 1990, and the lowest value ( $-11.9$  units) was attained in September 1991. Plot 2 in Fig. 11 shows the variations in the number of earthquakes used in calculations performed for plot 1 in a moving window of  $T = 2$  years.

A comparison of Fig. 11 with the results for the Sakhalin earthquakes (plots 1 in Figs. 1 and 5) indicates that the anomalies preceding these large earthquakes were comparable in amplitude. The Kamchatka and Sakhalin anomalies lasted 2 and 1 years, respectively. Sobolev and Tyupkin [9] found that the RTL anomalies for other Kamchatka earthquakes of energy class  $K = 14.6$ – $14.9$  also lasted several years. Another significant difference is that rather low magnitude events in Kamchatka will occur within  $R_{\max} = 100$  km around the epicenter of a future earthquake, while a radius of 400 km must be used for Sakhalin. A consequence of this difference is that the prediction of the location of a future large earthquake from quiescence maps is less accurate for Sakhalin.

We now compare the energy estimation results obtained using the CSA model for the standard March 2, 1992 Kamchatka earthquake (described above) with the results from the Neftegorsk and Uglegorsk earthquakes. The result for the Kamchatka event is shown in

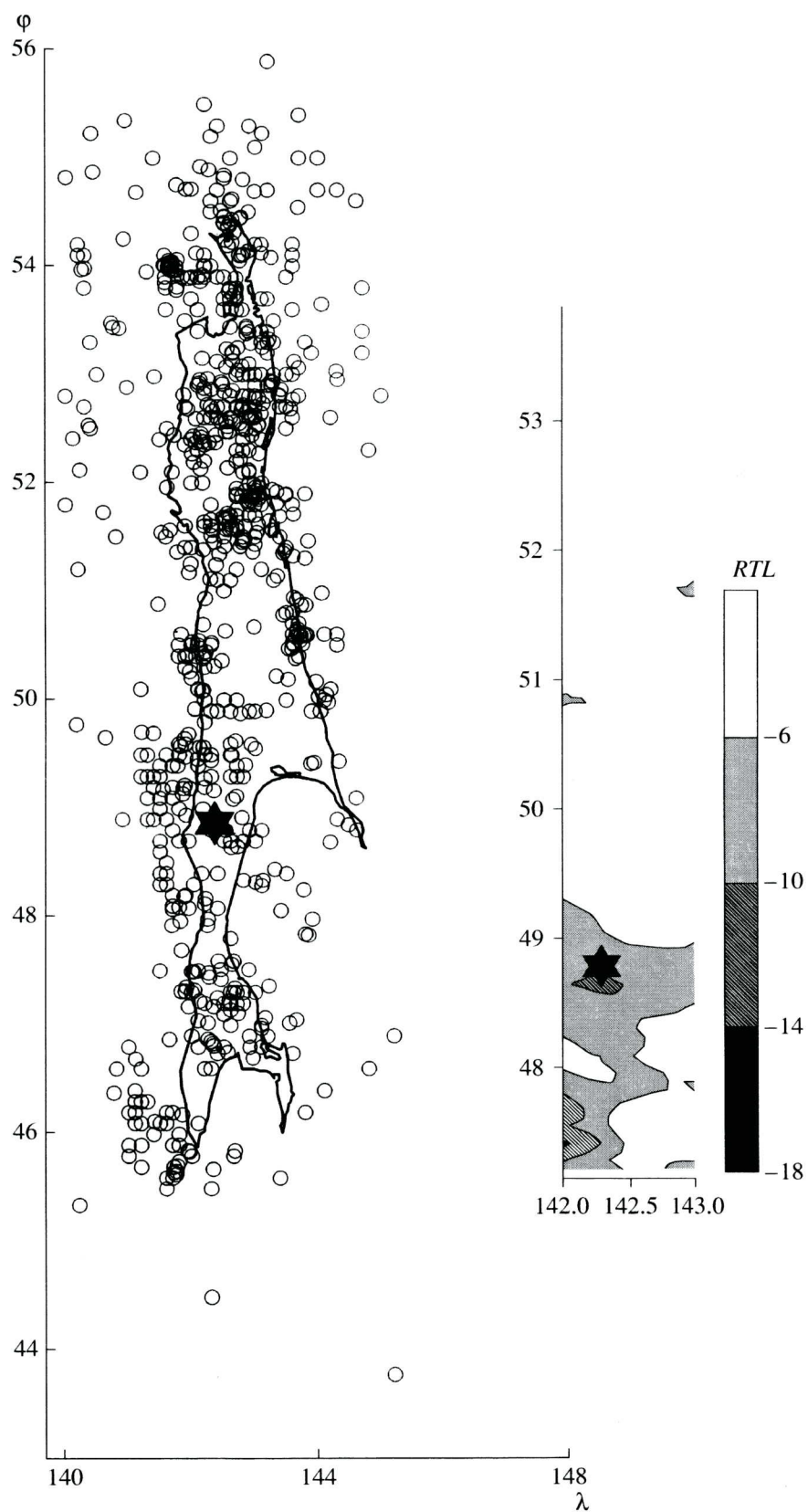


**Fig. 8.** The spatial distribution of the RTL anomaly (dark shading in the columns on the right) before the Ulegorsk earthquake (marked by the asterisk). The earthquake epicenter and seismicity ( $K_{\min} \geq 8.0$ ) are shown on the left.

**Table 1.** Occurrence probability  $P$  of earthquakes of energy classes  $K$  in the region of the Neftegorsk earthquake

| $K$ | $P$    | $K$  | $P$    |
|-----|--------|------|--------|
| 8.0 | 0.1276 | 9.9  | 0.0104 |
| 8.1 | 0.0781 | 10.0 | 0.0130 |
| 8.2 | 0.0755 | 10.1 | 0.0078 |
| 8.3 | 0.0651 | 10.2 | 0.0078 |
| 8.4 | 0.0755 | 10.3 | 0.0026 |
| 8.5 | 0.0703 | 10.4 | 0.0000 |
| 8.6 | 0.0651 | 10.5 | 0.0000 |
| 8.7 | 0.0521 | 10.6 | 0.0026 |
| 8.8 | 0.0365 | 10.7 | 0.0026 |
| 8.9 | 0.0495 | 10.8 | 0.0000 |
| 9.0 | 0.0417 | 10.9 | 0.0026 |
| 9.1 | 0.0391 | 11.0 | 0.0052 |
| 9.2 | 0.0521 | 11.1 | 0.0026 |
| 9.3 | 0.0339 | 11.2 | 0.0000 |
| 9.4 | 0.0208 | 11.3 | 0.0000 |
| 9.5 | 0.0182 | 11.4 | 0.0000 |
| 9.6 | 0.0130 | 11.5 | 0.0000 |
| 9.7 | 0.0156 | 11.6 | 0.0026 |
| 9.8 | 0.0078 | 11.7 | 0.0026 |

**Table 2.** Probability of accidental origination of seismic quiescence before the Neftegorsk earthquake

| $W$ (Years) | $P$      |
|-------------|----------|
| 0.5         | 0.015000 |
| 0.7         | 0.009250 |
| 0.9         | 0.004250 |
| 1.1         | 0.001250 |
| 1.3         | 0.000250 |
| 1.5         | 0.000000 |
| 1.7         | 0.000000 |
| 1.9         | 0.000000 |
| 2.1         | 0.000000 |
| 2.3         | 0.000000 |

Fig. 12. The radius of the sampling circle was  $R_{\text{eff}} = 1.5l_i = 29$  km. The predicted time  $T_m = 1992.3$  differs from the true value by 0.1 years, while the energy class  $K_m = 14.5972$  nearly coincides with the actual value. The free parameters are  $B = 90$  and  $m = 0.13$ .

**Table 3.** Occurrence probability  $P$  of earthquakes of different energy classes  $K$  in the region of the Uglegorsk earthquake

| $K$ | $P$    | $K$  | $P$    |
|-----|--------|------|--------|
| 8.0 | 0.1119 | 9.9  | 0.0163 |
| 8.1 | 0.0956 | 10.0 | 0.0093 |
| 8.2 | 0.0956 | 10.1 | 0.0070 |
| 8.3 | 0.0676 | 10.2 | 0.0070 |
| 8.4 | 0.0723 | 10.3 | 0.0000 |
| 8.5 | 0.0816 | 10.4 | 0.0047 |
| 8.6 | 0.0676 | 10.5 | 0.0047 |
| 8.7 | 0.0536 | 10.6 | 0.0000 |
| 8.8 | 0.0443 | 10.7 | 0.0000 |
| 8.9 | 0.0466 | 10.8 | 0.0000 |
| 9.0 | 0.0536 | 10.9 | 0.0047 |
| 9.1 | 0.0326 | 11.0 | 0.0070 |
| 9.2 | 0.0186 | 11.1 | 0.0023 |
| 9.3 | 0.0163 | 11.2 | 0.0023 |
| 9.4 | 0.0186 | 11.3 | 0.0023 |
| 9.5 | 0.0140 | 11.4 | 0.0000 |
| 9.6 | 0.0117 | 11.5 | 0.0000 |
| 9.7 | 0.0140 | 11.6 | 0.0023 |
| 9.8 | 0.0117 | 11.7 | 0.0023 |

**Table 4.** Probability of accidental origination of seismic quiescence before the Uglegorsk earthquake

| $W$ (Years) | $P$      |
|-------------|----------|
| 0.5         | 0.018250 |
| 0.7         | 0.013250 |
| 0.9         | 0.008500 |
| 1.1         | 0.003750 |
| 1.3         | 0.002000 |
| 1.5         | 0.001000 |
| 1.7         | 0.000250 |
| 1.9         | 0.000000 |
| 2.1         | 0.000000 |
| 2.3         | 0.000000 |

A comparison of Fig. 12 with Figs. 9 and 10 indicates that the number of pre-mainshock events involved in the calculation for the Kamchatka earthquake was 62, and the seismicity acceleration a few months before the main shock was clearly defined, which is not the

**Table 5.** Earthquakes used to calculate the time and energy of the Neftegorsk earthquake with the help of formula (4)

| Year | Month | Day | Hour | Min. | Sec. | N lat | E lon  | Depth | Class |
|------|-------|-----|------|------|------|-------|--------|-------|-------|
| 1988 | 9     | 4   | 2    | 30   | 42   | 52.72 | 142.80 | 0     | 8.7   |
| 1988 | 11    | 26  | 3    | 14   | 8    | 52.66 | 142.33 | 0     | 8.5   |
| 1988 | 11    | 29  | 21   | 32   | 16   | 52.62 | 143.00 | 0     | 8.5   |
| 1989 | 2     | 19  | 4    | 49   | 31   | 52.87 | 142.20 | 7     | 8.3   |
| 1989 | 7     | 19  | 20   | 49   | 40   | 52.92 | 142.12 | 0     | 8.6   |
| 1989 | 12    | 24  | 12   | 22   | 2    | 53.25 | 142.72 | 0     | 8.7   |
| 1990 | 2     | 18  | 3    | 35   | 25   | 52.81 | 143.38 | 0     | 9.0   |
| 1990 | 8     | 11  | 5    | 32   | 23   | 52.68 | 142.78 | 0     | 8.0   |
| 1990 | 11    | 12  | 8    | 48   | 3    | 52.84 | 142.51 | 0     | 8.9   |
| 1991 | 5     | 6   | 21   | 40   | 7    | 53.08 | 142.79 | 8     | 8.4   |
| 1992 | 3     | 25  | 9    | 46   | 58   | 52.65 | 142.86 | 9     | 9.1   |
| 1992 | 6     | 20  | 23   | 0    | 6    | 53.13 | 142.64 | 8     | 8.6   |
| 1992 | 8     | 30  | 8    | 42   | 50   | 52.93 | 143.29 | 7     | 8.2   |
| 1992 | 8     | 30  | 11   | 15   | 22   | 52.90 | 143.26 | 8     | 9.6   |
| 1992 | 10    | 7   | 13   | 0    | 5    | 52.68 | 143.57 | 9     | 8.7   |
| 1994 | 10    | 1   | 23   | 59   | 55   | 52.37 | 142.27 | 15    | 8.3   |

**Table 6.** Earthquakes used to calculate the time and energy for the Uglegorsk earthquake with the help of formula (4)

| Year | Month | Day | Hour | Min. | Sec. | N lat | E lon  | Depth | Class |
|------|-------|-----|------|------|------|-------|--------|-------|-------|
| 1989 | 12    | 26  | 21   | 59   | 23   | 48.70 | 141.95 | 0     | 8.1   |
| 1991 | 12    | 26  | 23   | 43   | 11   | 48.65 | 142.71 | 6     | 8.6   |
| 1996 | 12    | 14  | 11   | 51   | 46   | 49.00 | 142.17 | 0     | 9.8   |
| 1996 | 12    | 27  | 10   | 53   | 16   | 48.64 | 142.61 | 0     | 8.3   |
| 1998 | 1     | 4   | 9    | 38   | 34   | 49.09 | 142.64 | 8     | 8.9   |
| 2000 | 3     | 2   | 19   | 23   | 47   | 48.70 | 142.80 | 10    | 8.6   |

case for the Sakhalin earthquakes. The free parameter  $m$  for the Kamchatka earthquake was an order of magnitude greater than the Sakhalin value. This corresponds to a quicker accumulation of strain, the final value of which before the Kamchatka earthquake,  $Q_i = 50.1083 \times 10^{11}$ , is two orders of magnitude greater than the corresponding values for the Sakhalin earthquakes. In this case we emphasize that the observation period for Kamchatka (from 1988 to March 2, 1992) and the radius  $R_{\text{eff}}$  around the epicenter were smaller than the corresponding quantities for Sakhalin.

Sobolev and Tyupkin [12] examined other Kamchatka earthquakes. Results of comparison between the model results and the actual events carried out by these

authors are given in Table 7. We conclude that the seismological situation in Kamchatka is more favorable for application of the CSA model. This is logically explained by Figs. 13 and 14, which compared the actual data (circles) and linear approximations (dashed line and curve (6)) for the March 2, 1992 Kamchatka and May 27, 1995 Neftegorsk events. For convenience, the curve was calculated before the predicted time in order to exclude large values of (4) at  $(t_f - t_i) = 0$ . A comparison of Figs. 12 and 13 shows that the CSA model should not be used for the Sakhalin earthquake because the accumulated strain of preceding events shows no seismicity acceleration and is close to a

**Table 7.** Comparing results of predicting the time and energy class for Kamchatka earthquakes using formula (4)

| Date of event $T$ | Class $K$ | Model $T_m$ | Model $K_m$ | $T - T_m$ | $K - K_m$ |
|-------------------|-----------|-------------|-------------|-----------|-----------|
| 1971.957          | 15.4      | 1972.66     | 15.58       | -0.703    | -0.18     |
| 1973.162          | 15.5      | 1973.72     | 16.75       | -0.558    | -1.25     |
| 1992.171          | 14.6      | 1992.14     | 14.51       | 0.031     | 0.09      |
| 1993.437          | 14.9      | 1993.78     | 14.89       | -0.343    | 0.01      |
| 1993.869          | 14.6      | 1993.71     | 14.05       | 0.159     | 0.55      |
| 1997.930          | 14.9      | 1998.24     | 14.81       | -0.31     | 0.09      |

straight line. For the Kamchatka earthquake, the acceleration is obvious (Fig. 12).

The self-organized criticality concept assumes an increasing correlation distance in the collective behavior of small seismic events before a large earthquake (i.e., a catastrophe). Accordingly, accelerated seismic-

ity can manifest itself in a larger area compared with the radius we have used, ( $R_{\text{eff}} = 3l_i$ ). We tested this hypothesis by making calculations for the Neftegorsk earthquake with  $R_{\text{eff}} = 10l_i = 277$  km. The thin line in Fig. 9 shows the result. The theoretical fit (6) is based on 106 events (filled circles), the last of which occurred on

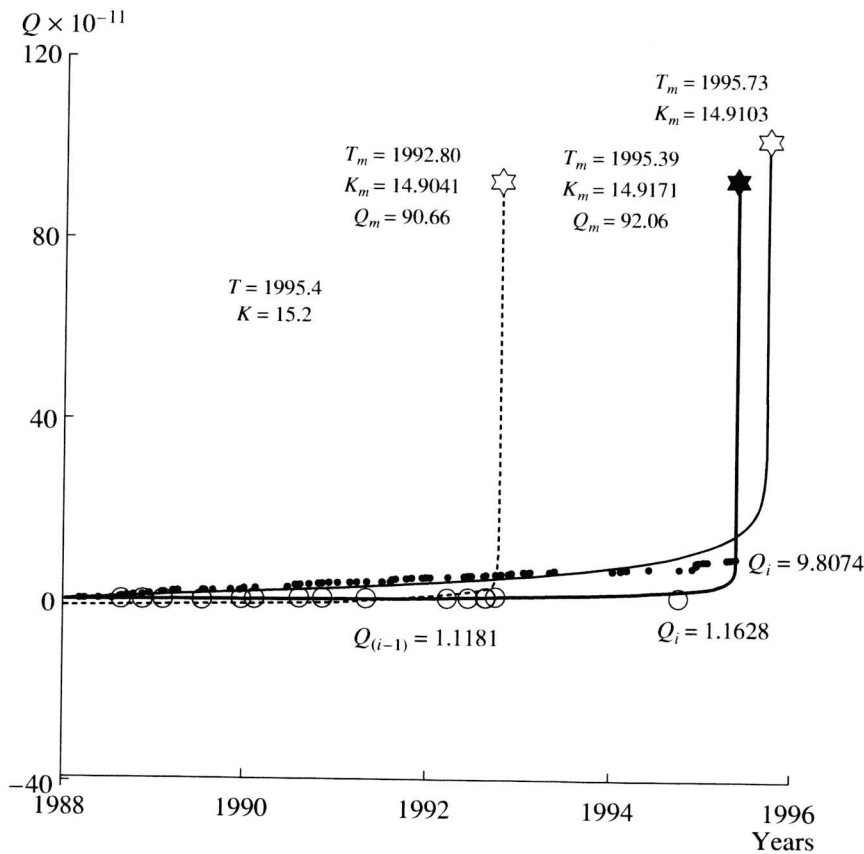


**Fig. 9.** Prognostic curves incorporating the last event (October 1, 1994) before the Neftegorsk earthquake (thick solid line) and without this event (dashed line) at a sampling radius of  $R_{\text{eff}} = 83$  km. The thin line is the prognostic curve for  $R_{\text{eff}} = 277$  km. The stars mark the termination of the prognostic curves.  $Q_i$  and  $Q_{(i-1)}$  are strains accumulated before the earthquake;  $Q_m$ ,  $T_m$ , and  $K_m$  are the strain, time, and energy class of the earthquake calculated from the model;  $T$  and  $K$  are the actual earthquake time and class.

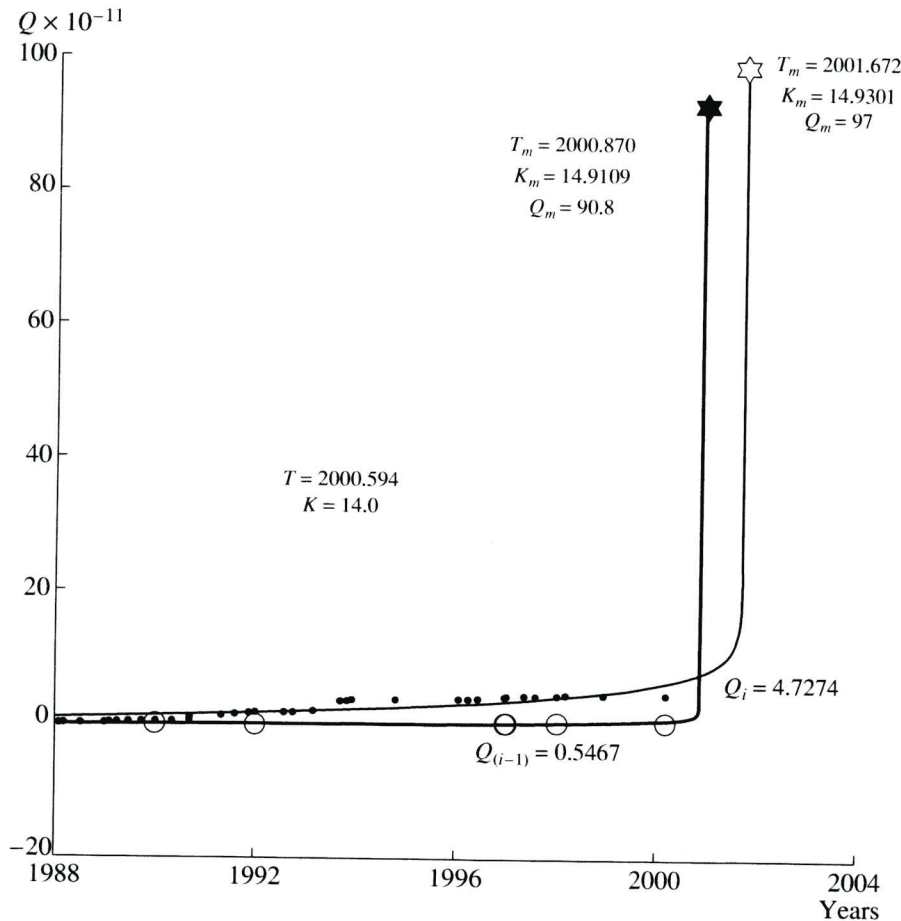


**Fig. 10.** Prognostic curves for the Neftegorsk earthquake at a sampling radius of  $R_{\text{eff}} = 42$  km (thick line) and  $R_{\text{eff}} = 141$  km (thin line). The stars mark the termination of the curves.  $Q_i$  is the strain accumulated before the earthquake;  $Q_m$ ,  $T_m$ , and  $K_m$  are the strain, time, and energy class of the earthquake calculated from the model;  $T$  and  $K$  are the actual earthquake time and class.

May 20, 1995, i.e., seven days before the main shock. The time predicted by the CSA model was  $T_m = 1995.73$ , which is four months later than the actual occurrence time for the Neftegorsk earthquake. In spite of an increase in the strain accumulated by the prediction time ( $Q_i = 9.8074$ ), the estimated energy class remained almost unchanged,  $K_m = 14.9103$ . In this case the sequence of experimental data (filled circles) is also close to a straight line and shows no seismicity acceleration.

A similar procedure was carried out for the Ulegorsk earthquake (Fig. 10). The calculation was based on the value  $R_{\text{eff}} = 10l_i = 141$  km. The thin line in Fig. 10 shows the result. The theoretical fit (6) was based in this case on 41 events (filled circles), the last of which occurred on March 2, 2000, i.e., 5 months before the main shock. The time predicted by the CSA model was  $T_m = 2001.672$ , which is 1.5 years later than the actual time of the Ulegorsk earthquake. This result is thus worse in comparison with that achieved

using the choice  $R_{\text{eff}} = 3l_i$ . The estimated energy class remained almost unchanged:  $K_m = 14.9301$ . The sequence of experimental data (filled circles) is again close to a straight line and shows no seismicity acceleration.

We now discuss the contradiction in the interpretation of the RTL method and energy estimation using the CSA model as applied to the Neftegorsk and Ulegorsk earthquakes. Plots 1 of the *RTL* parameter in Figs. 1 and 5 show foreshock activity during the last phase in the precursory periods of these earthquakes. At the same time, the accumulated strain (circles and dots) in Figs. 9 and 10 does not indicate an increase in seismicity. This apparent contradiction can be explained by the fact that the *RTL* algorithm (1) is more sensitive to slight variations in seismicity than cumulative strain  $Q_i$ . This may be seen by comparing plots 1 and 2 in Fig. 1. An insignificant increase in the number of earthquakes  $N$  (plot 2) before the Neftegorsk earthquake manifests itself in

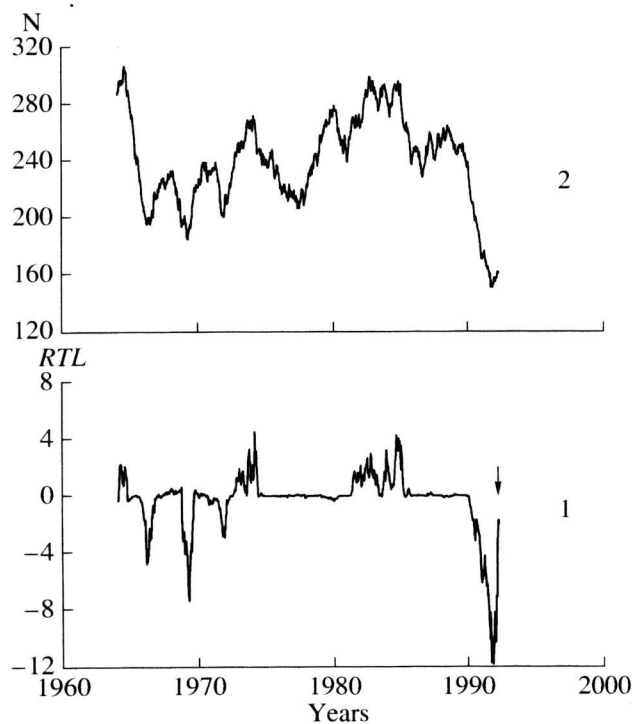


**Fig. 11.** The RTL prognostic parameter (1) and number of earthquakes N (2) before the Kamchatka earthquake of March 2, 1992, the time of which is marked by an arrow. The calculation parameters:  $K_{\min} \geq 8.5$ ,  $r_i \leq R_{\max} = 2r_0 = 100$  km,  $(t - t_i) \leq T = 2t_0 = 2$  years.

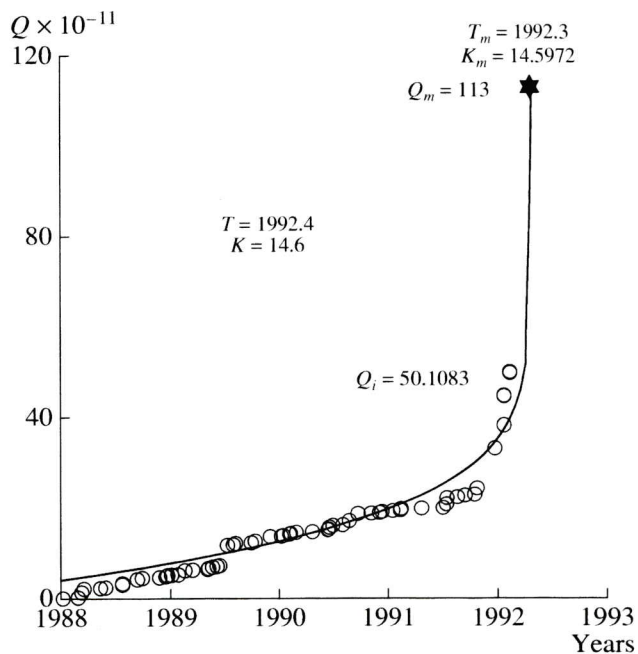


**Fig. 12.** The prognostic curve for the Kamchatka earthquake of March 2, 1992. The star marks the termination of the curve.  $Q_i$  is the strain accumulated before the earthquake;  $Q_m$ ,  $T_m$ , and  $K_m$  are the strain, time, and energy class of the earthquake calculated from the model;  $T$  and  $K$  are the actual earthquake time of occurrence and class.

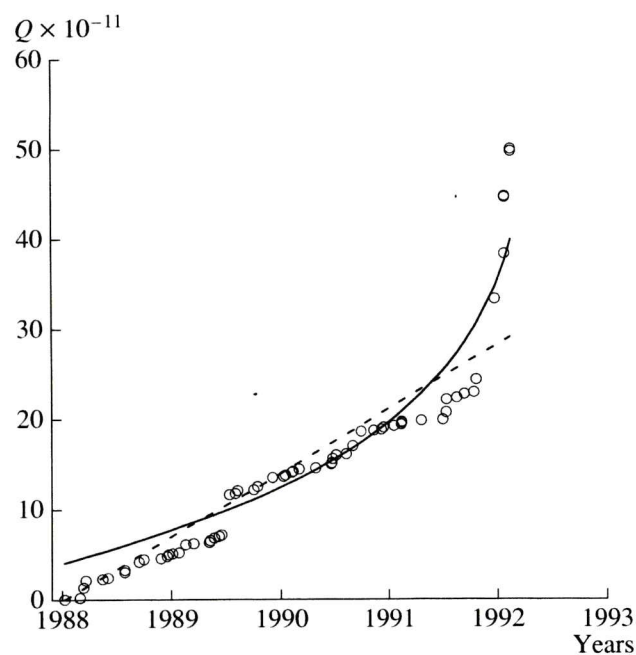


**Fig. 13.** The prognostic curve (solid line) and linear dependence (dashed line) compared with the strain  $Q$  accumulated before the March 2, 1992, Kamchatka earthquake. Open circles denote the earthquakes listed in Table 7.

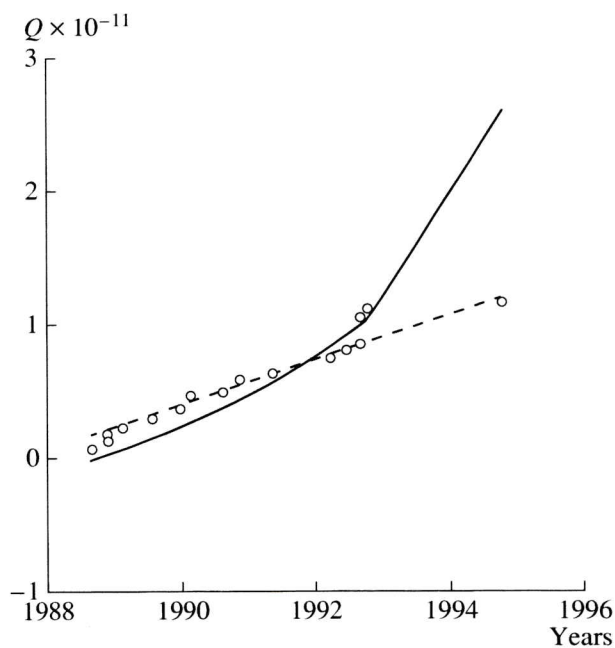


**Fig. 14.** The prognostic curve (solid line) and linear dependence (dashed line) compared with the strain  $Q$  accumulated before the May 27, 1995 Neftegorsk earthquake. Open circles denote the earthquakes listed in Table 5.

the dramatic rise of curve 1, which indicates foreshock activity in the RTL interpretation. This is provided by changing weights of the  $R$ ,  $T$ , and  $L$  functions depending on the remoteness of preceding events in distance and in time relative to the epicenter and occurrence time of a predicted earthquake.

### CONCLUSIONS

A retrospective analysis of seismicity prior to the Neftegorsk and Uglegorsk earthquakes, performed using the RTL algorithm, revealed two prognostic phases of seismic quiescence and foreshock activity. The probability of the accidental appearance of these phases was less than 1 and 2%, respectively. This made it possible to optimistically assess the possibility of applying this method on Sakhalin.

The estimates of the time and energy class of the Neftegorsk and Uglegorsk earthquakes, obtained using the model based on self-organized criticality concepts, proved to be unconvincing because no evident seismicity acceleration was recorded before these events. The applicability of this approach to Sakhalin seismicity should be tested for future large earthquakes.

### ACKNOWLEDGMENTS

I thank A.D. Zav'yalov for helpful remarks.

This work was supported by the Presidium of the Russian Academy of Sciences, program Change in the Environment and Climate: Natural and Related Man-Made Disasters and by Leading Scientific Schools, grant NSH-5009.2006.5.

### REFERENCES

1. Gabrielov, A.M., *Dolgosrochnyi prognoz zemletryaseni: (Metod, rekomendatsii)* (Long-Term Prediction of Earthquakes: Method, Recommendations), Moscow: IFZ AN SSSR, 1986.
2. Zav'yalov, A.D., *Srednesrochnyi prognoz zemletryaseni. Osnovy, metodika, realizatsiya* (Intermediate-Term Prediction of Earthquakes: Fundamentals, Technique), Moscow: Nauka, 2006.
3. Molchan, G.M. and Dmitrieva, O.E., Identification of Aftershocks: Review and New Approaches, *Vychislit. Seismol.*, 1991, no. 24, pp. 19–50.
4. Riznichenko, Yu.V., Crustal Earthquake Source Dimensions and Seismic Moment, in *Issledovaniya po fizike zemletryaseni* (Earthquake Physics Studies), Moscow: Nauka, 1976, pp. 9–27.
5. Sadovskii, M.A. and Pisarenko, V.F., *Seismicheskii protsess v blokovoii srede* (Seismic Process in a Block Medium), Moscow: Nauka, 1991.
6. Smirnov, V.B., Experience in Estimation of Earthquake Catalog Representativeness, *Vulkanol. Seismol.*, 1997, no. 4, pp. 93–105.
7. Sobolev, G.A., *Osnovy prognoza zemletryaseni* (Earthquake Prediction Fundamentals), Moscow: Nauka, 1993.
8. Sobolev, G.A., Chelidze, T.L., Zav'yalov, A.D., et al., Maps of Forthcoming Earthquakes Based on the Complex of Seismological Indications, *Izv. Akad. Nauk SSSR, Fiz. Zemli*, 1990, no. 11, pp. 45–56.
9. Sobolev, G.A. and Tyupkin, Yu.S., Anomalies in the Regime of Weak Seismicity before Strong Kamchatka Earthquakes, *Vulkanol. Seismol.*, 1996, no. 4, pp. 64–74.
10. Sobolev, G.A., Precursory Stages of Strong Kamchatka Earthquakes, *Vulkanol. Seismol.*, 1999, no. 4–5, pp. 63–72.
11. Sobolev, G.A. and Tyupkin, Yu.S., Precursory Stages, Seismic Precursors, and Prediction of Kamchatka Earthquakes, *Vulkanol. Seismol.*, 1998, no. 6, pp. 17–26.
12. Sobolev, G.A. and Tyupkin, Yu.S., Analysis of Energy Release during Formation of the Main Fracture in Laboratory Studies of Rock Fracture and before Strong Earthquakes, *Fiz. Zemli*, 2000, no. 2, pp. 44–55.
13. Sobolev, G.A. and Ponomarev, A.V., *Fizika zemletryaseni i predvestniki* (Earthquake Physics and Precursors), Moscow: Nauka, 2003.
14. Gitis, V.G., Osher, B.V., Pirogov, S.A., et al., A System for Analysis of Geological Catastrophe Precursors, *J. Earthquake Predict. Res.*, 1994, vol. 3, no. 4, pp. 540–555.
15. Kossobokov, V.G. and Keilis-Borok, V.I., Localization of Intermediate-Term Earthquake Prediction, *J. Geophys. Res. B*, 1990, vol. 95, no. 12, pp. 763–772.
16. Sobolev, G., The Examples of Earthquake Preparation in Kamchatka and Japan, *J. South Am. Earth Sci.*, 2001, vol. 338, nos. 3–4, pp. 17–28.
17. Sornette, D. and Sammis, C.G., Complex Critical Exponents from Renormalization Group Theory of Earthquakes: Implications for Earthquake Predictions, *J. Phys. I. France*, 1995, vol. 5, pp. 607–619.
18. Varnes, D.J., Predicting Earthquakes by Analyzing Accelerating Precursory Seismic Activity, *Pure Appl. Geophys.*, 1989, vol. 130, no. 4, pp. 661–686.
19. Wyss, M. and Habermann, R.E., Precursory Seismic Quiescence, *Pure Appl. Geophys.*, 1988, vol. 126, nos. 2/4, pp. 319–332.