

The fine structure of the dynamics of seismicity before $M \geq 4.5$ earthquakes in the area of Reggio Emilia (Northern Italy)

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Abstract

We present the results of studies of seismicity in the Reggio Emilia area (Northern Italy). The Istituto Nazionale di Geofisica instrumental earthquake catalogue (1975-1996) reported about three moderate-size earthquakes with $M \geq 4.5$ that occurred in this area (November 1983, May 1987, October 1996). The *RTL* prognostic parameter proposed by Sobolev and Tyupkin (1996a) was used for analysis. This parameter is designed in such a way that a seismic quiescence produces negative anomaly of the *RTL* parameter in comparison to its perennial background level and an activation of seismicity initiates the growth of its value. The *RTL* prognostic parameter indicates that all three earthquakes are preceded by activation of the seismicity. The interval between the commencement of the activation identified by *RTL* parameter and the event itself was about one year for the 1987 and 1996 earthquakes, and about three months for the 1983 earthquake.

Key words *seismicity – earthquakes – prognostic parameter – seismic quiescence – foreshock activation*

1. Introduction

The analysis of peculiarities of seismicity before potentially disastrous earthquakes is an important part of the study of earthquake prediction. There are several methods for earthquake prediction based on the study of seismicity variations. Among them the CN method has been extensively applied to Italian seismicity (Costa *et al.*, 1996). One of these approaches, based on the idea that seismic quiescence and

foreshock activation of seismicity consecutively follow one another in the focus of a future earthquake, was discussed by many authors (Wyss and Habermann, 1988; Purcaru and Pawelzik, 1991a,b; Sobolev, 1992, 1993; Zschau, 1995). Laboratory experiments and the results of a number of seismological studies confirm this assumption (Sobolev, 1992, 1993). The *RTL* prognostic parameter was proposed by Sobolev and Tyupkin (1996a) as a tool of analysis of this peculiarity of seismicity before strong earthquakes. The algorithm of calculation of the *RTL* prognostic parameter is based on the supposition that in the immediate vicinity of the epicenter of the future earthquake the mentioned effects are stronger the nearer the time of its occurrence. The tentative retrospective calculations of this parameter by the example of several strong earthquakes on Kamchatka, in Caucasus and in Greece produce satisfactory results

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Table I. Earthquakes with $M \geq 4.5$ occurring after 1975 in the Reggio Emilia area (Northern Italy).

Year	Month	Day	Hour	Min	Lat.	Long.	Depth	Magnitude
1983	11	09	16	29	44.70	10.34	35	4.9
1987	05	02	20	43	44.81	10.72	02	4.5
1996	10	15	09	56	44.78	10.61	31	4.8

(Sobolev and Tyupkin, 1996a,b, 1998; Sobolev *et al.*, 1997; Kapylova *et al.*, 1998). These studies show that in the interval of 2-3 years before a strong earthquake, the seismicity of its epicentral area had a quiescence stage followed by «foreshock» activation and an earthquake occurs shortly after the *RTL* parameter is restored to its normal level. The analysis of spatial distribution of the *RTL* anomaly before a strong earthquake gives that linear sizes of the anomalous area are several times larger than the source length found from empirical relation between source length and magnitude. The main shocks usually occurred at the edge of the anomalous area.

The earthquakes with $M = 4.5$ and above can be dangerous for Italy and these earthquakes are the important object for prediction. However, a manifestation of effects of seismic quiescence and foreshock activation before moderate-size earthquakes is markedly weaker than before the large earthquakes mentioned above and may depend on local geotectonic conditions. Foreshock statistics of earthquakes recorded by the Italian national seismological network between 1975 and 1991 were analyzed by Console *et al.* (1993). These authors observed a significant tendency of foreshock activation for the Central Italy. Similar analysis of seismicity of the zone of the Po valley (Northern Italy) has shown that foreshock activation is not typical for this area. (The Po valley zone is a large area which includes the Reggio Emilia zone).

We applied the *RTL* prognostic parameter to the analysis of peculiarity of seismicity before moderate-size earthquakes that occurred in the Reggio Emilia area

The Istituto Nazionale di Geofisica (ING) earthquake catalogue (1500 B.C. - present) reports 21 events occurring in the Reggio Emilia area and having macroseismic intensity greater

than or equal to the VII degree. Some earthquakes of intensity greater than VIII occurred before 1600 and other events of higher intensity occurred in 1831 (west of the Reggio Emilia epicenter). We performed our analysis of seismicity using the instrumental part of the ING catalogue (from 1975 to 1996). It contains more than 5700 events with $M > 1.4$ that occurred in the Reggio Emilia area and reports three events with $M \geq 4.5$: the 1983 Parma earthquake, the 1987 and 1996 Reggio Emilia earthquakes (see table I).

The *RTL* analysis of seismicity before Reggio Emilia earthquakes with $M \geq 4.5$ show that they are forestalled by foreshock activation of the *RTL* parameter, but a quiescence stage is not identified for these events.

We present a brief description of the algorithm of the *RTL* parameter calculation in the Appendix to make this paper independent from the reference.

2. Tectonic setting of Northern Italy

The Apennines are part of a complex collisional plate boundary in the Central Mediterranean, between Africa and Eurasia (Malinverno and Ryan, 1986; Royden *et al.*, 1987). The Northern Apennines arc is formed by several NE verging thrust sheets with eastward progressive migration of the compression front (upper Miocene-Pleistocene). Three main geodynamic provinces can be distinguished in the Northern Apennines (Bigi *et al.*, 1990):

- 1) A back-arc basin including the Tyrrhenian Sea and the peri-Tyrrhenian region of the Italian peninsula (extension prevalent since the upper Miocene).

- 2) A belt-foredeep region along the Adriatic margin characterized by crustal shortening and

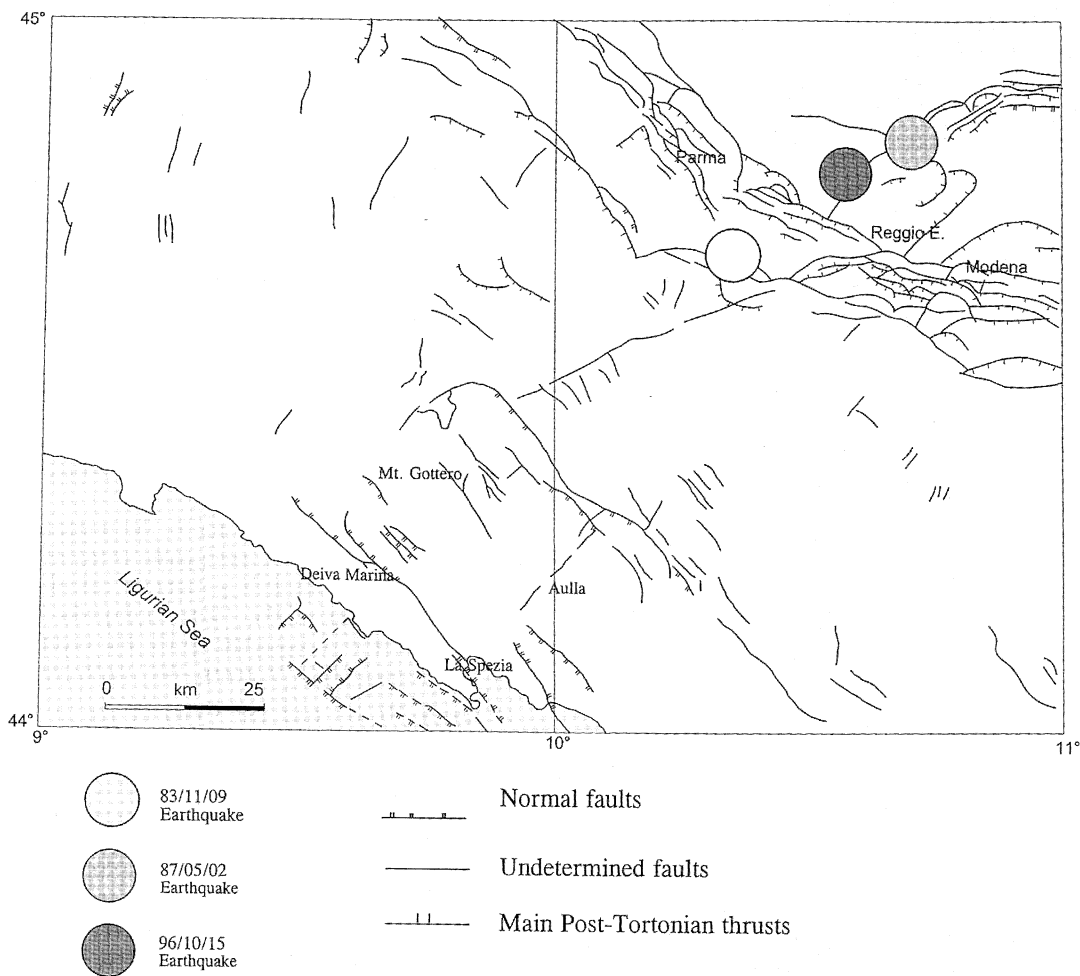


Fig. 1. The map of faults in the area of Reggio Emilia (after Bigi *et al.*, 1990).

westward passive subduction of the Adriatic plate (Reutter, 1981; Royden *et al.*, 1987).

3) A foreland region formed by the great sedimentary basin of the Padana plain and the Adriatic Sea, overlying the continental lithosphere.

Seismic reflection profiles and geological data (Castellarin *et al.*, 1986; Vai, 1987) indicate that the Northern Apennines outer margin is characterized by recent compression, and the inner belt portion is extending. In the Tyrrhenian region, post-orogenic extension was ac-

companied by the thinning of the crust, normal faulting, ductile deformation, volcanic activity, and high heat flow (Jolivet *et al.*, 1994). Later, the extension processes affected the Apennines (Plio-Pleistocene), where graben-like structures trending N-S to NW-SE overlying the compression features. In contrast, on the Adriatic margin, the outer front of the belt is probably still under compression (Patacca and Scandone, 1987). The analyses of focal mechanisms of earthquakes, recorded by the seismic network of the Istituto Nazionale di Geofisica (Barba *et al.*,

1995) during the period of 1988-1995, have confirmed the existence of two adjacent zones of contemporaneous extension and compression in the Northern Apennines (Frepoli and Amato, 1997). The Reggio Emilia area is located in the compression zone.

Figure 1 shows the scheme of faults in the Reggio Emilia area and the location of the epicenters for the three earthquakes evaluated. It is apparent that the structure of the analyzed area is considerably fractured.

3. Results of the *RTL* analysis

The earthquake catalogue of Istituto Nazionale di Geofisica for the period 01/01/1975-29/10/1996 was available for *RTL* analysis of seismicity of the Northern Italy. The algorithm proposed by V. Pisarenko (Sadovsky and Pisarenko, 1991) was used for estimating the completeness of the catalogue. Aftershocks were deleted from the catalogue with the help of the algorithm designed by Molchan and Dmitrieva (1991). Both algorithms were adopted and coded by V. Smirnov. The completeness of the catalogue differ for different time intervals (see table II).

Figures 2, 3 and 4 show the plots of the *RTL* parameter calculated for the epicenters of the 1983, 1987, and 1996 earthquakes respectively. Earthquakes with magnitudes $3 \leq M \leq 3.8$ are used for calculation of the *RTL* parameter for the 1983 earthquake. The number of earthquakes with $M \geq 3.0$ is small in the area under consideration (see, for example, fig. 2 top) and we have poor statistics if the restriction $M \geq 3.0$ is used for calculation of the *RTL* parameter. We have no choice for the case of 1983 earthquake (see table II) but for the cases of 1987 and 1996

earthquakes we can use the data of the catalogue after 1985. Then earthquakes with $2.2 \leq M \leq 3.8$ can be used for calculation of the *RTL* parameter (see table II). (Maximal magnitude of earthquakes that are used for the calculation of the *RTL* parameter must be smaller than the magnitude of tested main shocks. We had very limited choice of M_{\max} for main shocks with magnitudes 4.5-4.9 and selected it empirically). The solid vertical line on the plots shows the time of the main earthquakes, whereas the dashed vertical line indicates the commencement of foreshock activation. It is apparent that the interval between the start of the foreshock activation of the *RTL* parameter and the event is about one year for the earthquakes of 1987 and 1996 and about two months for the earthquake of 1983.

As indicated in figs. 3 and 4, the process of preparation of the 1987 earthquake is manifested on the plot of the *RTL* parameter calculated for the epicenter of the 1996 earthquake and *vice versa*. It was expected, since the distance between epicenters of these two earthquakes is about 10 km and the value of the $\alpha = \frac{r_i}{l_i}$ parameter, which characterizes the «proximity» of the event to the tested point, is equal to 1.98. (Here l_i – the linear size of the earthquake focus of 1987 calculated from the empirical relation between the characteristic fault length and the magnitude while r_i is the distance between the epicenters of earthquakes of 1987 and of 1996). To make an estimation of the linear size of earthquake focus we used the relation: $\log(l_i) = 0.44 M - 1.289$ applicable to Greece seismicity (Papadopoulos and Voidomatis, 1987). Possible small errors of the coefficients of this relation do not change the behaviour of parameter *RTL* essentially (see Appendix).

Table II. The results of analysis of completeness of the catalogue for different time intervals.

Time interval	Number of events	<i>B</i> -value	Dispersion of <i>B</i> -value	M_{\min}
1975/01-1979/12	217	0.7929	0.09	3.0
1980/01-1985/12	313	0.9915	0.08	2.8
1985/12-1989/12	1272	1.0351	0.04	2.2
1990/01-1996/10	2210	1.1256	0.04	2.2

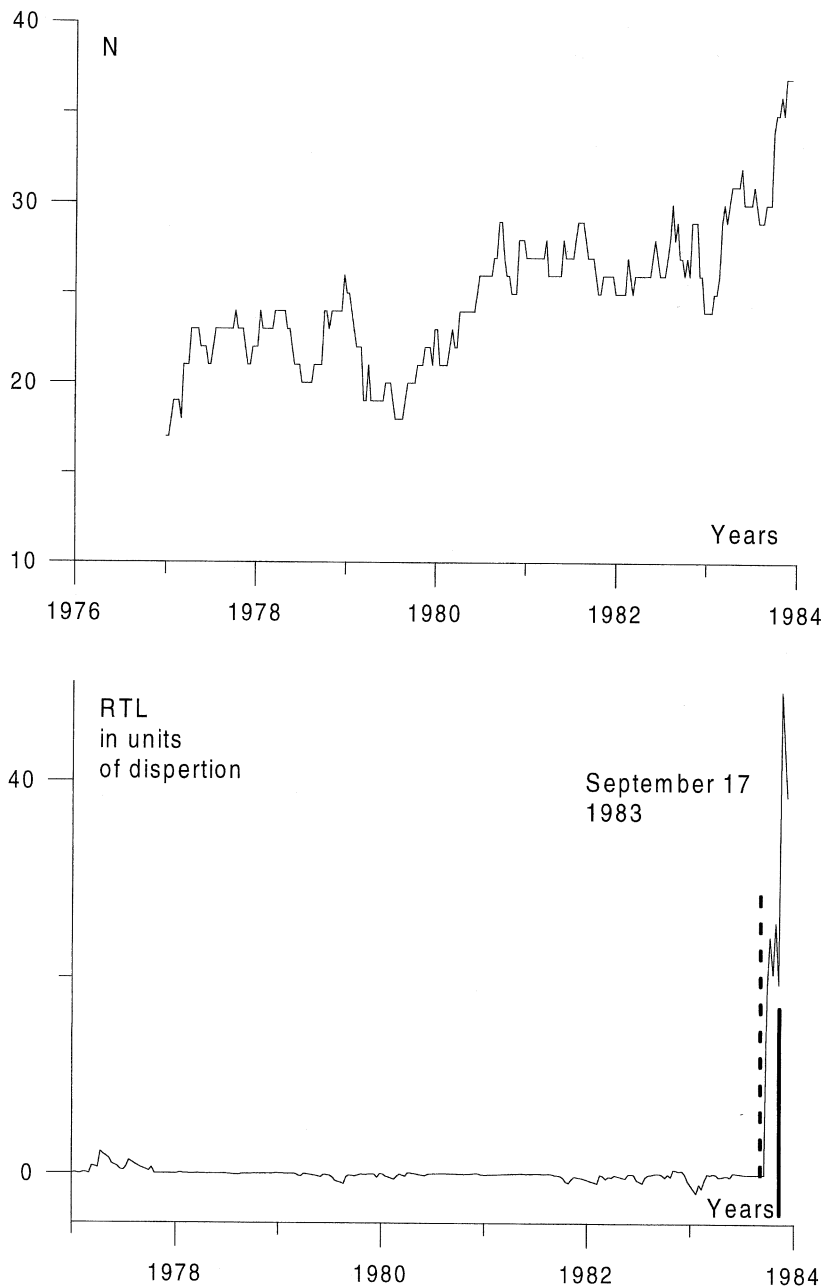


Fig. 2. The *RTL* plot is calculated for the epicenter of the 1983.11.09 earthquake (Lat. 44.7N, Long. 10.34E). The solid vertical line in plot shows the time of the earthquake (November 11, 1983), whereas the dashed vertical line indicates the time of commencement of foreshock activation (September 17, 1983). The top plot presents the plot of number of events N with $3.0 \leq M \leq 3.8$ that are used for calculation of the *RTL* parameter.

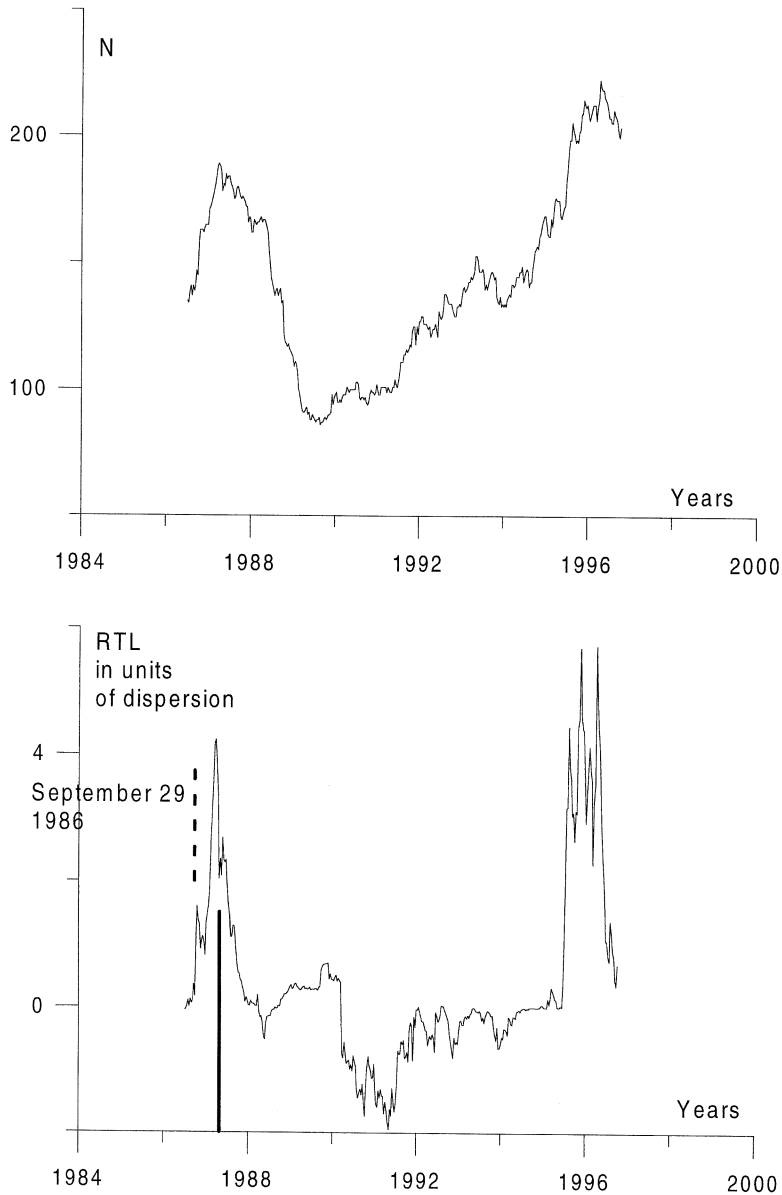


Fig. 3. The *RTL* plot is calculated for the epicenter of the 1987.05.02 earthquake (Lat. 44.81N, Long. 10.72E). The solid vertical line on the plot shows the time of the earthquake (May 2, 1987), whereas the dashed vertical line indicates the time of commencement of foreshock activation (September 29, 1986). The top plot presents the plot of number of events N with $2.2 \leq M \leq 3.8$ involved in the calculation of the *RTL* parameter. The process of preparation of the 1996 earthquake is manifested on the plot of the *RTL* parameter calculated for the epicenter of the 1987 earthquake. It is expected, since the distance between epicenters of these earthquakes is about 10 km and the value of a parameter, which characterizes the «proximity» of the event to the tested point, is equal to 1.98.

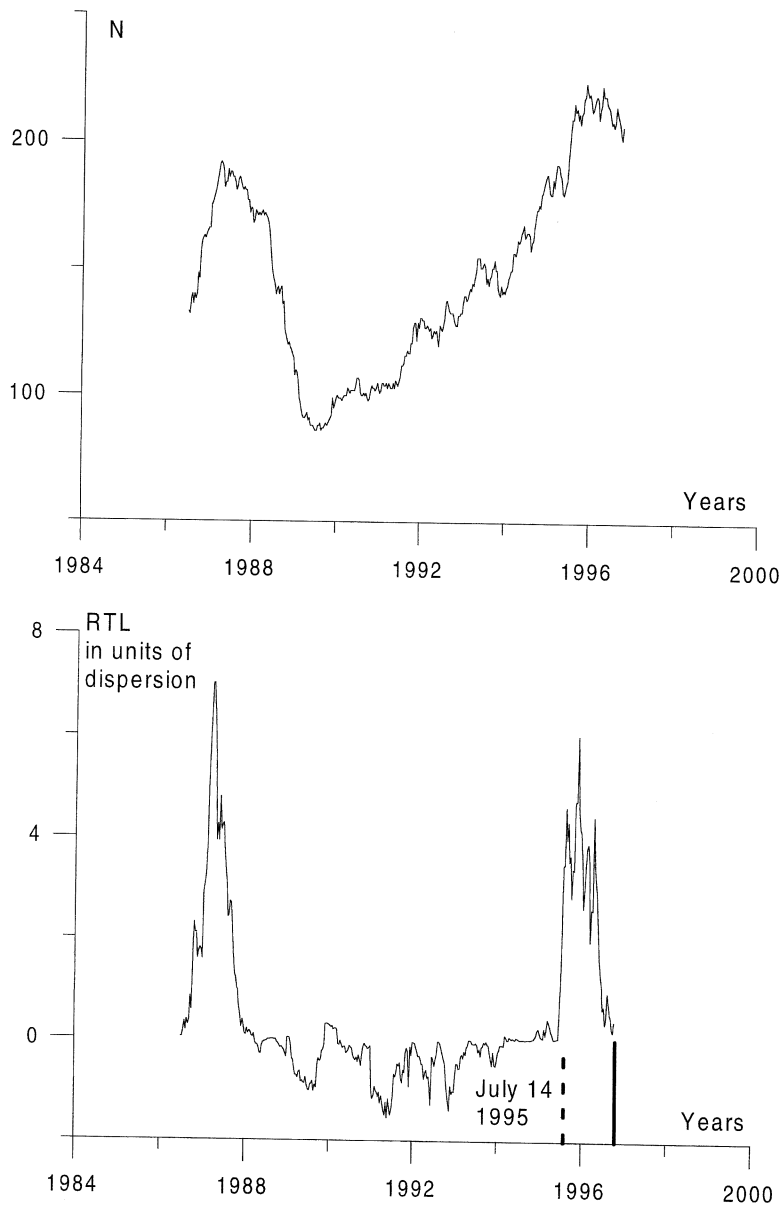


Fig. 4. The *RTL* plot is calculated for the epicenter of the 1996.10.15 earthquake (Lat. 44.78N, Long. 10.61E). The solid vertical line on the plot shows the time of the earthquake, whereas the dashed vertical line indicates the time of commencement of foreshock activation. The top plot presents the plot of number of events N with $2.2 \leq M \leq 3.8$ involved in the calculation of the *RTL* parameter. The process of preparation of the 1987 earthquake is manifested on the plot of the *RTL* parameter calculated for the epicenter of the 1996 earthquake. It is expected, since the distance between epicenters of these earthquakes is about 10 km and the value of a parameter, which characterizes the «proximity» of the event to the tested point, is equal to 1.98.

The plots of number of events $N(t)$ involved in the calculation of the RTL parameter are also presented in figs. 2, 3 and 4.

To analyze the influence of weak earthquakes we calculated the RTL parameter for different values of M_{min} . The RTL plots that are calculated for the epicenter of the 1996 earthquake (Lat. 44.78N, Long. 10.61E) for M_{min} equal to 2.5, 2.8 and 3.0 are presented in fig. 5a-d. One can see that activation of the RTL parameter before 1987 and 1996 earthquakes is observed for all these cases.

We discussed in the Introduction that strong earthquakes usually occurred when the RTL parameter is restored to its perennial background level after a quiescence stage as a result of followed «foreshock» activation. The quiescence stage is not observed for the analyzed events. These earthquakes occurred when a «foreshock» activation of the RTL parameter began to decrease but the RTL parameter did not necessarily achieve its background level. The RTL parameter even increases again during approximately ten days after the 1983 main shock (we

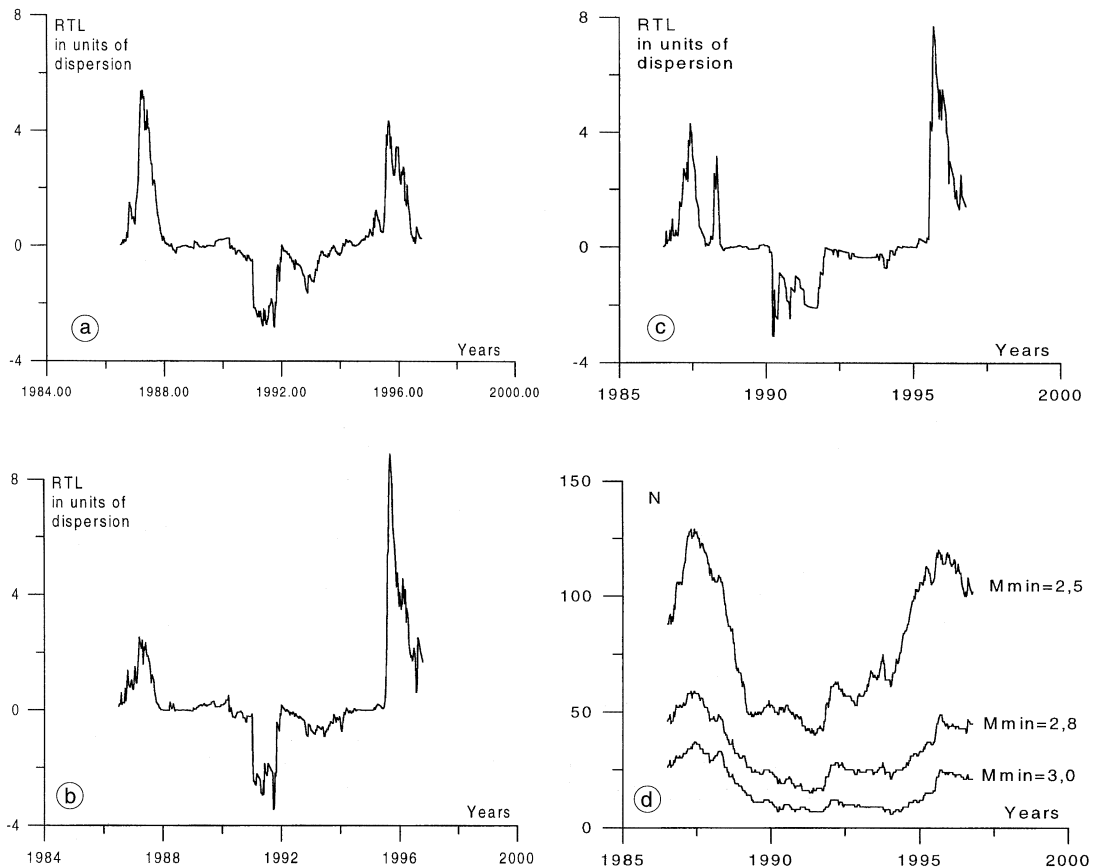


Fig. 5a-d. The RTL plots are calculated for the epicenter of the 1996.10.15 earthquake (Lat. 44.78N, Long. 10.61E) for M_{min} equal to 2.5 (a), 2.8 (b), and 3.0 (c). One can see that activation of the RTL parameter related with the preparation of 1987 and 1996 earthquakes is observed for all these cases. Plots of number of analyzed earthquakes for these three cases are presented in fig. 5d.

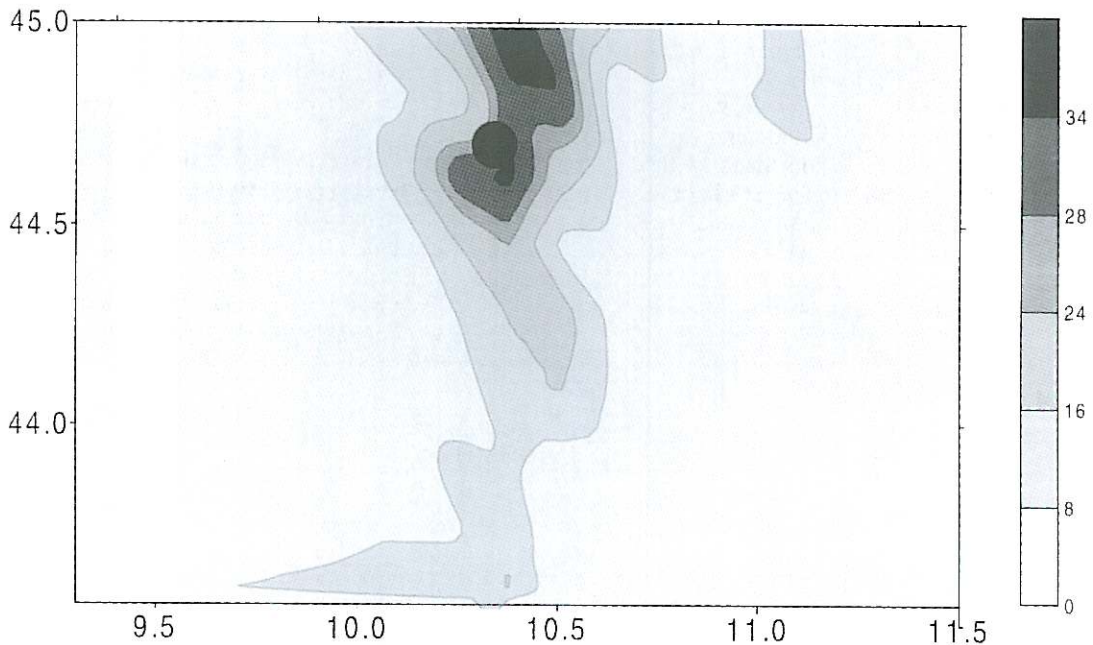


Fig. 6a. The map displays the distribution of maximal values of the *RTL* parameter in the area of epicenter of the 1983.11.09 earthquake for the time interval 83/01-84/01. The step of grid of calculation is 15 km. Black circle indicate main shock.

recall that the time step of calculation of the *RTL* parameter is equal to ten days).

Figure 6a,b, presents maps of a space distribution of maximal values of the *RTL* parameter during a one-year time interval before the analyzed earthquakes. A grid with a step equal to 15 km was used for construction of the maps. One can see that the 1983 main shock is located in the area of maximal values of the *RTL* parameter but epicenters of two other earthquakes are located in areas of intermediate values of this parameter. An additional analysis of seismicity and geological structure of a region is needed to make a conclusion about the location of the future earthquake.

4. Discussion

The retrospective calculations of the *RTL* parameter for several strong earthquakes on Kamchatka, in Caucasus and in Greece (Sobolev

and Tyupkin, 1996a,b, 1998; Sobolev *et al.*, 1997) show that in the interval of two to three years before an earthquake, the seismicity of its epicentral area had a quiescence stage followed by «foreshock» activation. The *RTL* analysis of seismicity in the area of Reggio Emilia has shown that all moderate-size earthquakes with $M \geq 4.5$, occurring over the time period 1975-1996, are forestalled by foreshock activation of the *RTL* parameter, but a quiescence stage is not identified for these events. We believe that a quiescence stage is poorly indicated because the analyzed earthquakes have relatively small magnitudes (in comparison with strong earthquakes of Kamchatka and the Caucasus).

The existence of activation of the *RTL* parameter before the earthquakes with $M \geq 4.5$ is probably a local effect of the Reggio Emilia area. It can be connected with considerably fractured structure of this area. Activation of the *RTL* parameter is not observed for the earth-

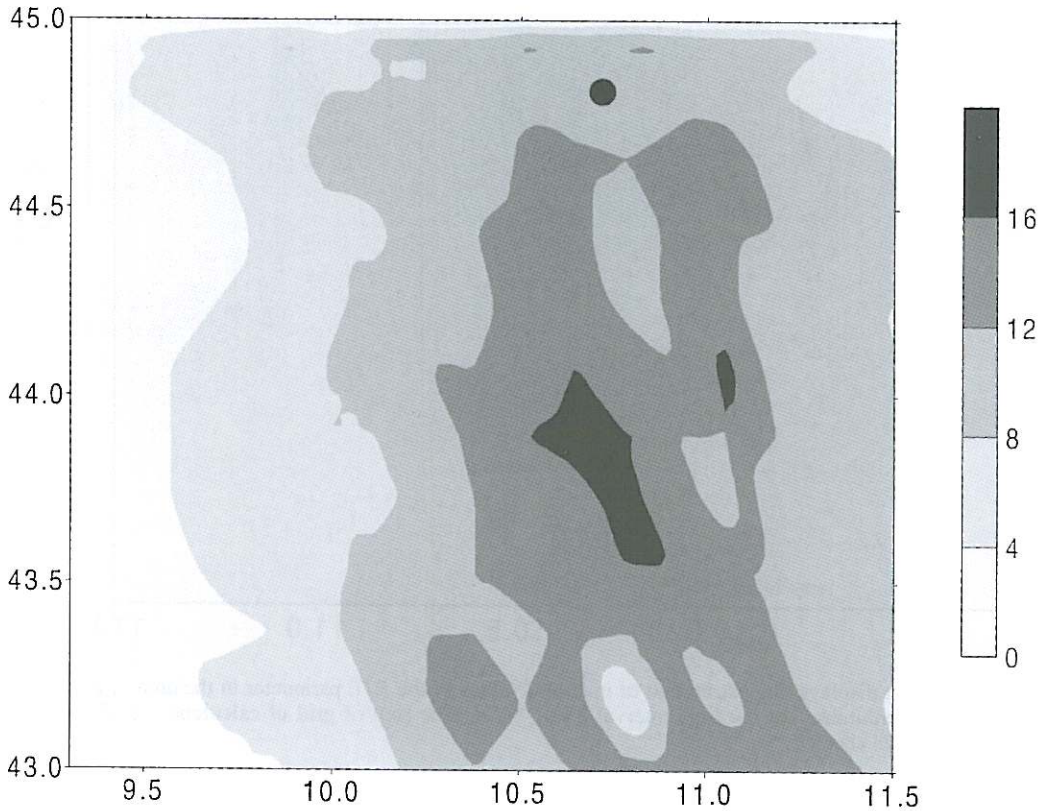


Fig. 6b. The map displays the distribution of maximal values of the *RTL* parameter in the area of epicenter of the 1987.05.02 earthquake for the time interval 86/08-87/08. The step of grid of calculation is 15 km. Black circle indicate main shock.

quake that took place in October 1995 in the Lunigiana area (Lat. 44.21N, Long. 10.08E) with $M = 4.8$. The areas of Reggio Emilia and Lunigiana belong to different seismotectonic provinces, which probably accounts for the difference in seismic regimes in these areas. In particular, the Reggio Emilia area is located in the compression zone and the Lunigiana area is under the extensional tectonic regime.

The results of analysis of foreshock statistics for Italy that was obtained by Console *et al.* (1993) confirm our supposition that the *RTL* foreshock activation discussed above is a local effect of the Reggio Emilia area. Unfortunately we have too few statistics to make a more or less definite conclusion that the foreshock activation

of the *RTL* parameter is typical for this area and can be used as a precursor of earthquakes with $M \geq 4.5$. Only subsequent earthquakes with $M \geq 4.5$ in the Reggio Emilia area will confirm or invalidate this finding.

5. Conclusions

The analysis of seismicity in the Reggio Emilia area has shown that all three moderate-size earthquakes with $M \geq 4.5$ that occurred in the area during the period 1975-1996 were foreshallied by activation of weak earthquakes. The *RTL* parameter indicates this foreshock activation.

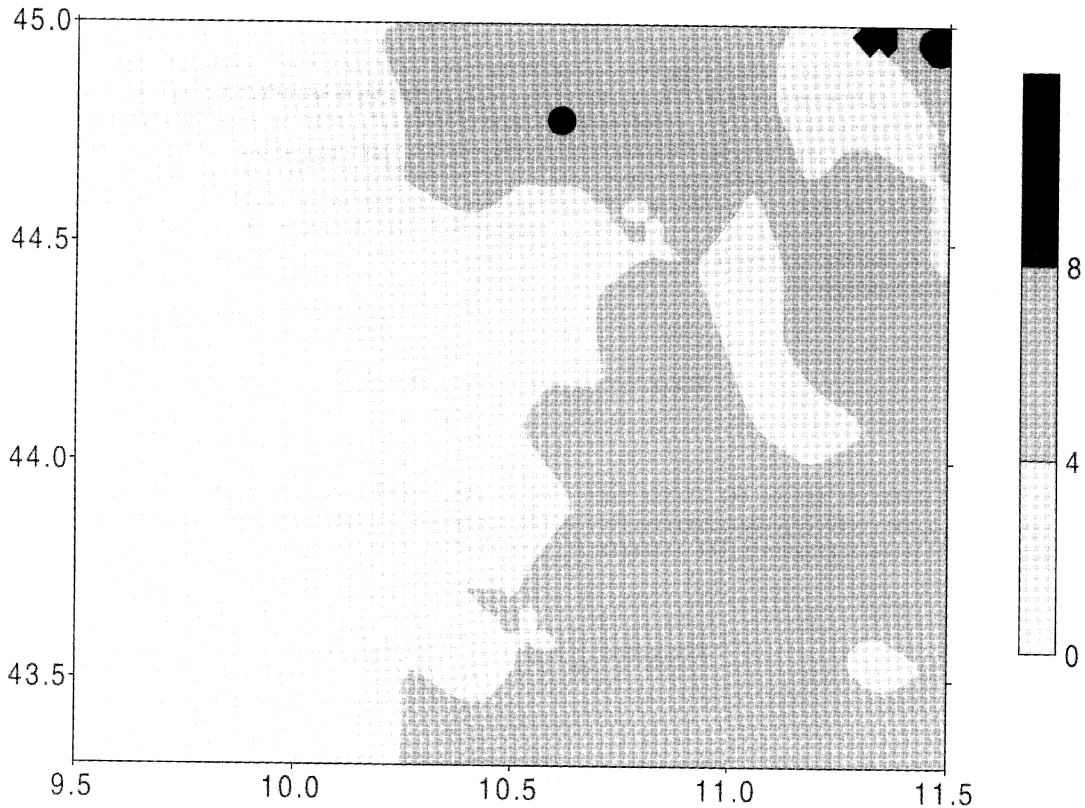


Fig. 6c. The map displays the distribution of maximal values of the *RTL* parameter in the area of epicenter of the 1996.10.15 earthquake for the time interval 95/11-96/11. The step of grid of calculation is 15 km. Black circle indicate main shock.

The time interval between the commencement of the foreshock activation of the *RTL* parameter and the main shock was about one year for the 1987 and 1996 earthquakes and about three months for the 1983 earthquake.

The quiescence stage was not observed before the analyzed events. These earthquakes occurred when a «foreshock» activation of the *RTL* parameter began to decrease but the *RTL* parameter did not necessarily achieve its perennial background level.

The activation of the *RTL* parameter before the earthquakes with $M \geq 4.5$ probably is a local effect of the Reggio Emilia area. For example, an activation of the *RTL* parameter is not observed for the October 1995 earthquake ($M = 4.8$) located at 44.21°N , 10.08°E , which occurred in

a different seismotectonic province of Northern Italy (in the Lunigiana area). The activation of the *RTL* parameter that is related with the process of clustering of weak earthquakes but did not precede the earthquakes with $M \geq 4.5$ is also observed for other areas of Italy

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Appendix

The *RTL* parameter is calculated for the tested point on the Earth's surface $x = (x, y)$ as function of time t . The value of prognostic parameter $RTL(x, y, t)$ is calculated from data on earthquakes with magnitude $M_{\min} < M < M_{\max}$ which fall into the time interval $(t - T_{\max}, t)$ and within a circle of radius R_{\max} with the center located at the tested point (x, y) . The level of completeness of the analyzed earthquake catalogue defines the value of M_{\min} . The value of M_{\max} must be smaller than the tested main shocks and is selected empirically. The optimal values of the R_{\max} and T_{\max} that characterize the space-time restrictions for earthquakes taking part in the calculation of the $RTL(x, y, t)$ are selected empirically. The $RTL(x, y, t)$ parameter is composed of three functions: the epicentral $R(x, y, t)$, the temporal $T(x, y, t)$, and the source size $L(x, y, t)$.

The indicated functions are

$$R(x, y, t) = \left[\sum_{i=1}^n \exp\left(-\frac{r_i}{r_0}\right) \right] - Rs. \quad (A.1)$$

Here r_i are the distances between the seismic events that occurred before time t and the tested point x (point of prognosis); r_0 is the coefficient characterizing the rate of reduction of the influence of the more remote seismic events from the point of prognosis. The parameter R_{\max} (see above) is equal to $2r_0$.

$$T(x, y, t) = \left[\sum_{i=1}^n \exp\left(-\frac{t-t_i}{t_0}\right) \right] - Ts. \quad (A.2)$$

Here t_i is the time of the preceding events. The t_0 parameter characterizes the rate of reduction of the influence of preceding seismic events as they recede into the past from the moment of prediction. The parameter T_{\max} (see above) is equal to $2t_0$.

$$L(x, y, t) = \sum_{i=1}^n \frac{l_i}{r_i} - Ls. \quad (A.3)$$

Here l_i is the size of source of the earthquake proceeding the moment of prediction. The value of l_i is calculated in accordance with the empirical relation $\log(l_i) = a \cdot M - b$ between the size of source l_i and the magnitude of earthquake M . Rs , Ts and Ls are corrections for the trend.

The functions R , T and L are reduced to a single dispersion. The prognostic parameter RTL is calculated as a product of the three functions described by expressions (A.1)-(A.3) and the value of the RTL parameter is measured in the units of its dispersion.

a and b coefficients in the formula (A.3) differ for different regions (see, for example, Wells and Coppersmith, 1994). We used $a = 0.44$ and $b = 1.289$ in the present study. These values of a and b coefficients are applicable to Greece seismicity (Papadopoulos and Voidomatis, 1987). It is possible that these coefficients are slightly different for Italy but small errors δa and δb of estimation of a and b coefficients lead to small variation of the function L . Namely, function L does not depend on the coefficient b . Direct calculations give that variation $|\delta a| \leq 0.2$ does not change the behaviour of parameter RTL essentially.

The activation of seismicity and seismic quiescence in the vicinity of the tested point causes the growth or decline of the RTL parameter, respectively, against the background value.

In the present study, we used the same parameters of the RTL algorithm as were used in the papers of Sobolev and Tyupkin (1996a,b, 1998; Sobolev *et al.*, 1997; ($r_0 = 50$ km, $t_0 = 1$ year, time step = 10 days)

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