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Time of Increased Probability for Earthquakes with M≥5.6 in Central Italy

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ABSTRACT: An important problem in earthquake prediction is the spatial uncertainty of the prediction. In this study the problem is analysed, using the algorithm CN, for the Central Italy region.

The algorithm CN makes use of normalized functions therefore the original algorithm, developed for the California-Nevada region, can be directly applied without any adjustment of the parameters also to the determination of the Time of Increased Probability (TIP) of strong earthquakes for Central Italy. The prediction is applied to the events with magnitude $M \geq M_0 = 5.6$, which, in Central Italy, have a return period of about 6 years, the same as the California-Nevada region. The availability of the computer files containing the earthquake bulletins of the Istituto Nazionale di Geofisica (ING) permits to extend to October 1991 the study made by Keilis-Borok et al. (1990).

The analysis of seismicity and seismotectonic considerations allows us to formulate a new regionalization. The use of this regionalization permits to reduce the total alarm time, the failures to predict and to narrow the spatial uncertainty of the prediction with respect to the results of Keilis-Borok et al. (1990). The completeness of the catalogue in this region permits also the analysis of the period 1904-1940.

1 INTRODUCTION

The algorithm CN is described in full detail by Gabrielov et al. (1986) and Keilis-Borok and Rotwain (1990), and an application of this algorithm to Central Italy is given by Keilis-Borok et al. (1990). The algorithm CN is designed to define the Time of Increased Probability of strong earthquakes (TIP). For this purpose the traits considered are the level of seismic activity, its variation in time, clustering of the earthquakes in space and time, and their concentration in space.

The functions which describe the traits for a given territory are defined in table 1. These functions are normalized so that they can be applied to different territories, with different seismicity, without any change. The normalization is obtained by choosing three magnitude ranges, m_1, m_2 and m_3, satisfying the condition that, in the territory under study, the average annual number of events with $M \geq m_i$ is equal to the costants, a_i, common to all seismically active territories.

The flow of the earthquakes is represented, at each time t, by the vector formed by the values of the different functions at the time t.

In the CN analysis of the flow of earthquakes, the time axis is divided into three intervals: *D* (dangerous), *N* (non-dangerous) and *X* (undetermined). The *D* intervals extend for two years before each strong event ($M \geq M_0$). Intervals *X* extend for three years after each strong event; if a strong earthquake occurs within three years the *X* period becomes a *D* period. The remaining time intervals are *N* intervals.

The functions, defined in table 1, are discretized by defining the thresholds small, medium and large, on the basis of the quantiles levels 1/3 and 2/3. We then estimate the combinations of the different discretized functions which are more typical for intervals *D*, and for intervals *N*. Following the procedure of pattern recognition, features *D* are defined by the condition that, in general, they occur during the intervals *D* and not during the intervals *N*. Features *N* are definited by the reverse condition. Each feature corresponds to a discretized value of the function, or to a combination of such values, for 2 or 3 functions.

SIGMA(t)	SIGMA(t)=$\Sigma 10^{\beta(M_i-\alpha)}$; the main shocks with $m_i \le M_i \le M_0$-0.1 and origin time (t-3 years)$\le t_i \le$t are included in the summation; α=4.5, β=1.00.
S_{max}(t)	S_{max}(t)=max{S_1/N_1, S_2/N_2, S_3/N_3} where S_j is calculated as SIGMA(t) for the events with the origin time (t-j years)$\le t_i \le$t-(j-1) years), and N_j is the number of earthquakes in the sum.
Z_{max}(t)	Z_{max}(t)=max{$Z_1/N_1^{2/3}$, $Z_2/N_2^{2/3}$, $Z_3/N_3^{2/3}$} where Z_j is calculated as S_j, but with β=0.5 and N_j is the number of earthquakes in the sum.
N_2(t)	Number of main shocks with M$\ge m_3$, which occurred in the time interval (t-3 years, t).
N_3(t)	Number of main shocks with M$\ge m_2$, which occurred in the time interval (t-10 years, t-7 years)
K(t)	*K*(t) =K_1-K_2, where K_i is the number of main shocks with $M_i \ge m_2$ and origin time (t-2·j years)$\le t_i \le$(t-2·(j-1) years).
B_{max}(t)	Maximum number of aftershocks for each main shock, counted within a radius of 50 km for the first 2 days after the main shock and for M>M_0-3.6.
G(t)	*G*(t)=1-P, where P is the ratio of the number of the main shocks with $M_j \ge m_2$ (m_2>m_1) to the number of the main shocks with $M_j \ge m_1$. Only main shocks with origin time (t-1 year)$\le t_j \le$t are considered.
q(t)	*q*(t)=$\Sigma^6_{j=1}$ max(0,6a_2-n_j), where a_2 is the average annual number of main shocks with $M_i \ge m_2$, n_j is the number of main shocks with $M_j \ge m_2$ and origin time (t-(8+j) years)$\le t_j \le$(t-(2+j) years).

Table 1. Functions used in the algorithm CN.

A TIP is declared at the time *t* for one year if:

$$n_{D(t)}-n_{N(t)} \ge V=5$$

$$\sigma(t)=10^{-\beta(M_0-\alpha)}\Sigma 10^{\beta(M_i-\alpha)}<E=4.9 \qquad (1)$$

where

$$\beta=1;\ \alpha=4.5$$

$n_{D(t)}$ is the number of characteristic features *D* that the flow of earthquakes has at the time t; $n_{N(t)}$ is the number of features *N*; σ(t) is a function proportional to the total number of events in each main shocks area contained in the studied region within a period of 3 years before the time t.

Consecutive TIPs may overlap and give an alarm period longer than one year. The TIP can be interrupted if σ(t)>E, then the TIP can be shorter than one year. If, during a TIP, we have not a strong event we have a 'false alarm'; if we have a strong event outside the TIP we have a 'failure to predict'.

All the constants and the definition of *D* and *N* features appearing in the algorithm CN are determined from the retrospective analysis of the California-Nevada seismicity (Keilis-Borok and Rotwain, 1990).

2 REGIONALIZATION

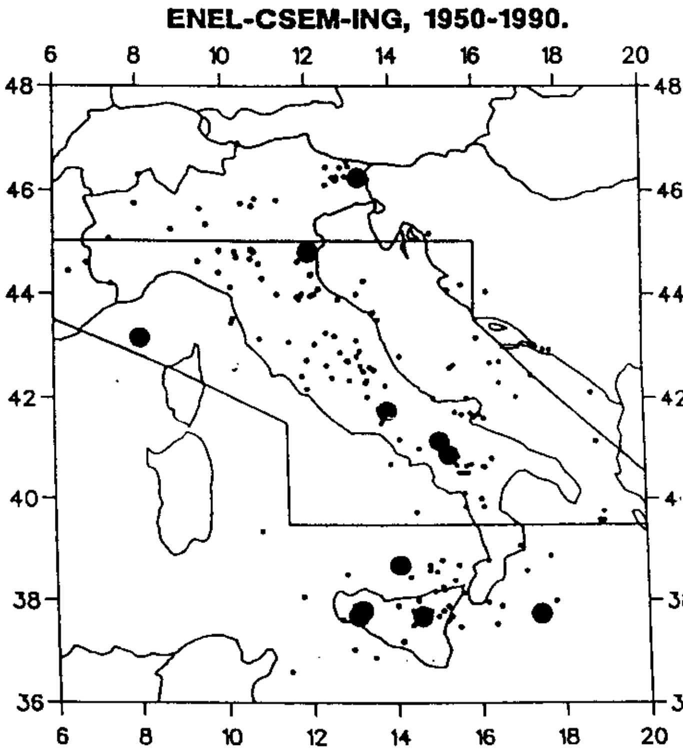

Figure 1. Epicenters recorded in the period 1950-1990; small dots indicate events with magnitude M≥4.4; large dots indicate events with magnitude M≥M_0=5.6; the poligon indicates the boundaries of the regionalization proposed by Keilis-Borok et al. (1990).

The regionalization is a very important factor to produce a useful prediction, minimizing the spatial uncertainty. The area where a strong earthquake has to be predicted must be the smallest possible, but there are some limitations to its minimum dimensions: 1) the borders of the area should not cross continuous seismotectonic zones and, 2) the annual number of earthquakes has to be ≥3 for the magnitude for which the catalogue is complete.

The regionalization used by Keilis-Borok et al. (1990) (fig. 1), based only on the boundaries and completeness of ENEL catalogue, covers an area of about 6.3×10^5 km^2 and allows us to obtain overall satisfactory results, but with not negligible false alarms and failures to predict (table 2).

Start of TIP	Strong earthquake		End of false alarm	Duration of TIP, months
	Date	M		
1/ 1/1958			1/ 1/1959	12
1/11/1961	21/ 8/1962	5.8;6.0		10
22/ 8/1962	19/ 7/1963	5.6		11
	30/12/1967	5.8		failure
1/ 3/1972			1/ 5/1975	38
1/11/1979	23/11/1980	6.5		13
1/ 3/1984	7/ 5/1984	5.7		2
8/ 5/1984			1/11/1986	30
1/ 5/1988				>15

Table 2. Strong earthquakes and TIPs for the regionalization proposed by Keilis -Borok et al. (1990) (M_0=5.6, V=5, E=4.9) accordingly with catalogues ENEL-CSEM-ING (1950-1989).

while the events in the Ancona zone and in the Gargano region occur only before the false alarms (fig. 4 and fig. 5). This may be taken as a strong indicator that the events in Ancona zone and Gargano region are associated with dynamic processes of the lithospheric blocks which are different from those characterizing the Apennines and that the earthquakes along the Apennines are independent from the seismicity of the other two areas (Ancona zone and Gargano region).

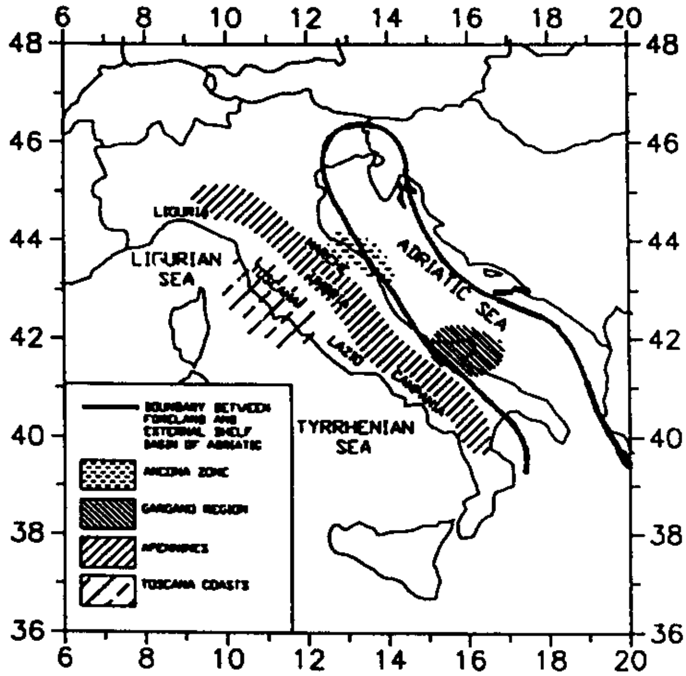

Figure 2. Map showing the boundaries of the Adriatic microplate after Horvath and Channel (1976) and other geographycal regions mentioned in the text.

Some events, in the area analyzed, can be easily correlated with the seismicity of the eastern border of the Adriatic microplate (compare fig. 1 and fig. 2). Furthermore, the analysis of the occurrence, just before the TIPs, of the events with magnitude greater than the minimum magnitude, m_1, used in the definition of the functions in the CN algorithm, shows that, in all the three-years time intervals which immediately precede the TIPs, it is possible to identify three distinct seismically active areas: the Apennines, the Ancona zone and the Gargano region (compare fig. 2 with fig. 3-6). The seismicity along the Apennines is present during all TIPs,

Furthermore, the map of the main shocks in Italy shows that there are two maxima in number of events in the Apennines (Umbria and Lazio) and, in general, a very large number of events along the Apennines from Liguria to Campania (fig. 7); this area can be separated from the other seismic regions in Italy. The map of the events with $M \geq m_1 = 4.4$, shown in fig. 8, indicates that the events in the Ancona and Gargano regions can be separated in space with respect to the events located in the Apennines.

The tectonic map by Patacca et al. (1990), shows that in the Central Apennines (Toscana,

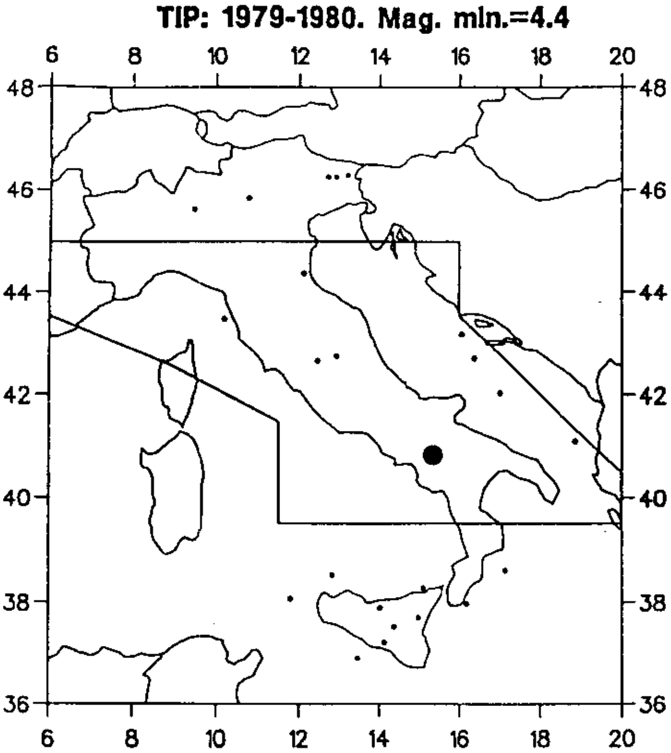

Figure 3. Main schocks (small dots) with $M \geq m_1 = 4.4$ for three years before the TIP, and strong earthquake (large dot). The polygon indicates the boundaries of the regionalization. Only the events inside the PFG polygon are considered.

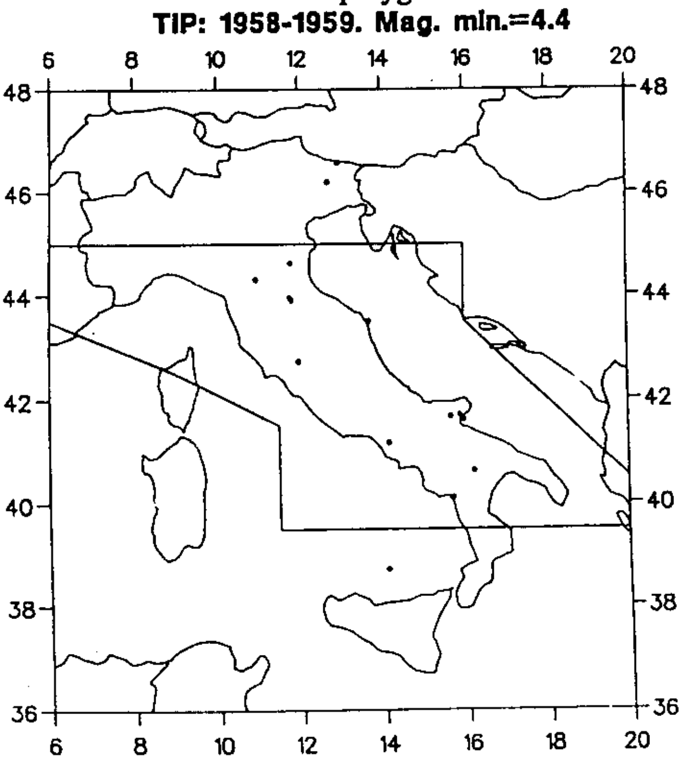

Figure 4. Main schocks (small dots) with $M \geq m_1 = 4.4$ for three years before the TIP. No strong earthquake occured during the TIP (false alarm). The polygon indicates the boundaries of the regionalization. Only the events inside the PFG polygon are considered.

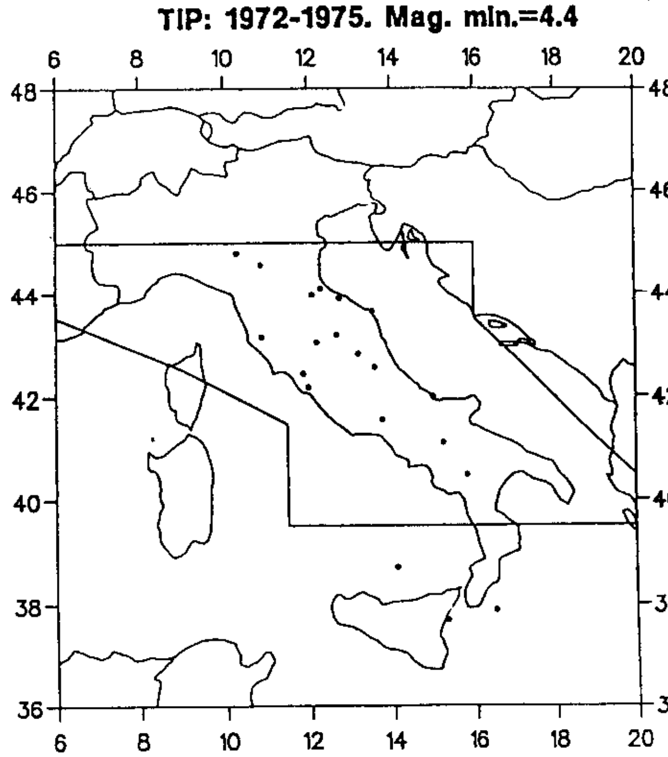

Figure 5. Main schocks (small dots) with $M \geq m_1 = 4.4$ for three years before the TIP No strong earthquake occured during the TIP (false alarm). The polygon indicates the boundaries of the regionalization. Only the events inside the PFG polygon are considered.

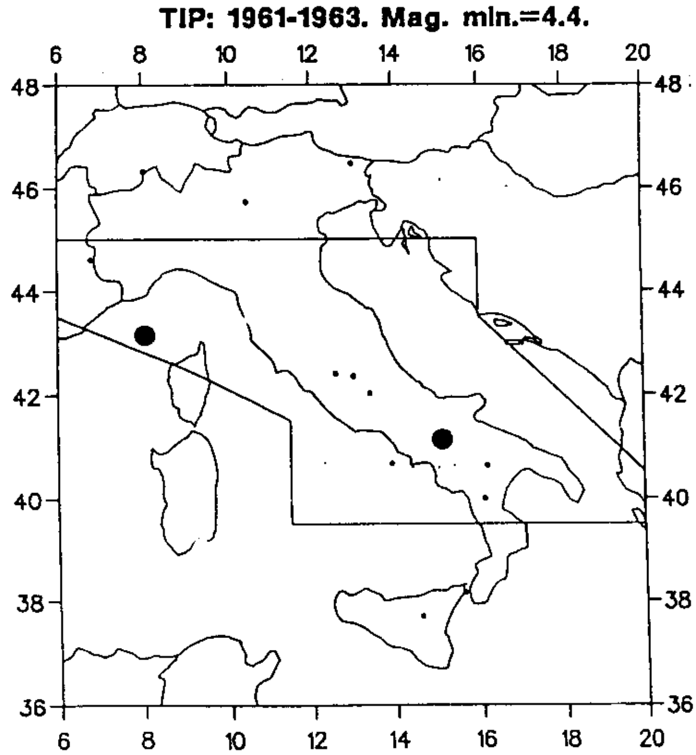

Figure 6. Main schocks (small dots) with $M \geq m_1 = 4.4$ for three years before the TIP, and strong earthquakes (large dots). The polygon indicates the boundaries of the regionalization. Only the events inside the PFG polygon are considered.

Umbria, Marche) there are two almost parallel NW-SE elongated active areas (fig. 9). The alignment near to the Adriatic Sea is in a compressive state, while the other, more to the west, has an extensional character. The Gargano region has, on the other hand, a tectonic behavior characterized by the coexistence of mechanisms of dip-slip, oblique slip, and strike slip type (Patacca et al., 1990).

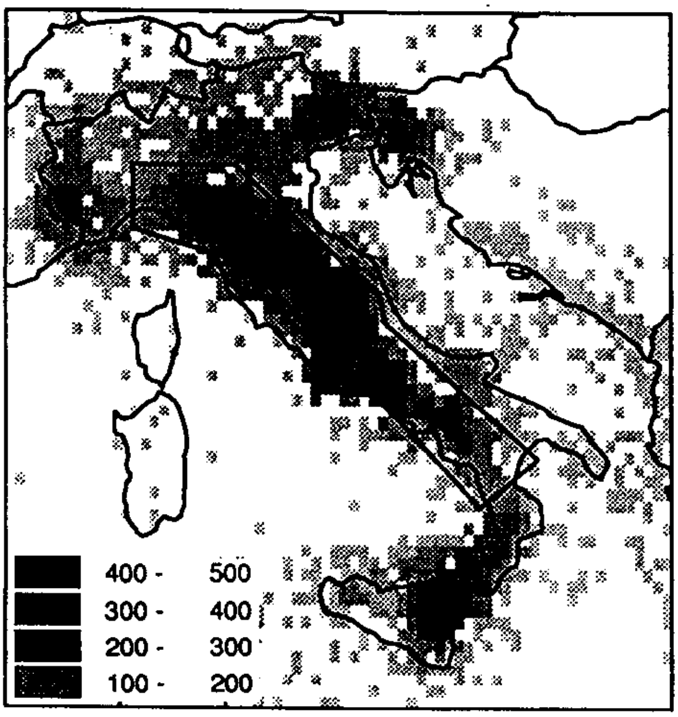

Figure 7. New regionalization for the diagnosis of TIPs superimposed to the map of seismicity. In the map is represented the total number of earthquakes smoothed within a 0.6° diameter circle. Each smoothing circle is centered on the knots of a grid of 0.2°x0.2°. Different shading correspond to the ranges of the number of the events shown in the scale. The main shocks catalogue from 1000 to 1990 has been used.

On the basis of these seismotectonic considerations, a new regionalization is proposed. The new regionalization (e.g. see fig. 7) includes the seismicity maxima present in the Apennines and the extensional areas oriented NW-SE, and excludes the Ancona zone and the Gargano region. The Ligurian Sea, Tyrrhenian Sea and the coasts of Toscana are also not included, since the very low seismicity in these areas does not occur in the periods just before the TIPs (fig. 4-7), and therefore does not influence the functions used by the CN algorithm.

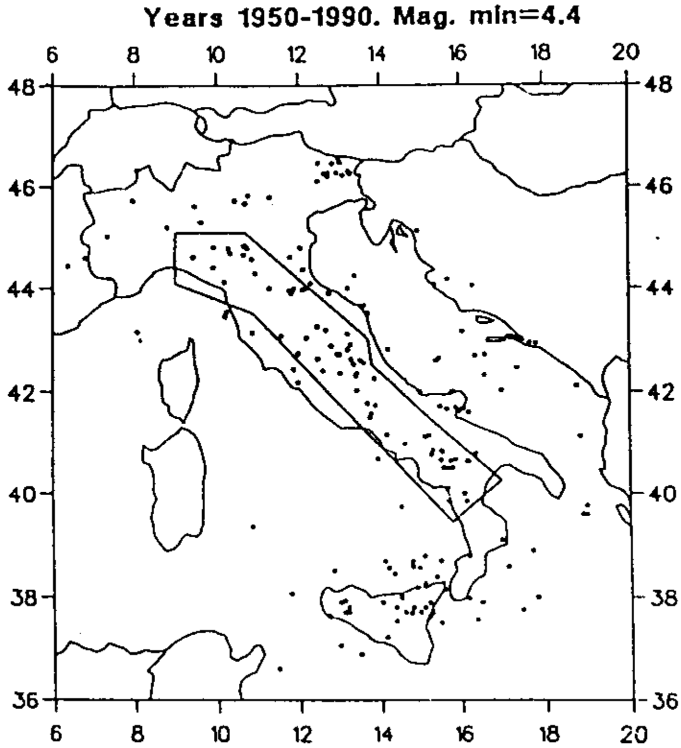

Figure 8. New regionalization for the diagnosis of TIPs and main events with magnitude M≥4.4. Catalogue ENEL-CSEM-ING.

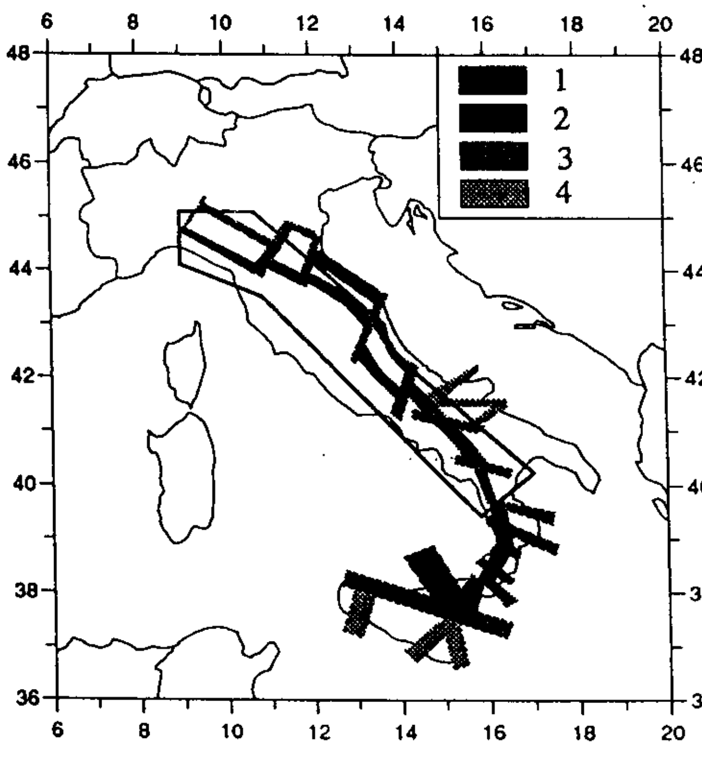

Figure 9. New regionalization superimposed to the seismotectonic map of Patacca et al. (1990): 1) extensional areas, 2) compressional areas, 3) transition areas and 4) areas of fracture in foreland zone.

In a first step the analysis of Keilis-Borok et al. (1990) has been repeated with the new regionalization, using the catalogue ENEL-CSEM-ING. In this case there are 4 strong events, all predicted (no failures to predict), and the total alarm period is about 32% of the total time (table 3).

Start of TIP	Strong earthquake		End of false alarm	Duration of TIP, months
	Date	M		
1/3/1956			1/7/1957	16
1/1/1958			1/11/1960	34
1/7/1962	21/8/1962	5.8;6.0		2
1/11/1965			1/5/1968	30
1/3/1980	23/11/1980	6.5		9
1/1/1984	7/5/1984	5.7		4
7/5/1984			1/11/1986	30
1/5/1988			1/7/1990	14

Table 3. Strong earthquakes and TIPs for the new regionalization (M_0=5.6, V=5, E=4.9) accordingly with catalogues ENEL-CSEM-ING (1950-1991).

In a second step a new catalogue has been prepared. For the period 1900-1979, the new catalogue is formed by the catalogue PFG, which is the revised version of the ENEL catalogue. From 1980, the catalogue ING has been used. The magnitude M_l (local magnitude) has been considered whenever available; if M_l is not available, the values M_I (magnitude from intensity), in PFG catalogue, and M_d (duration magnitude), in ING catalogue, have been used.

In the new catalogue the event of 7/5/1984 has a magnitude, 5.4, less than M_0=5.6, thus there are only 3 strong earthquakes. All of them have been predicted and the total alarm occupies about the 23% of the total time. This percentage is significantly less than the one determined from the analysis done with the ENEL-CSEM-ING catalogue (table 4).

The area considered with the new regionalization is only about the 15% of the one used by Keilis-Borok et al. (1990), therefore, the number of earthquakes is significantly reduced. The histogram Number of events-Magnitude has a minimum for M just less than 5.4. Events with such a magnitude have a return period of about 6 years. Therefore the analysis has been made using the value of M_0=5.4. In this case there are 5 strong events, 4 of which are predicted and the alarm occupies about 30% of the total time (table 5).

Start of TIP	Strong earthquake		End of false alarm	Duration of TIP, months
	Date	M		
1/9/1957			1/7/1960	34
1/9/1961	21/8/1962	5.8;6.0		12
1/11/1979	23/11/1980	6.5		13
1/1/1984			1/11/1987	44

Table 4. Strong earthquakes and TIPs for the new regionalization (M_0=5.6, V=5, E=4.9) accordingly with catalogues PFG-ING (1950-1991).

Start of TIP	Strong earthquake		End of false alarm	Duration of TIP, months
	Date	M		
1/9/1957			1/3/1961	42
1/9/1961	21/8/1962	5.8;6.0		12
1/3/1972			1/7/1975	40
	19/9/1979	5.5		failure
1/11/1979	23/11/1980	6.5		13
1/1/1984	7/5/1984	5.4		4
7/5/1984			1/11/1986	30

Table 5. Strong earthquakes and TIPs for the new regionalization (M_0=5.4, V=5, E=4.9) accordingly with catalogues PFG-ING (1950-1991).

3 PERIOD 1904-1940

The analysis of the PFG catalogue shows that information, sufficiently complete for the use of the algorithm CN, is contained also in the period 1904-1940, the incompleteness of the catalogue in the period 1941-1953 being strongly correlated with World war 2. Therefore the algorithm CN has been applied also to the period 1904-1940. The seismicity in this time interval is higher than in the period 1954-1991 and the magnitude corresponding to events with a return period of about 6 years in the area is about 6, i.e. M_0=6.0.

Start of TIP	Strong earthquake		End of false alarm	Duration of TIP, months
	Date	M		
1/ 3/1904			1/ 3/1905	12
1/ 7/1910			1/ 1/1914	42
	13/ 1/1915	6.8		failure
1/ 5/1918	7/ 9/1920	6.3		28
7/ 9/1920			1/ 7/1922	22
1/11/1923			1/11/1925	24
1/ 9/1929	23/ 7/1930	6.5		11
23/ 7/1930			1/ 9/1931	13
1/ 7/1939			1/11/1940	16
1/ 1/1941			1/ 1/1941	0

Table 6. Strong earthquakes and TIPs for the new regionalization (M_0=6.0, V=5, E=4.9) accordingly with catalogue PFG (1904-1941).

Start of TIP	Strong earthquake		End of false alarm	Duration of TIP, months
	Date	M		
1/ 3/1904			1/ 5/1906	26
1/ 7/1907			1/ 9/1908	14
	7/ 6/1910	5.9		failure
	28/ 6/1913	5.6		failure
1/ 9/1914	27/10/1914	5.7		2
	13/ 1/1915	6.8		failure
1/ 5/1918	10/11/1918	5.7		6
10/11/1918			1/ 9/1919	10
	7/ 9/1920	6.3		failure
1/ 7/1924			1/ 7/1925	12
1/ 5/1929	23/ 7/1930	6.5		15
1/11/1939			1/ 1/1941	14

Table 7. Strong earthquakes and TIPs for the new regionalization (M_0=5.6, V=5, E=4.9) accordingly with catalogue PFG (1904-1941).

The results obtained for M_0=6.0 are reportedin table 6. The number of strong events is 3, 2 of them are predicted, and the alarm occupies about 38.0% of the total time. If the value of M_0 is decreased to 5.6 the number of strong events becomes 7, 3 of them are predicted, and the alarm duration is equal to 22.3% of the total time (table 7). In both cases the learning period used goes from 1904 to 1940.

Even if the level of seismicity in the earlier time interval is much higher than in the later one, the good results of the diagnosis of TIPs for each item separately indicate that self-similarity seems to characterize the seismicity of the two periods.

4 CONCLUSION

A significant reduction of the spatial uncertainty in the identification of a TIP has been obtained using a regionalization based not only on catalogue completeness but also on analysis of seismicity and seismotectonic evidences. The new regionalization occupies 15% of the area used by Keilis-Borok et al. (1990). The use of this new regionalization for the analysis of the TIPs, using the CN algorithm, permits to reduce the false alarms and the failures to predict.

The analysis of the period 1904-1940 shows that even when the catalogue completeness threshold corresponds to a magnitude as high as 4.0 (Caputo and Postpischl, 1974) the CN algorithm gives still useful information. The comparison of the results obtained in the period 1904-1940 and in the period 1954-1991 supplies a further evidence in favour of the existence of self-similarity in the occurrence of earthquakes (e.g. Kagan and Knopoff, 1981).

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