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A proposal of regionalization for the application of the CN earthquake prediction algorithm to the Italian territory

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Abstract

A regionalization of the Italian territory, strictly based on seismotectonic zoning and the main geodynamic features of the Italian area, is proposed for intermediate-term earthquake prediction with CN algorithm. Three regions, composed of adjacent zones with the same seismogenic behaviour or with transitional properties, are selected for the north, centre and south of Italy, compatibly with the kinematic model. This regionalization allows us an average reduction of the spatial uncertainty of about 35% for the northern and central regions, and of about 70% for the southern region in comparison with previous studies. A general reduction of the percentage of total TIPs, with respect to the results obtained neglecting the seismotectonic zoning, has been observed as well. Therefore, it seems that the seismotectonic model is a useful tool selection of the fault systems involved in the preparation of strong earthquakes. The successful attempt of catalogue upgrading, accomplished using the NEIC Preliminary Determinations of Epicentres, appears to substantiate the robustness of the algorithm against changes in the catalogue.

Key words *earthquake prediction – CN algorithm – Italy – seismotectonic model*

1. Introduction

By means of the analysis of the seismic flow, the CN algorithm identifies the Time of Increased Probability (TIP) for the occurrence of an earthquake with magnitude greater than or equal to a fixed threshold M_0. Although CN has been designed by the retrospective analysis of the seismicity of California-Nevada, a region characterised by predominant strike-slip and thrust tectonics, it is currently used in several different areas of the world, without the necessity to adjust the parameters, because its functions are normalised by the level of the seismic activity of the considered region (Gabrielov *et al.*, 1986; Keilis-Borok and Rotwain, 1990).

After the first application of the CN algorithm to Italy (Keilis-Borok *et al.* 1990), Costa *et al.* (1995) showed that the results of predictions are sensitive to the choice of the region. In particular, they observed that a regionalization, roughly based on seismological and tectonic arguments, improves the stability of the algorithm, while reducing the percentage of TIPs and the failures to predict. In this work we consider a regionalization of the Italian territory defined following closely the borders of the seismotectonic zoning proposed by GNDT (Gruppo Nazionale per la Difesa dai Terremoti)

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in 1994 (Scandone *et al.*, 1994), with the purpose to further reduce the time-space uncertainty of the predictions. Since CN allows us to deal with regional geodynamic models, involving relations between the structural features and the choice of the optimal causative fault system for prediction purposes (Rundkvist and Rotwain, 1994; Costa *et al.*, 1996), the algorithm may be viewed as a tool to verify a given seismotectonic zoning.

The catalogue used for CN application to the Italian territory is the CCI1996 (Peresan *et al.*, 1997), indicated as CCI in the following, resulting from the revision of the PFGING catalogue (Postpischl, 1985; Costa *et al.*, 1995) accomplished according to the recent information supplied by Boschi *et al.* (1995), mainly regarding historical events. In order to provide timely predictions, the monitoring is currently performed updating the CCI catalogue with the NEIC Preliminary Determinations of Epicentres (shortly indicated as PDE). The procedure of data upgrading and the preliminary analysis necessary to preserve a certain homogeneity in the catalogue (Peresan and Rotwain, 1998), is briefly described here and the resulting catalogue is named CCIPDE.

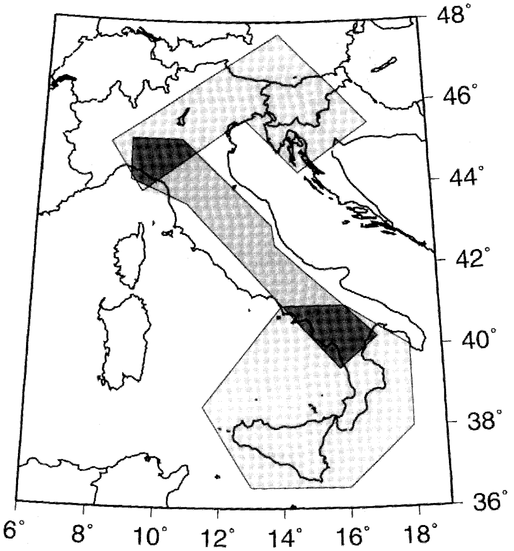

Fig. 1. Regionalization proposed for CN application to the Italian territory by Costa *et al.* (1996). The three region, partially overlapping, have been defined on the basis of the seismicity distribution and by roughly taking into account the seismotectonic model.

2. The regionalization

A choice of the region supported by seismological and tectonic evidence is essential to obtain reliable results and to minimise the time-space uncertainty of predictions. Previous applications of the CN algorithm to the Italian territory (Keilis-Borok *et al.*, 1990; Costa *et al.*, 1995, 1996 and 1997) led to the identification of three main regions, partially overlapping and corresponding approximately to the north, centre and south of Italy. Their borders were drawn close to seismicity minima and by roughly taking into account the regional seismotectonic model (fig. 1).

The complex geodynamic behaviour of the Italian peninsula, controlled by the Africa-Europe plate interaction and by the passive subduction of the south-western margin of the Adriatic plate (Meletti *et al.*, 1995), determines the coexistence of extremely fragmented and heterogeneous seismogenic structures. This complexity suggested the possibility to test a new criterion for the definition of the regions, following closely the borders of the seismotectonic zones proposed by Scandone *et al.* (1994) (fig. 2), a revised version of the preliminary zoning described by Scandone *et al.* (1990).

Regions defined for prediction purposes have to be as small as possible but must include the major seismic zones, where stronger earthquakes are expected. This choice clearly affects the frequency-magnitude distribution for events which occurred within each region, generally showing an upward bend starting at a certain magnitude. According to the standard procedure, the magnitude threshold M_0 for the selection of the events to be predicted is chosen close to this minimum in the number of events, because this guarantees the stability of the results (Molchan *et al.*, 1990, 1997; Costa *et al.*, 1995). Substantially, CN makes use of the information given by small and moderate earthquakes to predict the stronger earthquakes, which are rare events.

The area selected for the application of the CN algorithm must satisfy the following general rules: a) its linear dimensions must be about $5L$-$10L$, where L is the length of the expected source; b) the border of the region must correspond, as much as possible, to minima in the seismicity; c) on average, at least 3 events with magnitude over the completeness threshold should occur inside the region each year (Keilis-Borok and Rotwain, 1990). The quite large dimensions of the regions to be used for prediction purposes are intrinsically connected to the concept that earthquakes are due to the critical interaction of extended fault systems, and thus the analysed system may exhibit long range interactions. Nevertheless, once the diagnosis of a TIP is given for a certain region, it is possible to attempt a reduction of the area, where

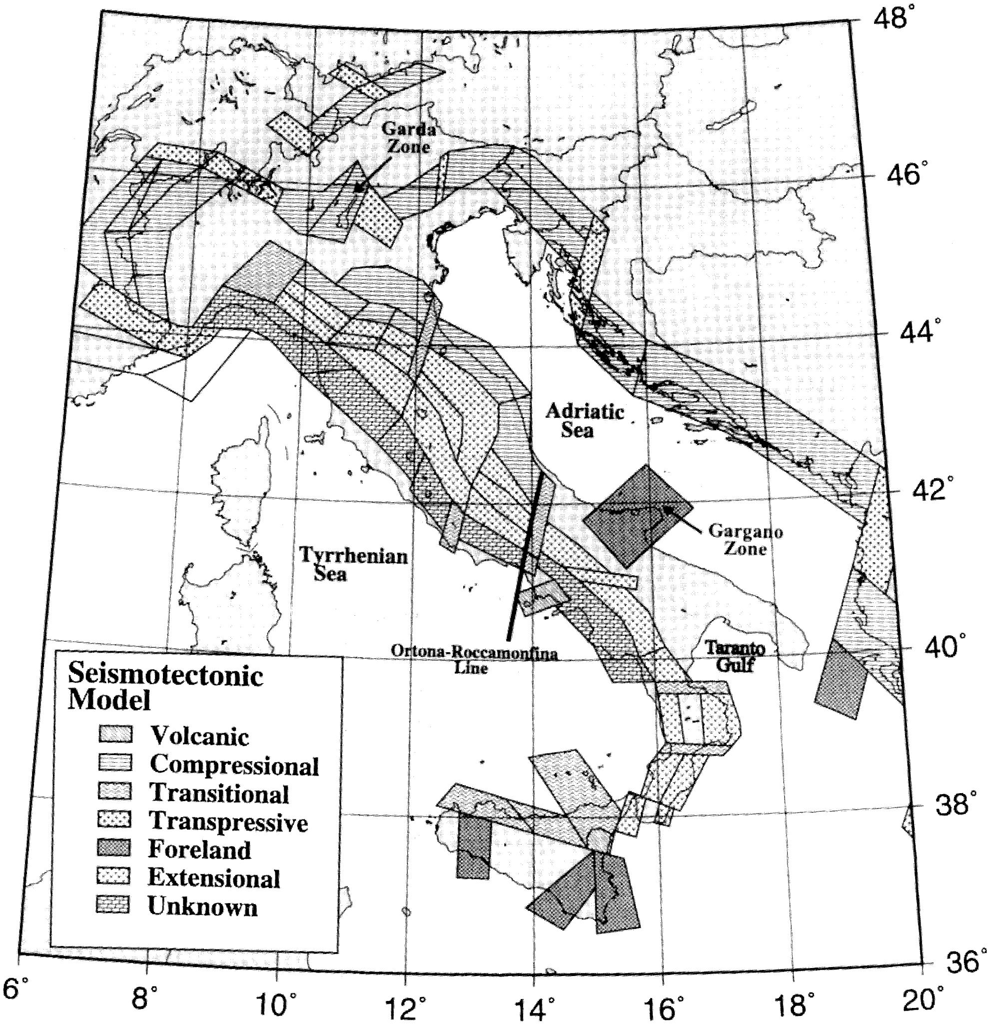

Fig. 2. Seismotectonic model of the Italian territory proposed by Scandone *et al.* (1994).

the strong event is expected, looking for further symptoms of instability in local seismicity and in a lower range of energy. Hence, the application of the algorithm named Mendocino Scenario (Keilis-Borok, 1996) requires a catalogue complete for a wide range of magnitude (about 4 units of magnitude below M_0). This indicates that the possibility to reduce the spatial uncertainty of predictions is limited by the completeness of data and by the difficulty of keeping the level of detection high.

Even if the normalisation of functions permits the application of the CN algorithm to regions with different seismicity, the following

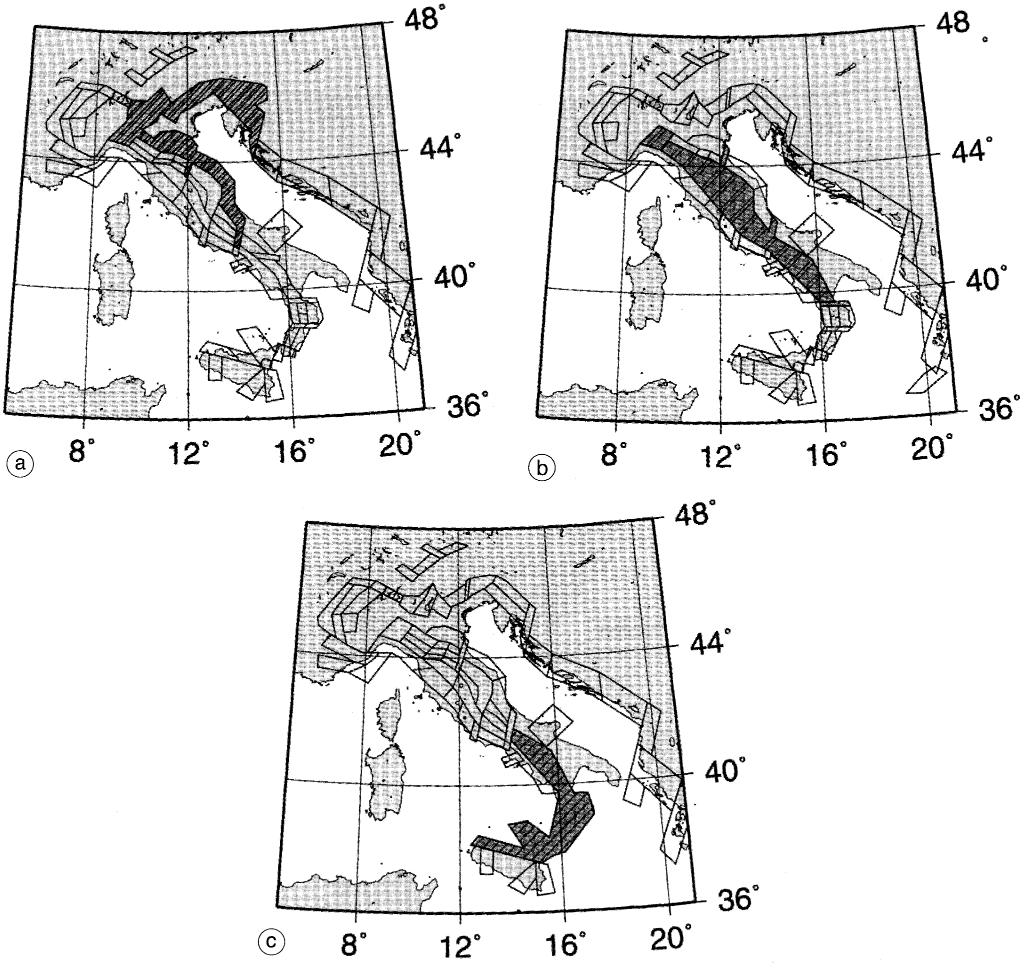

Fig. 3a-c. Regionalization of the Italian territory, defined closely following the seismotectonic model. a) Northern region: the compressional and transpressive zones along Eastern Alps and Northern Apennines and the seismogenic zoning of the Slovenian-Croatian territory (Zivcic *et al.*, 1997) is taken into account; b) central region: it includes the extensional belt north of the Calabrian arc and the transition zones at the edges; c) southern region: it includes the extensional band south of the Ortona-Roccamonfina line.

rule has been formulated in order to construct regions with some homogeneity in the seismotectonic regime. Each region includes only zones with the same seismogenic characteristics (*e.g.*, only compressive or only extensive) and the adjacent zones with transitional properties. A transitional zone is included in a region only if it is between zones of the same kind, or if it is located at the edges of the region and the space distribution of the aftershocks reveals a possible connection. For this purpose the identification of aftershocks is performed with the «minimax» method, proposed by Molchan and Dmitrieva (1992). Accordingly, the three regions shown in fig. 3a-c have been defined.

3. The updated catalogue

CN application to a fixed region consists of two steps: at a first stage, referred to as learning step, the magnitude M_0, the magnitudes for normalisation of functions and the thresholds for discretization of functions are defined. In the second step the monitoring of seismicity is performed using the parameters fixed in the learning phase. Thanks to the normalisation of its functions, when the general conditions of applicability of the algorithm are satisfied, CN can be applied to regions with a different seismicity level without any adjustment of parameters. Nevertheless, it is important to preserve the time homogeneity of the catalogue, since relevant variations could affect the results.

The monitoring of seismicity with CN algorithm is performed with a time step of two months and with a catalogue updated with a time delay of a couple of weeks. The catalogue used for CN application in Italy, up to July 1997, was the CCI1996 (Peresan *et al.*, 1997), that is a revised version of the PFGING catalogue (Costa *et al.*, 1995), composed of the PFG catalogue (Postpischl, 1985) for the period 1900-1979 and updated with the ING bulletins from 1980 to July 1997. Recently, in order to perform a timely upgrading of predictions, the necessity arose to make use of a different data set. Among the available databases we used the PDE data (Preliminary Determinations of Epicentres yearly, monthly, weekly revised versions and Quick Epicentral Determinations), officially distributed by NEIC in the Earthquake Hypocentres Data File version. The PDE catalogue, analysed for the entire Italian area (rectangle with Lat.: 35-50N and Long.: 5-20E), appears to satisfy the general conditions required for CN application, since it can be considered complete for magnitudes greater than 3.0, at least after 1985, and it is updated rapidly enough.

The CN algorithm requires an input catalogue that must be, as far as possible, homogeneous in time. The time homogeneity of the catalogue can be evaluated on the basis of the Gutenberg-Richter distribution. In the present case we are mainly concerned about the possible inhomogeneity that may result appending the PDE catalogue to the CCI catalogue. Therefore we require that the parameters of the frequency-magnitude distribution and the number of events do not change significantly passing from one catalogue to the other. CCI contains four estimations of magnitude: duration magnitude M_d, magnitude from intensities M_I, local magnitude M_L and body wave magnitude m_b from ISC; the priority used to select the operating magnitude in CCI is: M_L, M_d, M_I; m_b from ISC is not used, since it is given just for a few events and for a limited period of time. In the PDE catalogue, for each record, there are four possible different estimations of magnitude: m_b from NEIC, M_s from NEIC, $M1$ and $M2$; the last two values may correspond to magnitudes of different kind, supplied by different agencies. A preliminary analysis of the catalogue disclosed that, for the Italian area, both $M1$ and $M2$ are mainly M_L and M_d (are about ten times more frequent than M_d). In order to define a priority for the PDE catalogue that allows a choice of magnitude as homogeneous as possible with that of the CCI catalogue, we perform the following analysis:

1) A subcatalogue of events common to the CCI and PDE catalogues is selected and each magnitude from one catalogue is compared to the four estimations of the other catalogue. The linear regression (minimising distances normal to the fitting line), the standard deviation σ and the percentage P of points outside 2σ are calculated for each pair of magnitudes.

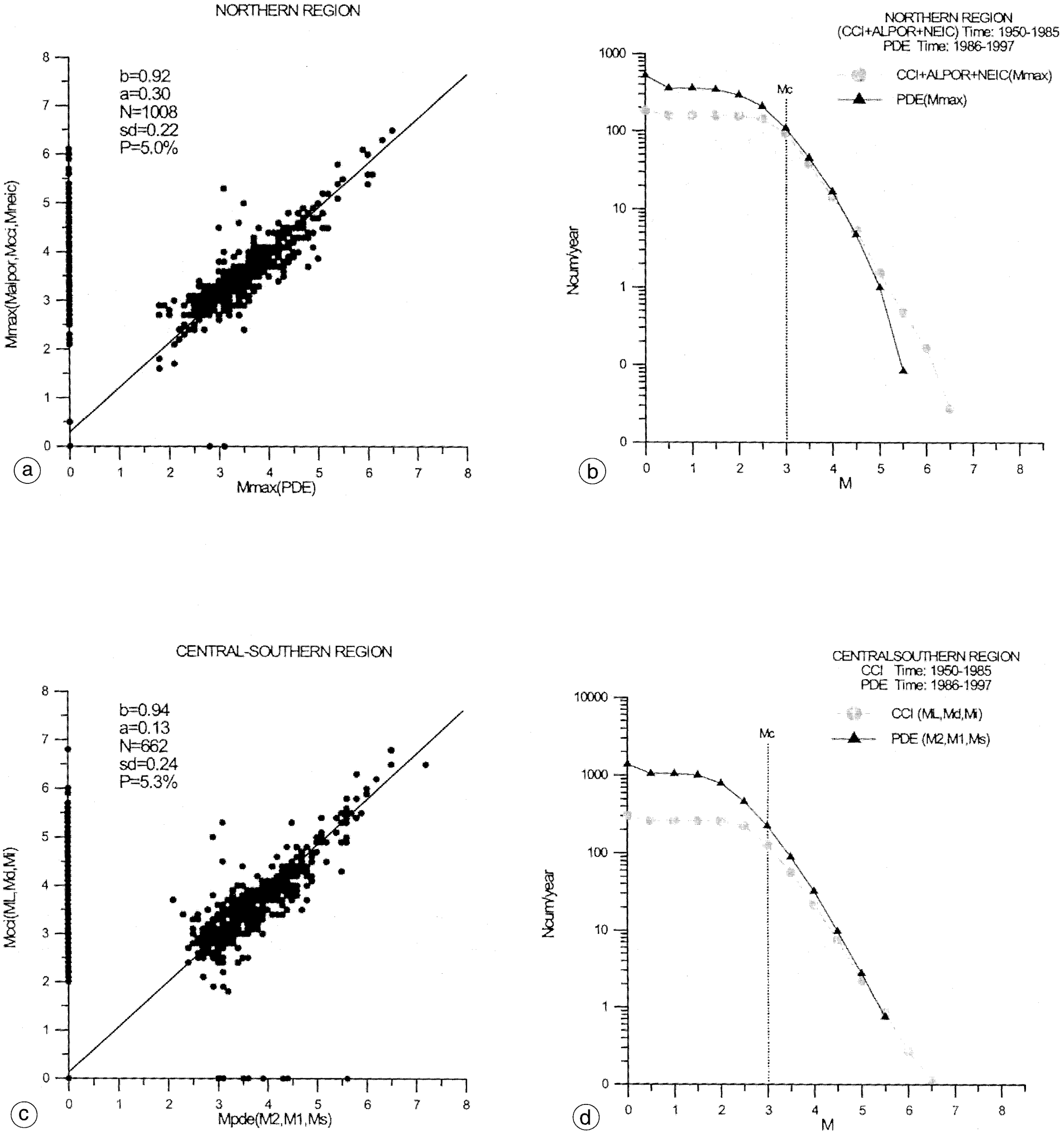

Fig. 4a-d. Diagrams considered to compare CCI and PDE catalogues, showing the distribution of M_{priority} (CCI) *versus* M_{priority} (PDE) for the common events and the Gutenberg-Richter relation for the consecutive intervals of time in which the different catalogues are used. The values reported in (a) and (c) are: the coefficients *a* and *b* of the fitted line; the number *N* of events used for the fitting; the standard deviations *sd*; the percentage *P* of points outside 2 standard deviations. The events for which no estimation of magnitude is given in one of the two catalogues (corresponding to the points lying on the axis) are not used in the regression.

2) For each of the three magnitudes M_L, M_d and M_l in the CCI catalogue a corresponding magnitude from PDE is selected, according to the rule that the standard deviation σ is minimal for this magnitude, P is small, and the parameters a and b of the fitting line: $M(\text{CCI}) = bM(\text{PDE}) + a$ are as close as possible to zero and one, respectively. Once the correspondence between magnitudes is found, the priority defined for the CCI catalogue can be transferred to the PDE.

3) The operating magnitude is selected from PDE according to the priority fixed in step 2.

4) The operating magnitudes from CCI and PDE are compared, considering for the common events the distribution of $M_{\text{priority}}(\text{CCI})$ *versus* $M_{\text{priority}}(\text{PDE})$.

5) The Gutenberg-Richter relations obtained with the CCI catalogue, for the period of time 1900-1985, and with the PDE catalogue for the time interval 1986-1997, are compared (fig. 4b,d).

According to the described procedure, a suitable choice of priority for magnitudes in the PDE catalogue appears to be M_{PDE} ($M2$, $M1$, M_S) for the central and southern regions and M_{PDE} (M_{max}) for the northern region (fig. 4a-d). The analysis was performed separately for the northern on one side and the central and southern regions on the other, because due to the presence of political borders across the Alpine arc, the catalogue CCI is fairly incomplete for CN application in the northern region. Consequently, according to Costa *et al.* (1996), the data have been integrated with the information contained in two other catalogues: ALPOR (Catalogo delle Alpi Orientali, 1987) and NEIC (PDE). The operating magnitude was selected as the maximum among M_{ALPOR} (M_L, M_l), M_{CCI} (M_L, M_d, M_l) and M_{NEIC} ($M1$, M_S, m_b), where the magnitudes in brackets indicate the priority chosen for each catalogue. The resulting catalogue will be indicated below as CCI + ALPOR + NEIC.

Once the operating magnitude has been selected, the catalogue for monitoring is compiled using the CCI data for the learning period and the PDE data for the forward analysis. In this way the learning is performed using the best available data, since CCI is more complete than PDE, while the forward monitoring is done using the currently updated available data (PDE). More details about the procedure of catalogue upgrading are given by Peresan and Rotwain (1998).

4. Northern region

From the geodynamic point of view, Northern Italy is characterised by the Africa-Europe convergence and by the counterclockwise rotation of the Adria plate, subducting under the Eastern Alps and Northern Apennines (Anderson and Jackson, 1987; Ward, 1994). A long compressional band, segmented by transpressive zones, extends from Hellenides, along Dinarides, to Southern Alps, which are generally uplifting (Mueller, 1982), and marks the border between Northern Apennines and the Adriatic Sea, till the Ortona-Roccamonfina line (fig. 1).

The extension of first-order geological structures outside the Italian borders necessitates drawing the boundaries of the north-eastern part of the region following the seismotectonic zoning proposed by Zivcic *et al.* (1997) for the Slovenian-Croatian territory.

The catalogue used for the northern region (CCI + ALPOR + NEIC) is complete for $M \geq 3.0$ beginning from 1960, and the threshold for the selection of events to be predicted is fixed at $M_0 = 5.4$, which corresponds to a minimum in the histogram of the number of main shocks *versus* magnitude (fig. 5). Only events with depth up to 100 km are considered and aftershocks are removed following the criteria proposed by Keilis-Borok *et al.* (1980), with space-time windows depending on the magnitude of the main event.

Some possible variants of regionalization have been considered. Initially we tested the possibility to include in the region the whole compressional band running along the Alps, from the Istrian peninsula to Liguria. Nevertheless, going from east to west, there are remarkable structural changes, and the Adria plate subduction under the Eastern Alps turns into overthrusting in the Western Alps, to become again subduction under the Northern Apennines (Scandone *et al.*, 1996). The unsatisfactory results obtained using this region are probably due to

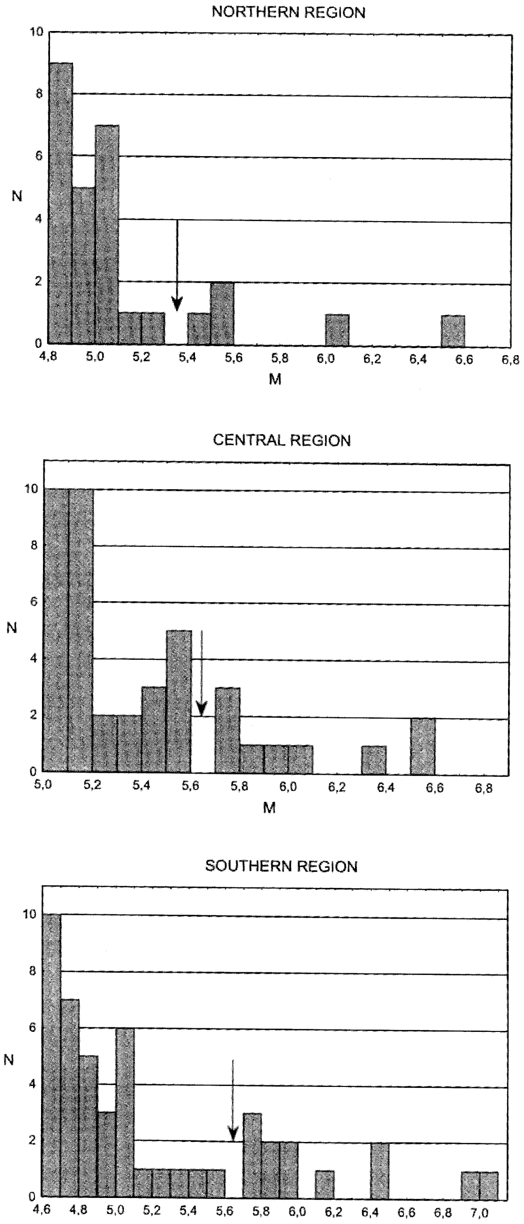

Fig. 5. Histograms of the number of events *versus* magnitude considered for the choice of the threshold M_0 for the definition of the events to be predicted. The arrows indicate the selected values in each of the three regions.

the structural and tectonic variations and to the different level of seismic activity, mainly related to the rotation of the Adria plate, together with a different completeness of the catalogue used (Molchan *et al.*, 1995).

As a second step, we analysed the seismicity of the Eastern Alps separately, taking into account the regions defined for Northern Italy by Costa *et al.* (1996), shown in fig. 1; these experiments disclosed a certain instability of the results, with respect to the location of the western boundary of the region corresponding to the Garda zone (fig. 2).

In a further step, we extended the region to include the compressive band along the Adriatic Sea; this extension allows us both to eliminate the instability previously detected and to reduce the percentage of TIPs. The region (fig. 3a) includes the northern extremity of the External Dinarides and the eastern part of the Southern Alps, then it includes the transition zone at the northern edge of the Apennines and the compressional band to the Ortona-Roccamonfina line. This regionalization is compatible with the kinematic model of rotation and subduction of the Adriatic microplate (Anderson and Jackson, 1987; Ward, 1994) and indicates a possible connection between the earthquakes that occur within the compressional band marking its boundaries.

The results obtained applying the CN algorithm to the new region and using the CCI catalogue, updated to July 1997, can be summarised as follows: both events with $M \geq M_0$ ($M = 6.5$, May 6, 1976 and $M = 5.4$, February 1, 1988) are correctly identified, with TIPs covering about 19% of the total time and 2 false alarms (table I and II and fig. 6a), while the reduction of the spatial uncertainty, with respect to the regionalization of Costa *et al.* (1996), shown in fig. 1, is about 38%.

The stability of the results has been satisfactorily tested with respect to changes in the learning period and to the exclusion of the transition zone containing the Ortona-Roccamonfina line.

Subsequently, the algorithm was applied to the updated catalogue composed of the ALPOR + CCI + NEIC for the time interval 1964-1994, corresponding to the learning period, and by

Table I. Results obtained applying the CN algorithm in Italy, using the three regions presented in fig. 3a-c. Two different catalogues have been considered: the CCI1996 and the CCIPDE, described in the section «The updated catalogue». The corresponding TIPs diagrams are shown in figs. 6a-c and 7a-c.

	Northern region		Central region		Southern region	
Catalogue	CCI	CCIPDE	CCI	CCIPDE	CCI	CCIPDE
Time of analysis	Jan. 1960 Jul. 1997	Jan. 1960 Nov. 1998	Jan. 1950 Jul. 1997	Jan. 1950 Nov. 1998	Jan. 1950 Jul. 1997	Jan. 1950 Nov. 1998
Learning period	Jan. 1964 Dec. 1994	Jan. 1964 Dec. 1994	Jan. 1954 Mar. 1986	Jan. 1954 Mar. 1986	Jan. 1954 Dec. 1986	Jan. 1954 Dec. 1986
M_0	5.4	5.4	5.6	5.6	5.6	5.6
Strong events	2	4	3	6	4	5
Predicted	2	4	3	6	4	4
Failures to predict	0	0	0	0	0	1
% of TIPs	19.0	24.9	18.2	22.1	38.1	34.4
False alarms	2	2	2	2	6	5

Table II. List of the events to be predicted which occurred within the three regions shown in fig. 3a-c, and reported in the updated catalogue CCIPDE. For each event, the part of the catalogue to which the record belongs (CCI or PDE), is indicated as «source catalogue».

	Time			Coordinates		M	Source catalogues
	Year	Month	Day	Lat.	Long.		
Northern region	1976	5	6	46.23	13.13	6.5	CCI
	1988	2	1	46.22	13.08	5.4	CCI
	1996	10	15	44.79	10.78	5.8	PDE
	1998	4	12	46.24	13.65	6.0	PDE
Central region	1962	8	21	41.15	15.00	5.8	CCI
	1962	8	21	41.15	15.00	6.0	CCI
	1980	11	23	40.85	15.28	6.5	CCI
	1997	9	26	43.05	12.88	5.7	PDE
	1997	9	26	43.08	12.81	6.0	PDE
	1998	9	9	40.03	15.98	5.7	PDE
Southern region	1957	5	20	38.70	14.10	5.8	CCI
	1962	8	21	41.15	15.00	5.8	CCI
	1962	8	21	41.15	15.00	6.0	CCI
	1980	11	23	40.85	15.28	6.5	CCI
	1998	9	9	40.03	15.98	5.7	PDE

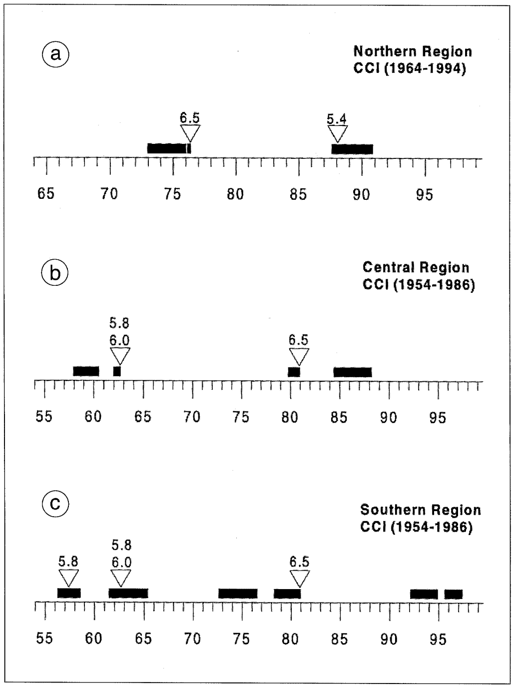

Fig. 6a-c. TIPs obtained with the CCI1996 catalogue, updated to July 1997, for the three regions shown in fig. 3a-c. The learning period is indicated in brackets, while the time of occurrence of a strong earthquake is indicated by a triangle with a number above it, giving the magnitude of the event (see also tables I and II).

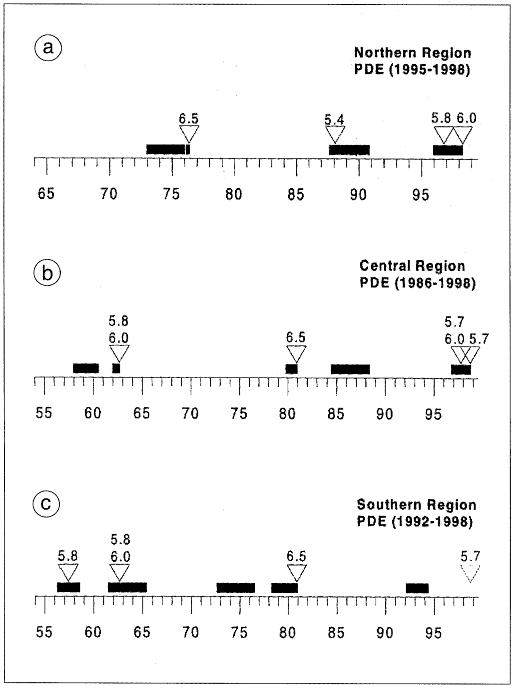

Fig. 7a-c. TIPs obtained using the PDE catalogue (see also tables I and II). The catalogue named CCIPDE is composed by the CCI1996 catalogue, for the learning period, and by the PDE determinations (NEIC) for the subsequent time interval. The time interval in which PDE data are used is given in brackets.

PDE since 1995, that is the period of forward predictions. The operating magnitude for PDE, in this area, is chosen to be the maximum one, because $M_{\text{PDE}}(M_{\max})$, according to the analysis previously described, appears homogeneous to the maximum magnitude among $M_{\text{ALPOR}}(M_L, M_I)$, $M_{\text{CCI}}(M_L, M_d, M_I)$ and $M_{\text{NEIC}}(M_L, M_s, m_b)$, that was used for the catalogue ALPOR + CCI + NEIC. The results of application of the CN algorithm to the obtained catalogue, updated to November 1998, show that all four events with $M \geq M_0 = 5.4$ which occurred within the region, from March 1964 to November 1998, are correctly preceded by a TIP, with alarms covering about 25% of the total time and two false alarms (tables I and II). The diagram showing the time distribution of TIPs and the occurrence of strong events in the northern region is given in fig. 7a. Comparing the TIPs diagram obtained with the catalogue ALPOR + CCI + NEIC to that obtained with the updated catalogue (see figs. 6a and 7a), it is possible to observe that in the second one there are two strong events, both of which occurred after the end of the learning period and correctly preceded by TIPs. In particular, the event with $M = 6.0$ which occurred on April 12, 1998 in Slovenian territory, is a real forward prediction. This success appears to validate the new regionalization and to support the robustness of the algorithm, showing that the change in the catalogue does not compromise its predictive power.

5. Central region

The Apenninic chain can be separated into two major arcs, connected along the Ortona-Roccamonfina line and corresponding to the Northern and Southern Apennines. Their evolution seems to be completely controlled by passive subduction processes (Scandone *et al.*, 1996), hence their shape is due to the differential sinking of the lithosphere with varying velocity of retreat of the axis of flexure. As a consequence of the passive subduction of the Adria plate, the Apennines are characterised by a belt with prevailing dip-slip focal mechanism, extending along the whole Italian peninsula, from the Po plain to the Calabrian arc. A belt, composed of purely extensional seismogenic zones, runs parallel to it along the Tyrrhenian margin, while a compressional belt marks the boundary between the Northern Apennines and the Adriatic Sea.

According to the general rule formulated for the regionalization, we exclude the foreland Gargano zone and we include in the region only the central belt with tensional characteristics and the transitional zones connected to them. This choice is in agreement with the model proposed by Meletti *et al.* (1995) for the deep structure of the Northern Apennines, that indicates a connection at depth between the Adriatic compressional front and the uplifting of the asthenosphere along the Tyrrhenian rim. This model is supported by the studies performed on the lithosphere-asthenosphere system, such as heat-flow and gravimetric measurements and seismic waves analysis (Panza *et al.*, 1980; Calcagnile and Panza, 1981; Della Vedova *et al.*, 1991; Marson *et al.*, 1995). Some experiments made perturbing the regionalization indicate that the central tensional belt cannot be separated along the Ortona-Roccamonfina line, because the Irpinia earthquakes in 1962 and 1980 and their precursors seem to affect the seismic activation even in the Northern Apennines. In both cases the alarm was activated by the occurrence of a quite strong event ($M = 4.9$ on October 31, 1961 and $M = 5.4$ on September 19, 1979) and by the associated seismic activity (bursts of aftershocks) that took place north of L'Aquila.

Catalogue CCI was used, with aftershocks removed according to Keilis-Borok *et al.* (1980), and considering only shallow earthquakes (with depths lower than 100 km), in conformity with the standard rules for the application of the CN algorithm. The selection of the operating magnitude follows the priority order: M_L, M_d, M_I. Consequently, the catalogue can be considered complete for $M \geq 3.0$ since 1950, and the threshold for the identification of strong events is fixed at $M_0 = 5.6$ (fig. 5).

The results obtained for the Central region (fig. 3b) can be summarised as follows: all three strong earthquakes ($M = 5.8$ and $M = 6.0$, both on August 21, 1962 and the Irpinia earthquake, with $M = 6.5$, on November 23, 1980) are correctly identified with TIPs covering about 18% of the total time and two false alarms (tables I and II; fig. 6b). The reduction of the spatial uncertainty, with respect to the regionalization proposed by Costa *et al.* (1996), shown in fig. 1, is almost 30%.

Several tests performed by Costa *et al.* (1995) evidence the stability of CN results for Central Italy. Here we check for possible changes in the results of the forward predictions, when the CCI catalogue is updated, according to the procedure described in the pertinent section above, with the PDE catalogue, that is used from the end of the learning period. The catalogue is constructed using CCI from 1954 to 1985, and PDE since 1986. The priority used for the CCI catalogue is M_{CCI} (M_L, M_d, M_I), while for PDE the priority is M_{PDE} ($M2$, $M1$, M_S), which guarantees a satisfactory homogeneity between the two parts of the catalogue (fig. 4a-d). The results of the application of the CN algorithm in Central Italy are shown in fig. 7b and can be described as follows: all the six strong earthquakes with $M \geq M_0 = 5.6$ which occurred within the region from 1954 to November 1998 are correctly identified with TIPs covering about 22% of the total time and there are two false alarms. The last strong event, an earthquake with $M = 5.7$, occurred on September 9, 1998 close to the southern edge of the region, was predicted in advance, terminating an alarm prolonged after the Umbria-Marche event (September 26, 1998). This result represents a successful test of the adequacy of the regionalization and of the catalogue used and seems to indicate that the CN algorithm can detect the symptoms of instability in the PDE catalogue, with the same parameters and discretization thresholds fixed during the learning period with the CCI catalogue.

6. Southern region

According to the model proposed by Meletti *et al.* (1995), the geodynamics of Southern Italy is controlled by the sinking of the Adriatic-Ionic plate under the Southern Apennines and by the opening of the Tyrrhenian Sea. The flexure retreat, due to the passive subduction in the Southern Apennines, currently seems to continue only in the Calabrian arc, while it has ceased along the extensional belt from the Ortona-Roccamonfina line to the Taranto Gulf; the shear zone characterising Northern Sicily represents the track of the eastward movement of the Calabrian arc (Scandone *et al.*, 1990). Therefore a region, including the whole extensional belt along the Southern Apennines and the connected transitional zones to the western edge of Sicily, has been defined for Southern Italy (fig. 3c).

Following the general regionalization rule, the foreland zones have been excluded, as well as the transitional zone containing the Ortona-Roccamonfina line, because the distribution of aftershocks of the main events which have occurred in the area since 1900 seems not to reveal (Peresan *et al.*, 1999) any connection between this transitional zone and the extensional belt south of it (Molchan *et al.*, 1995). For this purpose the selection of aftershocks is performed using the «minimax» method proposed by Molchan and Dmitrieva (1992), because it allows a better spatial identification of such events, with respect to the method by Keilis-Borok *et al.* (1980). In no case can the algorithm be applied to the region composed of the foreland zones in the south of Sicily and in the Gargano zone, because the small number of recorded events does not satisfy the general conditions of applicability.

The CN algorithm is applied to the southern region (fig. 3c) using the CCI catalogue, that can be considered complete for $M \geq 3.0$ since 1950. As in the central region, only shallow events, with focal depth less than 100 km, are included in the analysis and the threshold for the identification of strong events is fixed at $M_0 = 5.6$ (fig. 5). The four strong events ($M = 5.8$, May 20, 1957; $M = 5.8$ and $M = 6.0$ on August 21, 1962; $M = 6.5$ on November 23, 1980) are correctly identified with TIPs covering about 34% of the total time and 6 false alarms (tales I and II). In Southern Italy the regionalization based on the seismotectonic criteria, allows us to reduce the space uncertainty by about 72%, with respect to the regionalization of Costa *et al.* (1996), shown in fig. 1, increasing at the same time the stability of the algorithm.

The compilation of the updated catalogue CCIPDE for CN application in Southern Italy, presents a further problem since the completeness threshold for the PDE catalogue in this area is about $M = 4.0$ up to 1992, and has only reached $M = 3.5$ since 1992, as shown by Peresan and Rotwain (1998). Therefore, due to the lower completeness threshold in this area, it is not possible to use the PDE for the whole period of forward analysis, but it is necessary to keep CCI at least up to 1991. The functions of seismic flow in the southern region are evaluated using the events with $M \geq 3.8$, while to count aftershocks, the earthquakes with $M \geq 3.0$ are considered. Hence using PDE data since 1992, we must bear in mind that one precursor, based on bursts of aftershocks, could be lost due to the lack of aftershocks, and this increases the probability of failures to predict. Keeping into mind these necessary warnings, the updated catalogue for Southern Italy can be compiled using the CCI for the period: 1954-1991, with magnitude priority $M_{\rm CCI}$ (M_L, M_d, M_I), followed by the PDE (1992-1998), with the same priority $M_{\rm PDE}$ ($M2$, $M1$, M_S), used for the central region. The results of the monitoring updated to November 1, 1998 are the following (tables I-II and fig. 7c): four out of five strong events with $M \geq M_0 = 5.6$ are correctly identified by retrospective analysis, with TIPs covering about 34% of total time and with 5 false alarms. The earthquake with $M = 5.7$ which occurred on September 9, 1998 located in the overlapping part of the two regions, is a failure to predict in Southern Italy, while, as we have seen, it was correctly predicted in the context of the central region.

7. Conclusions

A new regionalization has been proposed to be used for intermediate-term earthquake prediction in Italy, using the CN algorithm. The three regions, defined strictly following the seismotectonic zones, correspond approximately to the north, centre and south of Italy. Each region is composed of adjacent zones with similar seismogenic characteristics or with transitional behaviour, and are compatible with the main geodynamic features of the Italian area.

The new regionalization allows a general reduction of the spatial uncertainty of predictions, on the average around 35%, with respect to the regionalization proposed by Costa *et al.* (1996) for Northern and Central Italy. The reduction of the area appeares particularly remarkable in Southern Italy where, however, the M_0 threshold has also been lowered, making a comparison of the new results with the ones obtained with the previous regionalization difficult. The percentage of total TIPs, indicating the time uncertainty of predictions, is in general reduced and, on average, is close to the global one (Keilis-Borok and Rotwain, 1990; Keilis-Borok, 1996). On the basis of these results, we can conclude that the use of the seismotectonic model, supported by kinematic arguments, optimises the selection of the fault systems involved in the generation of strong earthquakes. The regionalization of the Italian territory, that closely follows the seismotectonic zoning and is compatible with the kinematic model of the Central Mediterranean area, allows a reduction of the space-time uncertainties of predictions. Hence it can be considered adequate for the application of the CN algorithm in Italy.

The CN algorithm seems to be quite robust with respect to the errors that can affect earthquake catalogues. In fact, the inadvertent change in magnitude indicated by Zuniga and Wyss (1995) for the Italian catalogue, in the time period 1980-1981, does not seem to be responsible for the TIP preceding the 1980 Irpinia event, since the TIP duration differs when considering the central and the southern region and, in the same time interval, no false alarm is detected in the northern region.

The robustness of the algorithm has been successfully tested with respect to the upgrading of the Italian catalogue CCI 1996 with the global PDE catalogue distributed by NEIC.

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