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Experiments with Intermediate-term Medium-Range Earthquake Prediction Algorithms in Italy and Seismic Hazard

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PART 1

Experiments with intermediate-term medium-range Earthquake prediction Algorithms in Italy and seismic hazard

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Experiments with intermediate-term medium-range Earthquake prediction Algorithms in Italy and seismic hazard

- Introduction
- Earthquake precursors
- Premonitory seismicity patterns
- Earthquake prediction
- Algorithms M8 and CN
- Evaluation of prediction results
- Integrated deterministic hazard

INTRODUCTION

"Earthquakes' modelling involves a detailed knowledge of the related physics, which is not available at present time. [...] A firm and complete phenomenological picture should be established before any effort can result effective, but such a picture is not easy to draw due to the long time scales involved. [...] The analysis of seismicity patterns is useful not only for prediction purposes, but it provides also the wide set of systematic observations, without which any physically based model remains a merely theoretical speculation."

Earthquake prediction: the scientific challenge

(Knopoff, 1996)

Characteristics of the lithosphere

- Scale invariance of earthquake distribution in time and space
- Self-organization of earthquake occurence
- Non-linear mechanics of earthquake generation
- Statistical features of earthquake sequences

Strongly indicate that the lithosphere behaves as a **deterministic chaotic system** (Keilis-Borok, 1990).

How we can predict earthquakes?

Deterministic prediction?

NO

For complex or chaotic systems, even an accurate modelling would not allow for predictions.

Statistical prediction?

NO

Time scales involved in the seismogenic process are too long and observations too limited.

Possibility: **Identification of precursory phenomena.**

EARTHQUAKE PRECURSORS

Earthquake precursors

Possible precursors are those phenomena that may take place in the lithosphere during the accumulation of stresses.

Difficulty: to establish a clear precursory connection, i.e. to separate the precursory signal from natural fluctuations. This is due to the lack of sufficiently prolonged and systematic records.

"Signals" proposed as earthquake precursors

+ Variations in the seismic activity

+ Changes in the velocity and in the spectral content of seismic waves and earthquakes sources

+ Crustal deformations and variations of the stress in the crust

+ Gravitational, geomagnetic and geoelectrical precursors

+ Anomalous changes in the underground water level and chemical components

+ Anomalies in the atmospheric pressure, temperature and heat flow

IASPEI Preliminary List of Significant Precursors

Validation criteria for precursor candidates:

+ the observed anomaly should be related to some mechanism leading to earthquakes;

+ the anomaly should be simultaneously observed at more than one site or instrument;

+ the definition of the anomaly and of the rules for its association with subsequent earthquakes should be precise;

+ both anomaly and rules should be derived from an independent set of data, than the one for which the precursory anomaly is claimed.

IASPEI Preliminary List of Significant Precursors

Only five possible precursors, out of the forty proposed, seem to deserve further study *(Wyss, 1997)*:

+one based on ground water chemistry,

+one on crustal deformation and

+three on seismicity patterns

PREMONITORY SEISMICITY PATTERNS

Premonitory seismicity patterns

Some changes are observed in the earthquake's flow before a large event.

These changes are akin to the general symptoms of instability of many non-linear systems before a catastrophe (*Keilis-Borok, 1996*).

In particular, the response to a perturbation:

- increases,
- becomes more chaotic and
- acts at long distances.

Premonitory seismicity patterns

- In the case of seismicity the non-linear system is the hierarchical structure made up by the lithospheric blocks and by their boundaries (i.e. faults).
- The large earthquake is a catastrophic event, corresponding to abrupt changes of the system characteristics, that may involve a large domain of the system.
- The small earthquakes may be regarded as sources of perturbation of the system.

Premonitory seismicity patterns

Thus, before a strong earthquake, which represents the collapse of the system, we must observe:

- increase of the seismic activity, clustering of the earthquakes in time and space, and spatial concentration of sources; in other words, the increase of the response to the perturbation;
- increase of the variation of seismicity and its clustering, which reflects the chaotic response to the perturbation;
- long-range interaction of earthquakes, which can be interpreted as an increase of the range of influence of the perturbation.

Single seismicity patterns formally defined as premonitory

- **the *burst of aftershocks*** (*Keilis-Borok et al., 1980; Molchan et al., 1990*)**, which is associated to moderate magnitude events characterised by a large number of aftershocks;**
- **the *seismic quiescence*** (*Wyss et al., 1992*)**;**
- **the relative increase of the *b-value* for the moderate events, with respect to smaller events** (*Narkunskaya and Shnirman, 1994*)**;**
- **the increase of the *spatial correlation* in the earthquake flow and the log-periodic variations of the earthquake flow on the background of its exponential *rise*** (*Bufe et al., 1994*)**.**

Multiple seismicity patterns formally defined as premonitory

- **M8** (*Keilis-Borok and Kossobokov, 1987; Kossobokov et al., 1999*)
- **CN** (*Gabrielov et al., 1986; Keilis-Borok and Rotwain, 1990; Rotwain and Novikova, 1999*)
- **Mendocino scenario** (*Kossobokov, Keilis-Borok, and Smith, 1990; Kossobokov et al., 1999*)**;**
- **Next Strong Earthquake** (*Vorobieva, 1999*)

EARTHQUAKE PREDICTION

What does it means to predict an earthquake?

To predict an earthquake means to indicate the possibility that an earthquake will occur in a given range of

space
time
magnitude

What does it means to predict an earthquake?

- **The prediction can miss events or have false alarms, but forecasts must demonstrate more predictability than a random guess.**
- **The space-time-magnitude volume considered to declare the alarms should be appropriate to public needs, i.e. to enable the relevant authorities to prepare for an impending destructive earthquake.**

Space Scale of Prediction

Predictions	Territorial uncertainty
Exact	Earthquake Size (EqS)
Narrow - range	Two-three EqS
Medium - range	Five-ten EqS
Long - range	Up to 100 EqS

Time Scale of Prediction

Predictions	Alarm duration
Immediate	Few hours
Short term	Few days
Intermediate - term	Few years
Long - term	Decades

Medium-range Intermediate-term Prediction

Currently a realistic goal appears to be the **medium-range intermediate-term prediction**, which involves an area with linear dimension about one order of magnitude larger than the linear dimension of the impending event and a time uncertainty of years.

Medium-range Intermediate-term Prediction

- **Time uncertainty:** few years
- **Space uncertainty:** hundreds Km

Allows:

- To increase preparedness and safety measures
- To define priority for detailed seismic risk studies
- Observation of possible short-term precursors (generally local)

Medium-range Intermediate-term Prediction

- **A family of medium-range intermediate-term earthquake prediction algorithms has been developed, applying pattern recognition techniques, based on the identification of premonitory seismicity patterns.**

Algorithms for Medium-range Intermediate-term Prediction

The algorithms are based on a set of empirical functions to allow for a quantitative analysis of the premonitory patterns which can be detected in the seismic flow:

- **Variations in the seismic activity**
- **Seismic quiescence**
- **Space-time clustering of events**

Algorithms for Medium-range Intermediate-term Prediction

Algorithms globally tested for prediction are:

- **M8 algorithm** (*Keilis-Borok and Kossobokov, 1987; Kossobokov et al., 1999*)
- **CN algorithm** (*Gabrielov et al., 1986; Rotwain and Novikova, 1999*)

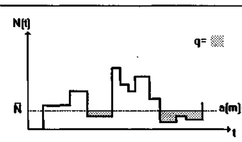
They allow to identify the TIPs (Times of Increased Probability) for the occurrence of a strong earthquake

Algorithms for Medium-range Intermediate-term Prediction

- The **algorithm MSc** (Mendocino Scenario, *Kossobokov, Keilis-Borok, and Smith, 1990; Kossobokov et al., 1999*) can be applied as a second approximation of M8. It allows us to reduce significantly the area of alarm (by a factor from 5 to 20).
- Independently, the **algorithm NSE** (Next Strong Earthquake, *Vorobieva, 1999*) is applied to predict a strong aftershock or a next main-shock in a sequence.

ALGORITHMS M8 AND CN

Functions of the seismic flow



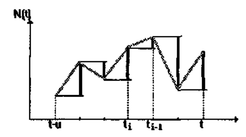
$$q(t|\underline{M},s)=\sum_i\left[a(\underline{M})\cdot s-N(t_i|\underline{M},s)\right]$$

__ : is the the average yearly number of events

Quiescence

corresponds to the sum of the grey areas for the time intervals (t-s,t) where the number of earthquakes is less than the average

Functions of the seismic flow



$$V(t|\underline{M},s,u)=\sum_i |N(t_i|\underline{M},s)-N(t_{i-1}|\underline{M},s)|$$

$i=1,\dots,n \quad u=ns$

Variation of seismic activity

$V(t|\underline{M},s,u)$

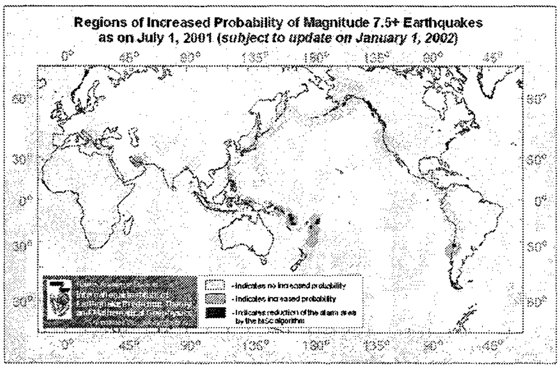
It is a measure of the cumulative changes in time of the earthquake number

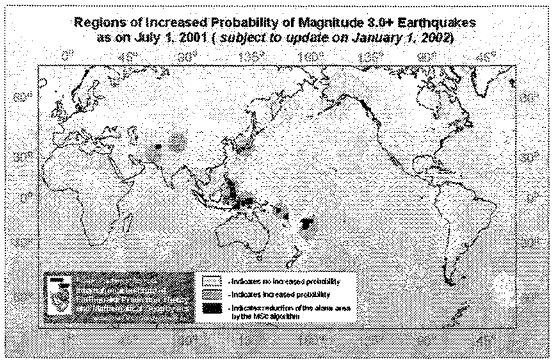
ALGORITHM M8

The algorithm M8 is applied on a global scale for the prediction of the strongest events:

Magnitude ≥ 8.0 Area: 667 Km radius

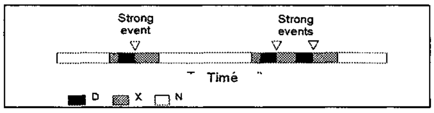
Magnitude ≥ 7.5 Area: 427 Km radius





CN algorithm: the learning procedure

- **Fix Mo (average return period not lower than 6-7 years)**
- **Definition of the classes:**
  - **D: "dangerous" periods (2 years before each strong earthquake)**
  - **N: "non dangerous" periods**
  - **X: periods not classifiable as D or N (3 years after a strong event + 1 year before each D period)**



Definition of the discretization intervals and of the characteristic properties (X objects are excluded from this stage of the analysis)

CN algorithm: the recognition procedure

- **Selection of the objects for recognition with a fixed time step (2 months)**
- **Discretization and coding of functions**
- **TIPs diagnosis**

Algorithm CN

Area: 5L-10L (L is the source linear dimension)

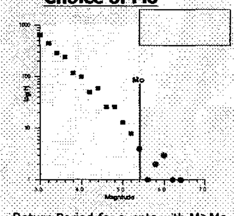
Magnitude:

$$M_0 - 3 \geq M_c$$

Yearly average number of events with magnitude above completeness must be > 3:

$$N(M \geq M_c) \geq 3$$

Choice of Mo



Return Period for events with M≥Mo not lower than 6-7 years

Performance of the algorithms

Algorithm	Regions considered	Strong earthquakes predicted/total	Time-space of alarms, %	Confidence level, %
M8	Circum Pacific, M ≥ 8 *	8/9	35	> 99
M8+MSc	"	7/9	18	> 99
CN	20 regions worldwide	16/21	24	95
NSE	Areas around 20 strong earthquakes worldwide	Predictions correct/wrong 17/3		98

* Prediction made within 170 overlapping circles of 1333-km diameter. The space-time volume has been determined by the most conservative measure that allows for various seismic activity of the territories.

Multiscale seismicity model and Algorithm CN

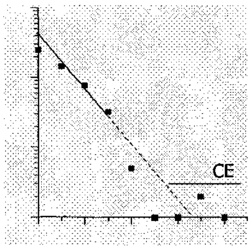
Gutenberg-Richter law

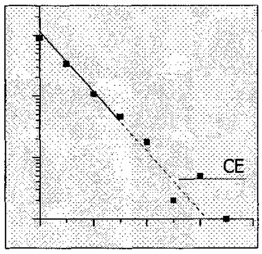
- The analysis of global seismicty shows that a single Gutenberg-Richter (GR) law is not universally valid and that a multiscale seismicity model can reconcile two apparently conflicting paradigms (Molchan et al., 1997):

Gutenberg-Richter law

- Self-Organized Criticality (SOC) mechanism
- Characteristic Earthquake (CE) concept.

The Gutenberg Richter law when applied to small parts of Italy (linear dimension 100-200 km) is linear only over a small magnitude interval [3-4.5].





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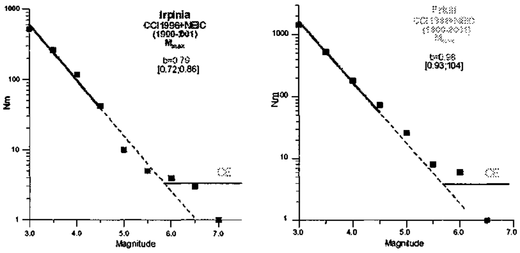
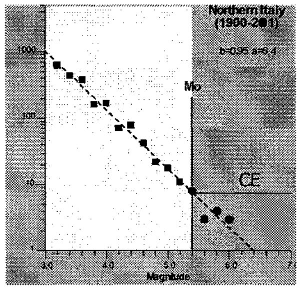


(cumulative)

The Gutenberg Richter law when applied to ***large*** parts of Italy (linear dimension 400-500 km) is linear over the magnitude interval [3-5.4].



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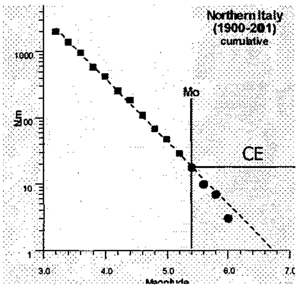
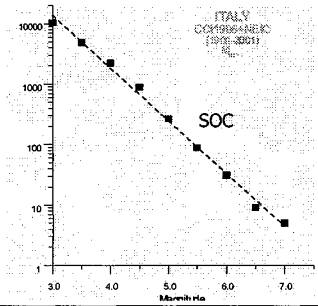


The GR law for the entire Italian territory (linear dimension larger than 1000 km) follows a linear trend over the magnitude interval [3-7].



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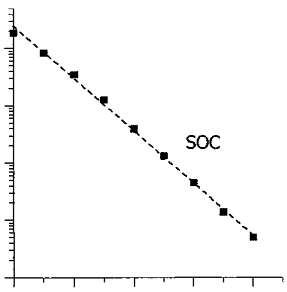


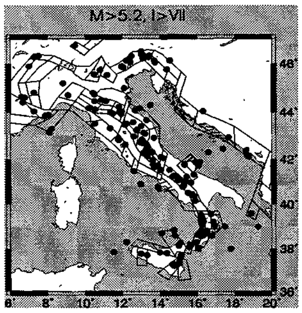
Gutenberg-Richter law

- The multiscale seismicity model, implies that only the set of earthquakes with dimensions that are small with respect to the elements of the zonation can be described adequately by the Gutenberg-Richter law.

Gutenberg-Richter law

- This conditon, fully satisfied in the study of global seismicity made by Gutenberg and Richter, has been violated in many subsequent investigations.
- Such a violation has given rise to the concept of Characteristic Earthquake (CE) in opposition to the Self-Organized Criticality (SOC) paradigm.

Gutenberg-Richter law

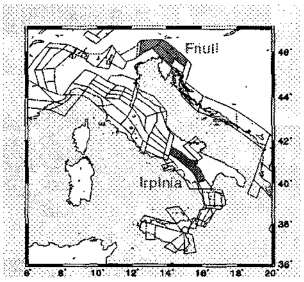


Seismogenic zone as defined by GNDT (Meletti et al., 2000).

For zones with characteristic dimensions of 200-300km (zones of level 1), i.e. 2-3 times larger then the maximum observed dimension for the areas covered by the aftershocks of the strongest main events (source dimensions), GR law is linear if M<4.5

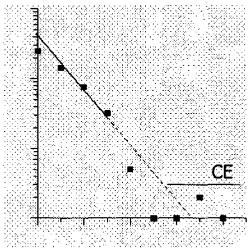
• main events in the period 1000-1980.

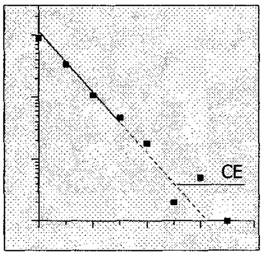
Gutenberg-Richter law



Union of GNDT zones used for the definition of zones of level 1. We show the examples of the Friuli (1976) and Irpinia (1980) quakes. The union is given by the GNDT zones where aftershocks have been recorded.

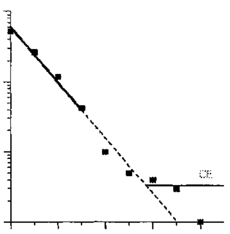
Gutenberg-Richter law

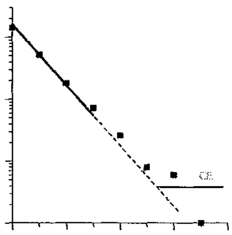




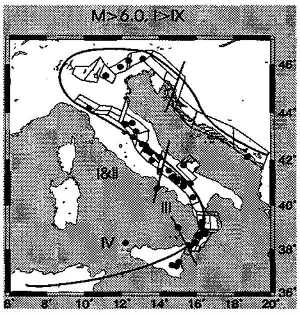
Gutenberg-Richter law

(cumulative distribution)





Gutenberg-Richter law

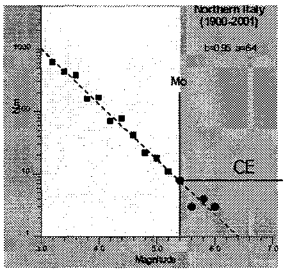


Union of the GNDT zones (Meletti et al., 2000) that define zones of level 2.

In level 2 zones, with characteristic dimensions of 400-500km, GR law is linear if M<5.4

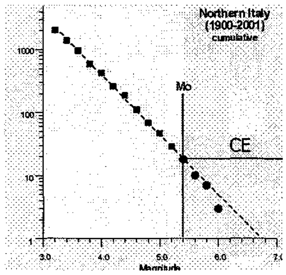
• main events in the period 1000-1980.

Gutenberg-Richter law



GR law for the "Nord Italia" (level 2 zone). The linear trend is followed only by the events with $M<M_0=5.4$

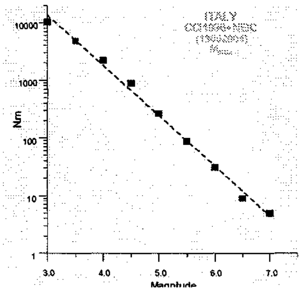
Gutenberg-Richter law



(cumulative)

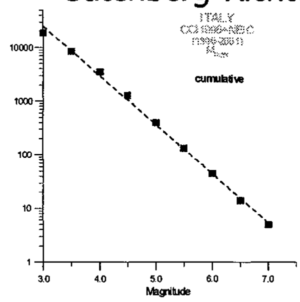
GR law for the "Nord Italia" (level 2 zone). The linear trend is followed only by the events with $M<M_0=5.4$

Gutenberg-Richter law



GR law for the Italian territory (level 3 zone); it is linear in the magnitude interval (3-7).

Gutenberg-Richter law

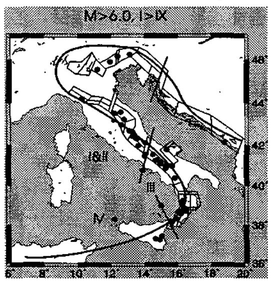


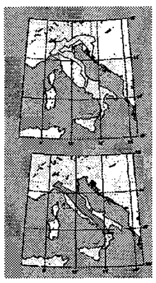
GR law for the Italian territory (level 3 zone); it is linear in the magnitude interval (3-7).

Gutenberg-Richter law

- The zone of size 400-500 km (level 2) well reproduce the dimensions and shapes of the regions used for the application of the intermediate-term medium-range earthquake prediction algorithm CN.

Gutenberg-Richter law





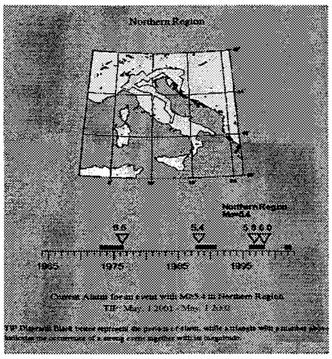
Level 2 zones and CN zones

Gutenberg-Richter law

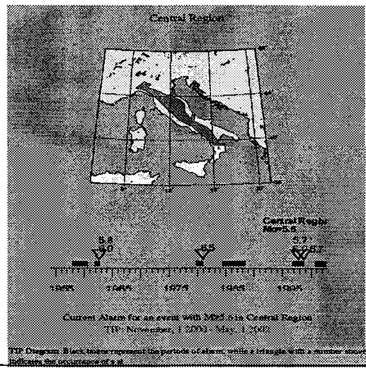
Algorithm CN predicted 76% of the events occurred in the monitored zones in Italy.
It is based on the formal analysis of the anomalies in the flux of the seismic events that follow the GR law, and predicts the strong events ($M>M_0$) that are anomalous (CE) with respect to this law.

PART 2

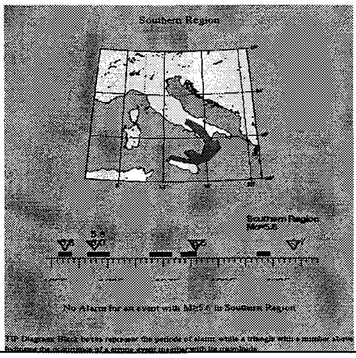
Intermediate-term earthquake prediction CN



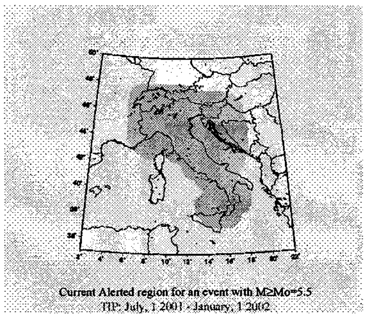
Intermediate-term earthquake prediction CN



Intermediate-term earthquake prediction CN



Intermediate-term earthquake prediction M8



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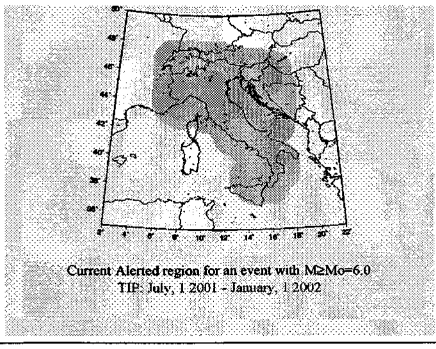
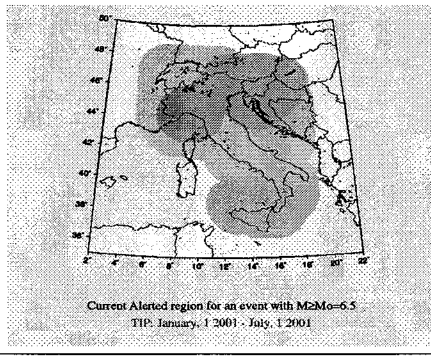


Intermediate-term earthquake prediction M8



Evaluation of prediction results

The quality of prediction can be defined by using two prediction parameters:

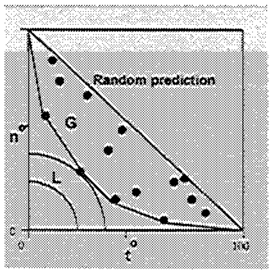
***N*°=*n*/*N*: the rate of failures-to-predict**

***T*°=*t*/*T*: the rate of alarm times** (*Molchan, 1997*).

***N* is the number of strong earthquakes occurred during the time period *T* covered by prediction**

The alarms cover altogether the time *t* and they have missed *n* strong events

Evaluation of prediction results



The performance of the prediction algorithm is characterized by its error curve G, which demonstrates how far from a random guess are the resulting predictions. To make use of prediction and optimize its benefits one needs to specify a cost-benefit function L, i.e. the cost of safety measures imposed by prediction minus the cost of the damage which the measures prevent. The point where G and L touch each other determines both the minimum loss and the optimal set of parameters in the prediction algorithm to be used for prediction.

Development of decision making procedures for cases of earthquake alarm

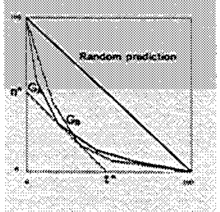
The problem of comparing prediction methods for stationary point processes (like a sequence of strong earthquakes in a region) may be solved using the two prediction parameters:

n^0: the rate of unexpected earthquakes

t^0: the rate of alarm times

(*Molchan, 1997*)

Development of decision making procedures for cases of earthquake alarm



Comparison of algorithms A and B by their error diagrams.

The curves G_A and G_B describe two algorithms: *A* and *B*.
When t^0 is small, G_A is under G_B, algorithm *A* is preferable in application with great values of $\beta/\alpha\lambda$, where β is the cost rate of alert and $\alpha\lambda$ is the loss rate from unexpected earthquakes.
The line (n^*, t^*) is the common line of support for curves G_A and G_B. If $\beta/\alpha\lambda > n^*/t^*$ then the algorithm A is preferable because it yield lesser losses.

IASPEI Preliminary List of Significant Precursors vs. M8 and CN

IASPEI: the observed anomaly should be related to some mechanism leading to earthquakes;

M8 and CN: the equations to describe the dynamics of the lithosphere are still missing thus M8 and CN are algorithms based on empiricism "guided" by the concept of deterministic chaos.

IASPEI: the anomaly should be simultaneously observed at more than one site or instrument;

M8 and CN: give statistically significant results at global scale.

IASPEI Preliminary List of Significant Precursors vs. M8 and CN

IASPEI: the definition of the anomaly and of the rules for its association with subsequent earthquakes should be precise;

M8 and CN are formalized published algorithms; regular workshops are held at ICTP every second year.

IASPEI: both anomaly and rules should be derived from an independent set of data, than the one for which the precursory anomaly is claimed;

M8 and CN prediction criteria have been defined globally, using information on past seismicity to predict new strong earthquakes.

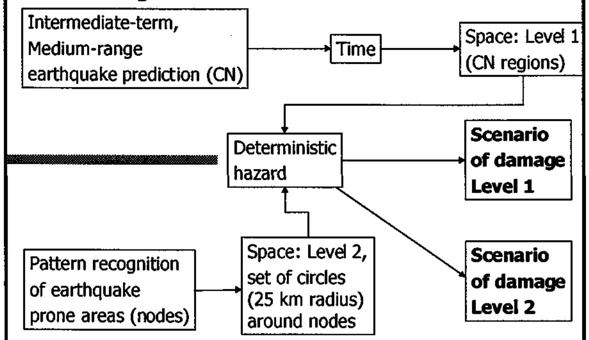
IASPEI Preliminary List of Significant Precursors vs. M8 and CN

None of the precursors from the IASPEI list has been subject to forward prediction testing, while M8 and CN are routinely globally tested.

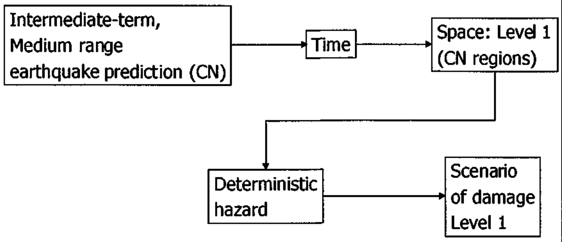
PART 3

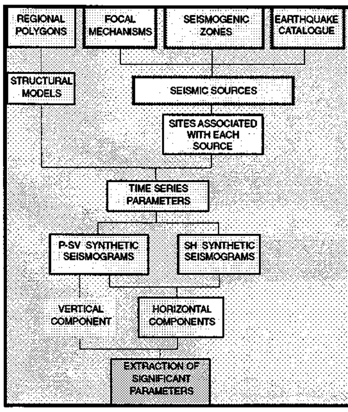
INTEGRATED DETERMINISTIC HAZARD

Integrated Deterministic Hazard



Integrated Deterministic Hazard Level 1



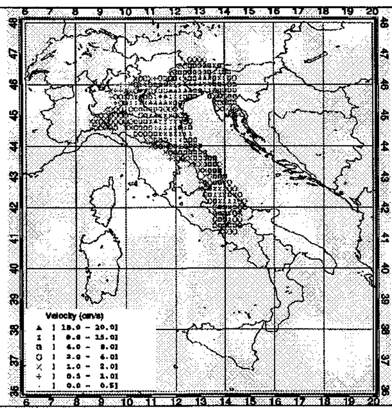


Flow-chart of the deterministic hazard method

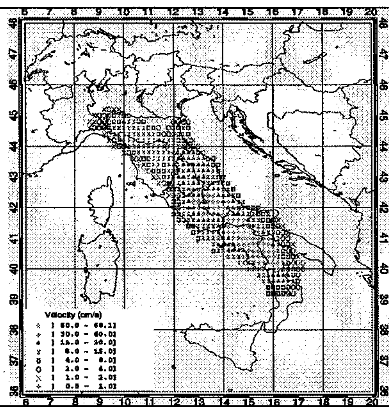
Seismic sources are defined either within the CN regions (Level 1) or in the nodes (Level 2).

Integrated deterministic hazard

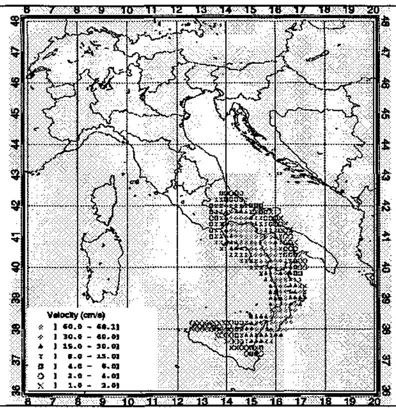
Integrated Deterministic Hazard
-
TIP in Northern region



Integrated Deterministic Hazard
-
TIP in Central region



Integrated Deterministic Hazard
-
TIP in Southern region



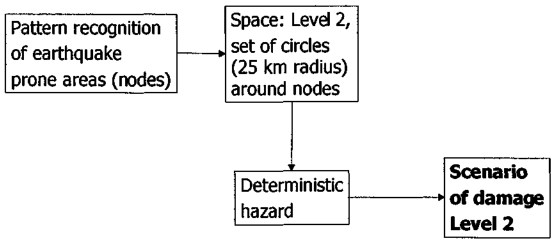
Integrated Deterministic Hazard

Impending intensities
for some Italian cities, when a TIP is declared in a CN region

(Regression with ISG observed intensities, Panza et al., 1999)

City	CN region	Imax (observed)	Imax (impending)		
			Displacement	Velocity	DGA
Trieste	north	VII	VI	VII	VI
Bologna	north, centre	VIII	VIII	VIII	IX
Firenze	centre	VIII	VII	VIII	VIII
Roma	centre	VIII	IX	VIII	IX
Napoli	centre,south	VIII	X	IX	IX
Messina	south	X	X	X	X

Integrated Deterministic Hazard Level 2



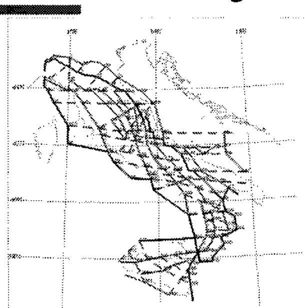
Pattern Recognition of Earthquake Prone areas

- Pattern recognition technique is used to identify sites where strong earthquakes are likely to occur, based on the assumption that strong events nucleate at the nodes, specific structures that are formed around intersections of fault zones.
- Nodes are defined by the Morphostructural Zonation Method, that allows to delineate a hierarchical block structure of the studied region, using tectonic and geological data, with special care to topography.

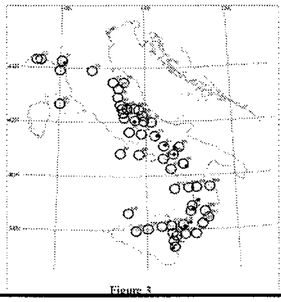
Pattern Recognition of Earthquake Prone areas

- Unstable tectonic structures are identified evaluating the following topographic characteristics :
  - Elevation and its variations in mountain belts and watershed areas;
  - Orientation and density of linear topographic features;
  - Type and density of drainage pattern,
- These features indicate higher intensity in the neotectonic movements and increased fragmentation of the crust at the nodes

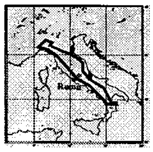
Lineaments and Nodes in the Italian region



Nodes prone to earthquakes with M≥6.5 in the Italian region



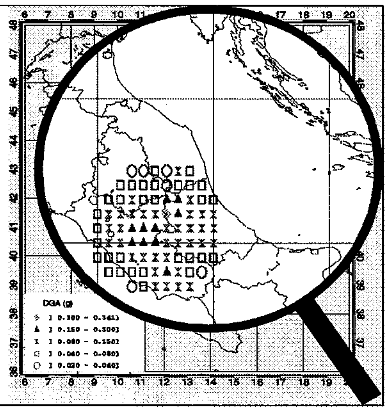
Integrated Deterministic Hazard



Roma

Imax(expected): IX

Imax(observed): VIII



Integrated Deterministic Hazard

Impending intensities for events with M≥6.5

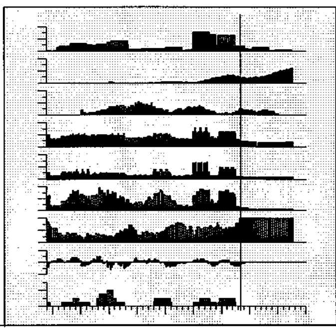
(Regression with ISG observed intensities, Panza et al., 1999)

City	CN region	N° of Circles	Imax (observed)	Imax (impending) Displacement	Velocity	DGA
Bologna	centre	1	VIII	VIII	VIII	VIII
Firenze	centre	2	VIII	VII	VIII	VIII
Roma	centre	8	VIII	IX	VIII	VIII
Napoli	centre south	5	VIII	X	IX	IX
Messina	south	9	X	X	X	X

CN: detective of anomalous variations in reported magnitudes

CN: detective of anomalous variations in reported magnitudes

CN functions for the Central Region: anomalous behaviour starting in 1987



Magnitude comparison: Central Region

Duration Magnitude

M_d(NEIC)-M_d(ING)

$M_d \geq 3.0$

(1983-1997)

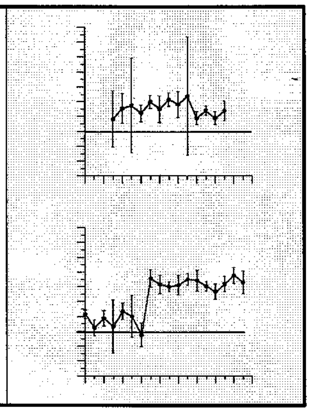
$\Delta M_d = 0.30 \pm 0.04$

Yearly Average

Yearly Average differences NEIC-ING

Local Magnitude

$M_L \geq 3.0$



Magnitude comparison: Italian territory

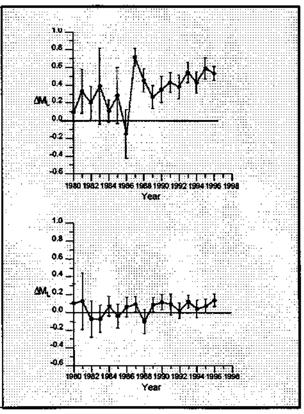
LDG - ING

$M_L(LDG)-M_L(ING)$
$M_L \geq 3.0$
(1980-1986)
$\Delta M_L=0.18\pm0.08$
(1988-1996)
$\Delta M_L=0.44\pm0.04$
Yearly Average

Local Magnitude: Yearly Average differences

NEIC - LDG

$M_L(NEIC)-M_L(LDG)$
$M_L \geq 3.0$
(1980-1986)
$\Delta M_L=0.03\pm0.06$
(1988-1996)
$\Delta M_L=0.06\pm0.03$
Yearly Average



CN: detective of anomalous variations in reported magnitudes

- The analysis of CN functions in Central Italy allowed us to detect a relevant long lasting change in the reported magnitudes.
- The comparison of individual magnitudes, reported by ING and NEIC, indicates, since 1987, an average underestimation of about 0.5 in the Local Magnitude provided by ING.
- The presence of a general local magnitude underestimation in the Italian ING bulletins is substantiated by the cross-comparison performed between ING, LDG and NEIC catalogues.

PART 4

Proc. 30th Int'l. Geol. Congr., Vol. 5 pp. 193-201
Ye Hong (Ed)

CN Algorithm in Italy: Intermediate-term Earthquake Prediction and Seismotectonic Model Validation.

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Abstractt

The CN algorithm is here utilized both for the intermediate-term earthquake prediction and to validate the seismotectonic model of the Italian territory. Using the results of the previous analysis, made through the CN algorithm and taking into account the seismotectonic model, three main areas, one for Northern Italy, one for Central Italy and one for Southern Italy, are defined. The separation among them is not marked by sharp boundaries, and on the basis of different zonations, it is possible to identify intersection areas, which can be assigned to either bordering main areas. The earthquakes occurred in these areas contribute to the precursor phenomena identified by the CN algorithm in each main area when the TIPs duration decreases when the intersection areas are included.

In a further step we have constructed a revised catalogue using the most recent information about the seismicity in Italy, and we have considered a regionalization that follows strictly the boundaries of the areas defined in the seismotectonic model of Italy. Each of these new regions contains only the zones with similar seismotectonic characteristics. The results obtained in this way are good and stable and represent an improvement with respect to the previous investigations.

Keywords: CN Algorithm, intermediate-term earthquake prediction, seismotectonic model, Italy

INTRODUCTION

The analysis of the Time of Increased Probability (TIP) of a strong earthquake with magnitude greater than, or equal to a given threshold M_0, based on the algorithm CN, makes use of normalized functions, which describe the seismicity pattern of the analyzed area. Therefore the original algorithm, developed for the California-Nevada region, can be directly used, without any adjustment, in areas with different size and level of seismicity. The algorithm CN is described in full detail by Keilis-Borok et al.[5,6].

It has been shown [3, 4] that a regionalization, supported by seismological and tectonic arguments, leads to the reduction of the alarm duration (TIP) and of the failures to predict, and increases the stability of the algorithm compared with the results obtained when the borders of the studied area are defined simply according to the completeness of the used catalogue [7]. Therefore, the CN algorithm permits to deal with the development of modern regional geodynamic models, involving relationships between the key structural features which control the seismicity, and the selection of the optimal causative fault system for prediction purposes [12].

Considering the information contained in the seismotectonic model of Italy [10] and the spatial distribution of the epicentres, the country can be divided into three main areas (Fig. 1) [4]. Each of them is characterized by a dominant seismotectonic behavior, with varying seismicity level, therefore the appropriate M_0 is used in each area.

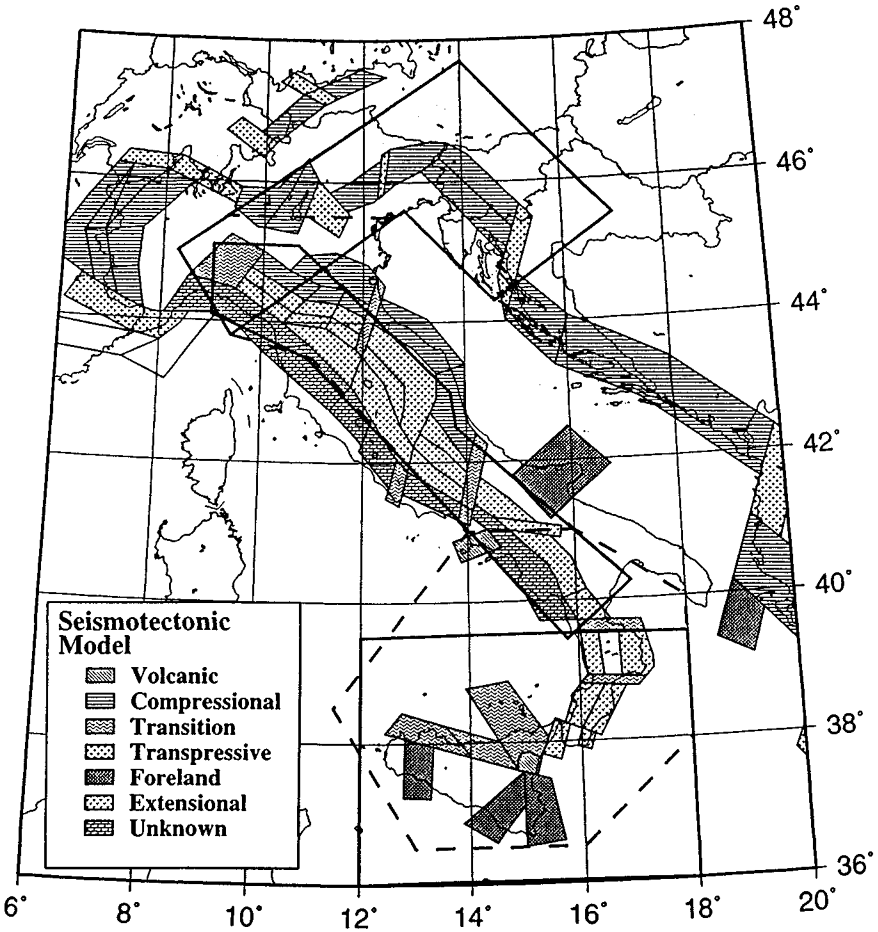

Fig. 1 Seismotectonic model of Italy [10] and regionalization into three main and two transition areas.

We introduce here a more detailed regionalization for Nord, South and Central Italy which follows strictly the boundaries of the seismotectonic zones [10]. Only the seismotectonic zones with the same characteristic, and with transitional behavior between them, are contained in each new area.

In the present analysis a new catalogue "CCI96" is routinely used for the application of the CN algorithm in Italy. The catalogue has been compiled revising the PFGING [2,3, 11] catalogue with the recently published data about the seismicity, mainly historical [1]. Some relevant differences, also for large magnitudes, have been found between the PFGING catalogue and the new CCI96 catalogue, mainly for Southern Italy where maximum magnitude is used.

REGIONALIZATION

To minimize the spatial uncertainty, the area where a strong earthquake has to be predicted, should be as small as possible, but there are three rules that limit its minimum dimensions: 1) the border of the area must be drawn following as much as possible the minima in the seismic activity; 2) the annual number of earthquakes with magnitude greater or equal to the completeness threshold of the catalogue has to be greater or equal to 3; 3) the linear dimension of the region must be about 5L to 10L, where L is the length of the expected source.

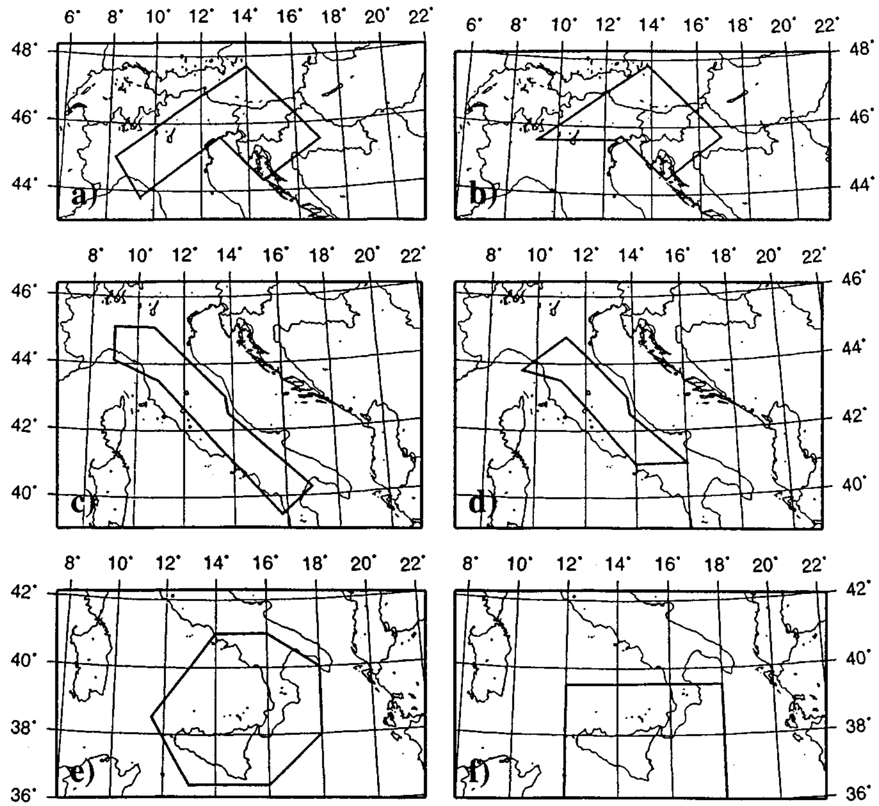

Fig. 2 Regionalization considered in [4]: first variant in Northern Italy (area 1); b) second variant in Northern Italy (area 2); c) first variant in Central Italy (area 1); d) second variant in Central Italy (area 2); e) first variant in Southern Italy (area 1); f) second variant in Southern Italy (area 2).

In the regionalization proposed by Costa et al. [4], the borders between the three main areas: Northern, Central and Southern are not sharply defined and they can be better represented by a transition domain (Fig. 1). In fact, the division of the Italian territory in three main areas, separated by two transition areas, seems to be consistent with the indications given about the properties of seismicity by the CN algorithm. In each main region, in order to analyze the effect on the prediction of the transition domains seismicity, two different regions have been tested, which blandly follow the border of the seismotectonic zones (Fig. 1, 2). In all the cases considered, the best results are obtained for the regions which include the transition areas [4].

The earthquakes information contained in ALPOR[1] has been used to construct the new catalogue, CCI96, used in the CN analysis performed in the framework of a new regionalization (Fig. 3), which follows strictly the borders of the seismotectonic zones, and in the forward monitoring in Italy.

CN ANALYSIS IN NORTHERN ITALY

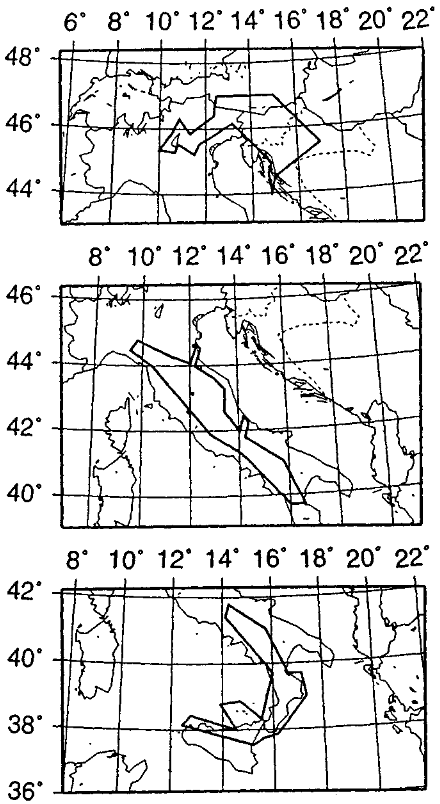

Fig. 3 Regionalization considered in the present study (solid line) Italy; b) Central Italy; c) Southern Italy; dashed lines indicate some of the variants used in [4].

The Alpine arc, the most important tectonic feature in Northern Italy, is crossed by different political borders and consequently the catalogue PFGING is fairly incomplete for our purposes [4]; to fill in the gap the information contained in two other catalogues, ALPOR [1] and NEIC [9] , has been included.

According to the standards used in the CN algorithm [3], the magnitude threshold for the definition of strong earthquakes is chosen to be M_0=5.4. The period 1960-1992 is analyzed, because of the significant incompleteness of the catalogue before 1960 [4]. In the region (Fig. 2a), only 2 strong earthquakes occurred during the last 30 years (M=6.5, May 6, 1976 and M=5.4, January 2, 1988), in fact the M=6.0 September 15, 1976 event is a strong aftershock, identified as Related Strong Earthquake [8], and therefore it is not a target of the CN algorithm.

The seismogenic region, thus defined, is shown in Fig. 2a. The two strong events are predicted and the TIP duration is 27% of the total time (see Fig 4a). There is only one false alarm after the strong earthquake of 1988.

In order to test the hypothesis that the earthquakes, concentrated on the edges of a tectonic structure or in the areas of

intersection with other structures, cannot be neglected for the purposes of intermediate term earthquake prediction, a second regionalization (Fig. 2b), which includes only the compressive domains in the Eastern Alps (Fig. 2b), is considered by Costa et al. [4]. The two strong events are predicted (Fig 4b), but the TIP duration increases to 34% of the total time, and there are three false alarms.

The new regionalization considered here follows the compressional zones of the seismotectonic model for Northeast Italy and therefore is disconnected from Central Italy (Fig. 3a). In the Austrian and Slovenian territory the seismotectonic zones have been defined only near the border with Italy and a complete zonation is not available, therefore the border outside Italy is defined by seismicity only. The results obtained with such regionalization and using the CCI96 catalogue (Fig. 5a) are: the two strong events are predicted and the TIP duration is 28.8% of the total time with two false alarms. The reduction of the spatial uncertainty is about 28%.

CN ANALYSIS IN CENTRAL ITALY

The CN algorithm has been initially applied to Central Italy [3, 6], because the catalogue PFGING is rather complete here. Subsequently a regionalization based on seismotectonic consideration has been proposed [3] (see Fig. 2c). Only the crustal earthquakes occurred in Central Italy are used, even if, according to the model proposed by Costa et al.[4] few intermediate and deep earthquakes belong to Central Italy and should be considered when using the CN algorithm. In fact, their inclusion in the data set does not affect the results, and this is not surprising since the number of these events and their size is small. The magnitude threshold for the definition of the strong earthquakes is chosen to be M_0=5.6. The two strong events are predicted and the alarm occupies about 30% of the total time with two false alarms (see Fig. 4c).

The definition of the areas in Northern and Southern Italy [4] make it necessary a revision of the regionalization proposed by Costa et al.[3] for Central Italy. This revised regionalization is presented in Fig. 2d. Due to the smaller dimension of the area, the magnitude threshold is M_0=5.4. Four strong earthquakes occuned in the area. As it can be seen from Fig. 4d, three of them are predicted by the CN algorithm, while the 1979 event is a failure to predict; there are 4 false alarms and the TIPs increase, with respect to the previous study, from 30% to 38% of the total time.

The new regionalization (Fig. 3b) , which follows strictly the border of the seismotectonic zones, includes the extensional zones and some transitional ones. The magnitude threshold for the definition of the strong earthquakes is M_0=5.6 and the catalogue used is the CCI96. All the three strong events are predicted and the alarm occupies about 21% of the total time, with three false alarms (Fig. 5b).

CN ANALYSIS IN SOUTHERN ITALY

The catalogue PFGING can be considered complete in this part of Italy only after 1950, and for magnitude above 3. The magnitude threshold in the definition of the strong earthquakes, used by Costa et al.[4], is M_0=6.5.

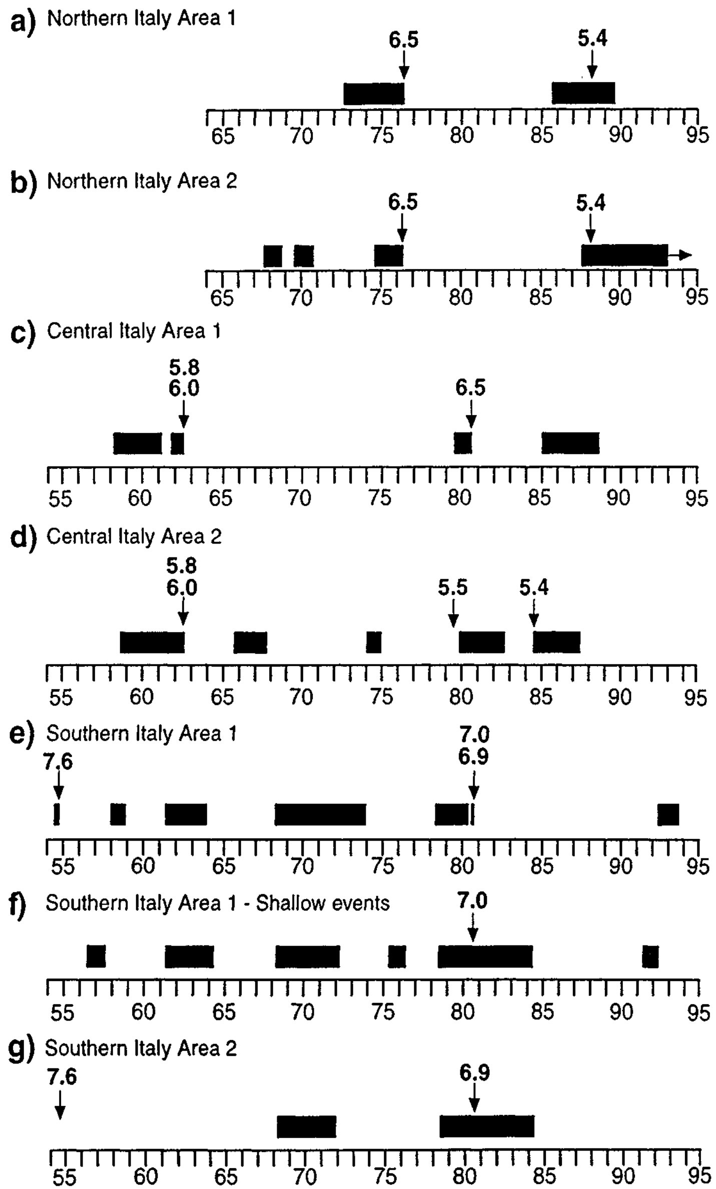

Fig. 4 Results of the CN analysis in Italy using the regionalization of figure 2. The catalogue used is the PFGING. The arrows indicate earthquakes with $M \geq M_0$, TIPs are marked by black rectangles. In e) and g) the magnitude 6.9 marks an intermediate-depth earthquake in the Tyrrhenian sea; in e) and f) the magnitude 7 marks the Irpinia, 1980, earthquake and in a) and b) the magnitude 6.5 marks the Friuli 1976 event. In the Southern Italy the maximum magnitude present in the catalogue is used for the analysis, while in Northern and Central Italy the priority magnitude M_{pr} (M_L, M_I, M_d, M_p) [3] is used.

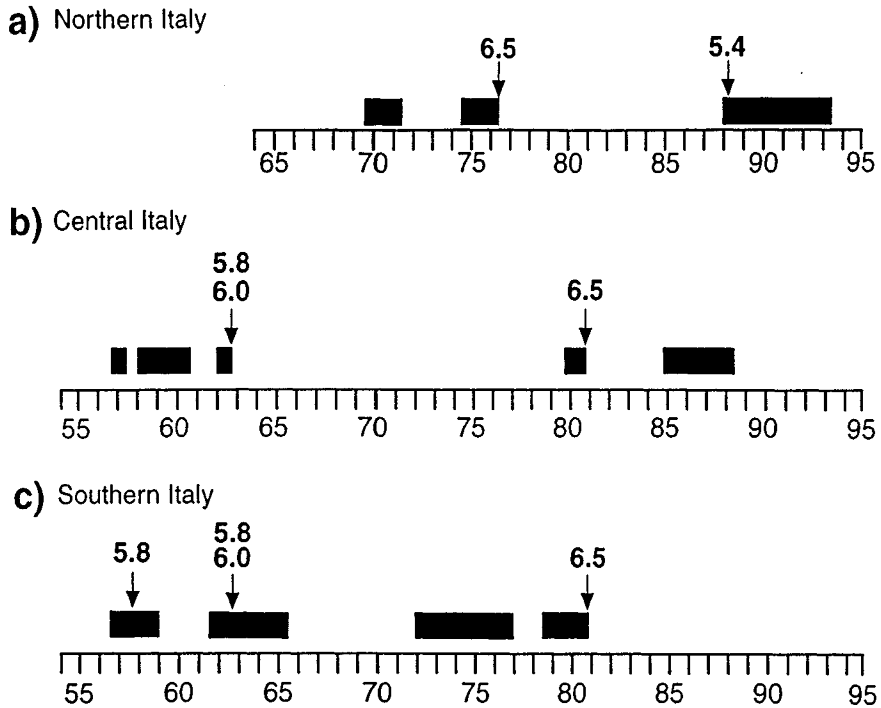

Fig. 5 Results of the CN analysis in Italy using the regionalization of figure 3. The catalogue used is the CCI96. The arrows indicate earthquakes with $M \geq M_0$, TIPs are marked by black rectangles. The priority magnitude M_{pr} (M_L, M_I, M_d, M_p)[3] is used.

Following the idea that the 41°N parallel divides the Apennines into two completely different tectonic domains [10], for Southern Italy the area shown on Fig. 2e has been considered. The results of the CN algorithm applied to this area [4] are reported in Fig. 4e. All three strong earthquakes (M=7.6, November 23, 1954, M=7.0 November 23, and M=6.9, November 24, both in 1980) are predicted and the duration of TIP is 33% of the total time. There are 5 false alarms.

To study the influence of the relevant deep seismicity [4] only the shallow earthquakes is considered and thus the strong event to be predicted is the M=7.0, November 23, 1980 earthquake. The diagnosis of the CN algorithm is given in Fig. 4f. The strong event is predicted, but the duration of TIP increases up to 44% of the total time and there are six false alarms.

As a second test, according to the regionalization for Central Italy [3], the northern border of Southern Italy is traced along the 39.5° parallel (Fig. 2f). In this area the two strong earthquakes to be predicted are the M=7.6, November 23, 1954 and the M=6.9, November 23, 1980 events. The 1980 earthquake is predicted with a TIP duration lasting for 25% of the total time; the 1954, M=7.6, event is a failure to predict and there are two false alarms (Fig. 4g).

The new regionalization (Fig. 3c) follow strictly the extensional and transitional seismotectonic zones present in South Italy (below the 42°N parallel). The small, but with a intense seismicity, volcanic zone present in Sicily is included as well, while the foreland seismotectonic zones have been excluded, as it was done in Central Italy in [3].

In Southern Italy the differences in the magnitude between the PFGING catalogue and the CCI96 catalogue are very large also for the events with $M>M_0$. Therefore a direct comparison with the results obtained by Costa et al. [4] is not possible. The improvement introduced by the new catalogue and the new regionalization permits to use for Southern Italy the same criteria used in Northern and Central Italy. The magnitude threshold is $M_o=5.4$ and the strong events to be predicted are 4. All of them are predicted and the duration of TIP is 31.8% of the total time (Fig. 5c). There are 3 false alarms. The spatial uncertainty reduction with respect to the results of Costa et al.[4] is relevant, about 72%.

CONCLUSIONS

The CN algorithm has been here utilized both for the intermediate term earthquake prediction and to validate the seismotectonic model of the Italian territory.

The catalogue PFGING used by Costa et al. [3, 4] has been revised using the earthquakes information contained in ALPOR [1] and a new catalogue, the CCI96, has been compiled and used here. Some relevant differences, for large magnitudes, have been found between the PFGING catalogue and the new catalogue, mainly for Southern Italy, when maximum magnitude is considered.

A new detailed regionalization for Northern, Southern and Central Italy, which follows strictly the boundaries of the seismotectonic zones [10], has been proposed. Only the seismotectonic areas with the same characteristic, or with transitional behavior, are contained in each new area. This regionalization represent an improvement of the regionalization proposed by Costa et al. [4], the average spatial uncertainty reduction of the prediction is about 45% with a general reduction of the TIPs duration and of the false alarms. The improvement of the results is particularly relevant in Southern Italy.

On the basis of the results obtained, Costa et al. conclude that the separation among the three regions proposed is not marked by sharp boundaries, and on the basis of different zonations, it is possible to identify intersection areas, which can be assigned to either bordering main areas[4]. When these intersection areas are included in the CN analysis, an improvement of the results is obtained. This result hasbeen confirmed, for Southern and Central Italy, by the results obtained using the newregionalization proposed here. In Northern Italy, the compressional seismotectonic zones are disconnected from the transitional and compressional seismotectonic zones included in the regionalization proposed by Costa et al. [4]. Therefore, a comparison is possible only with the region shown in Fig. 2b: there is an improvement with respect to the previous results, but the best result remains the one obtained when the intersection areas are included.

Acknowledgments

The authors are very grateful to Prof. V.I.Keilis-Borok for stimulating discussions. We acknowledge financial support from MURST funds, CNR-Gruppo Nazionale per la Difesa dai Terremoti contracts n.° 95.00608.54 and 96.02968.54 and INTAS grant 94-0232.

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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.

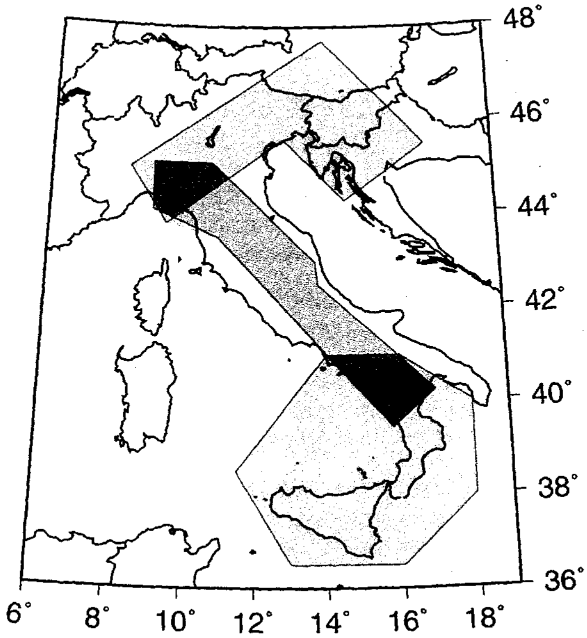

Fig. 1. Regionalization proposed for CN application to the Italian territory by Costa *et al.* (1996). The three region, partially overlapping, have been defined on the basis of the seismicity distribution and by roughly taking into account the seismotectonic model.

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

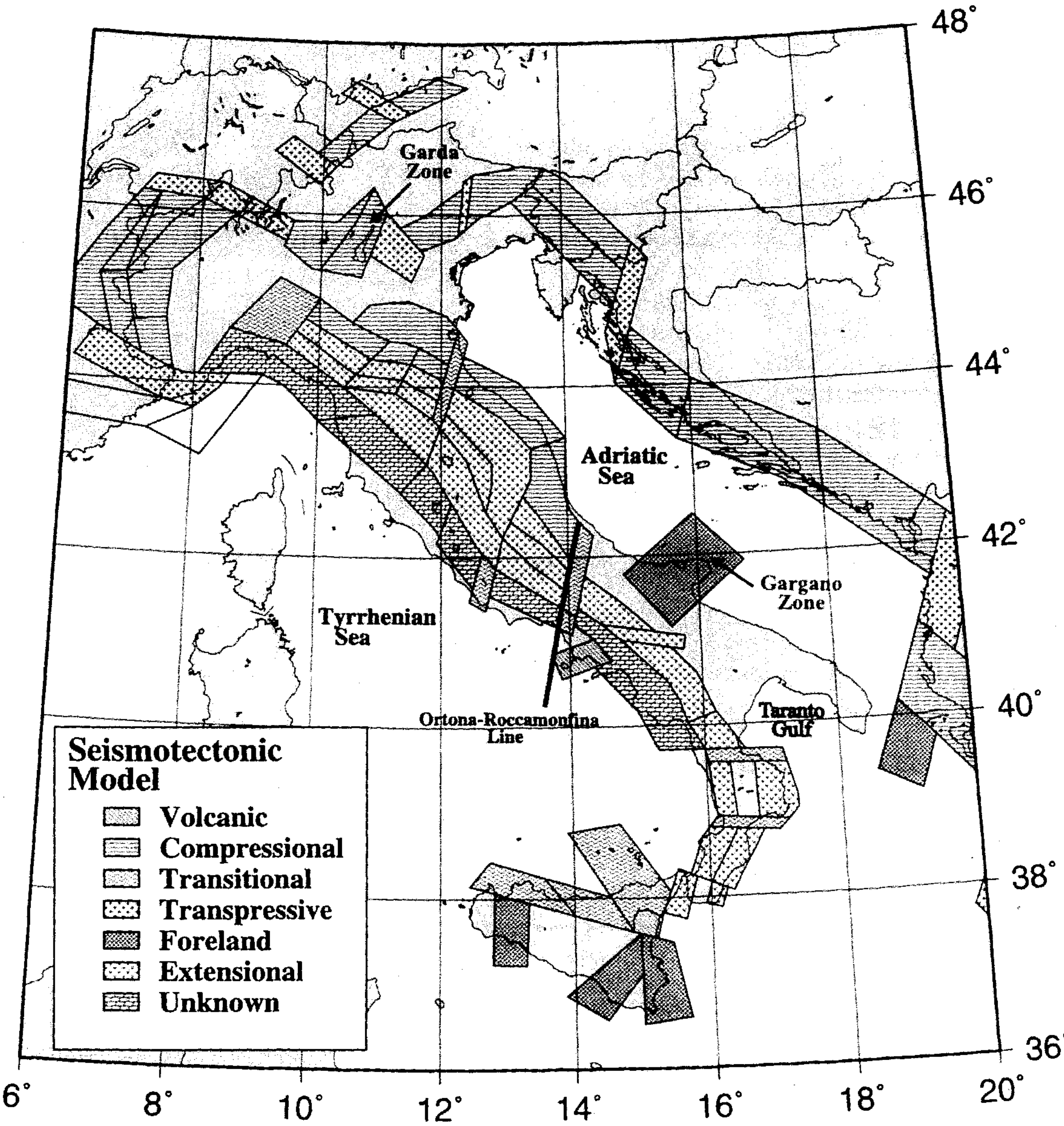

Fig. 2. Seismotectonic model of the Italian territory proposed by Scandone *et al.* (1994).

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

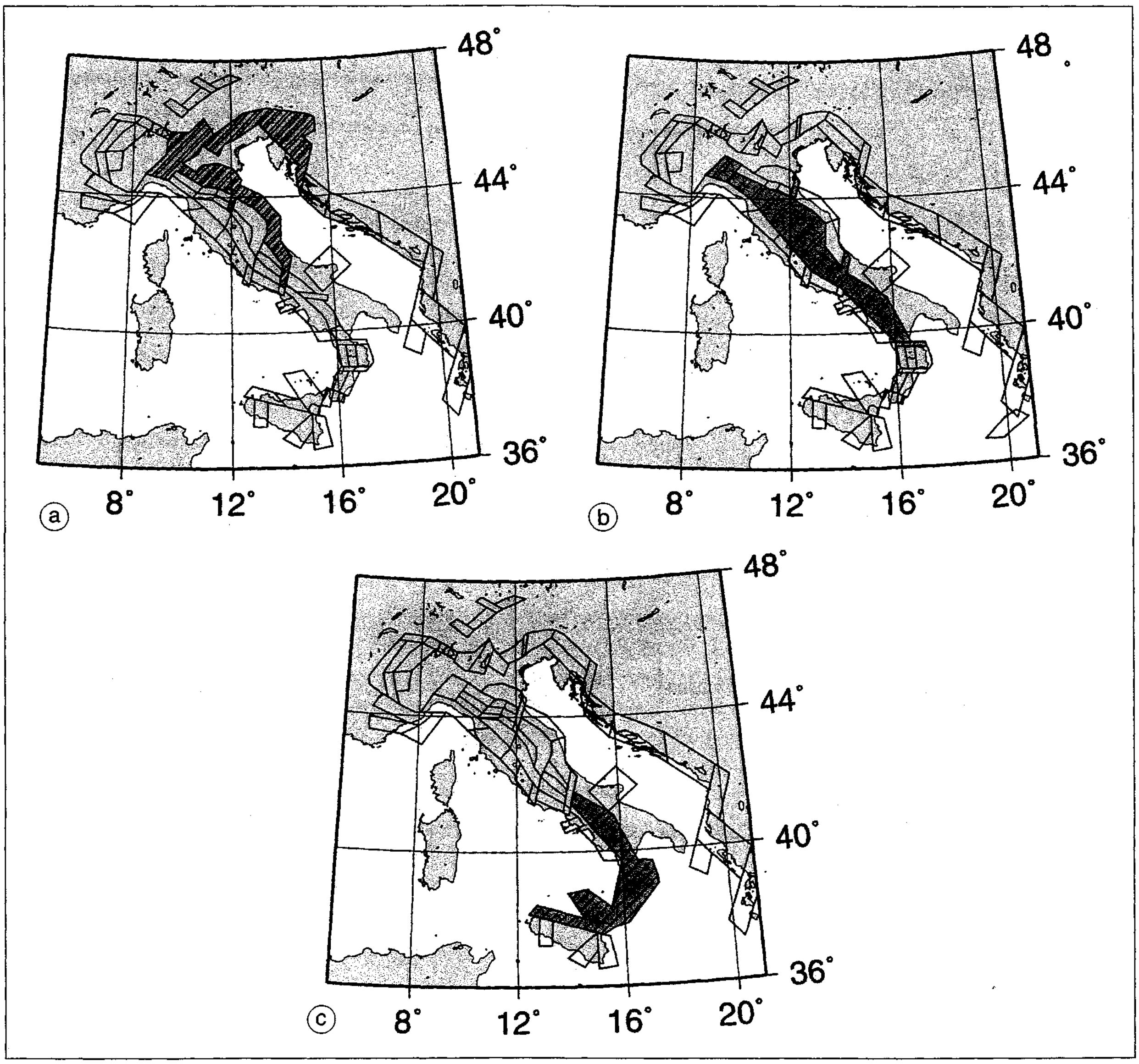

Fig. 3a-c. Regionalization of the Italian territory, defined closely following the seismotectonic model. a) Northern region: the compressional and transpressive zones along Eastern Alps and Northern Apennines and the seismogenic zoning of the Slovenian-Croatian territory (Zivcic *et al.*, 1997) is taken 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.

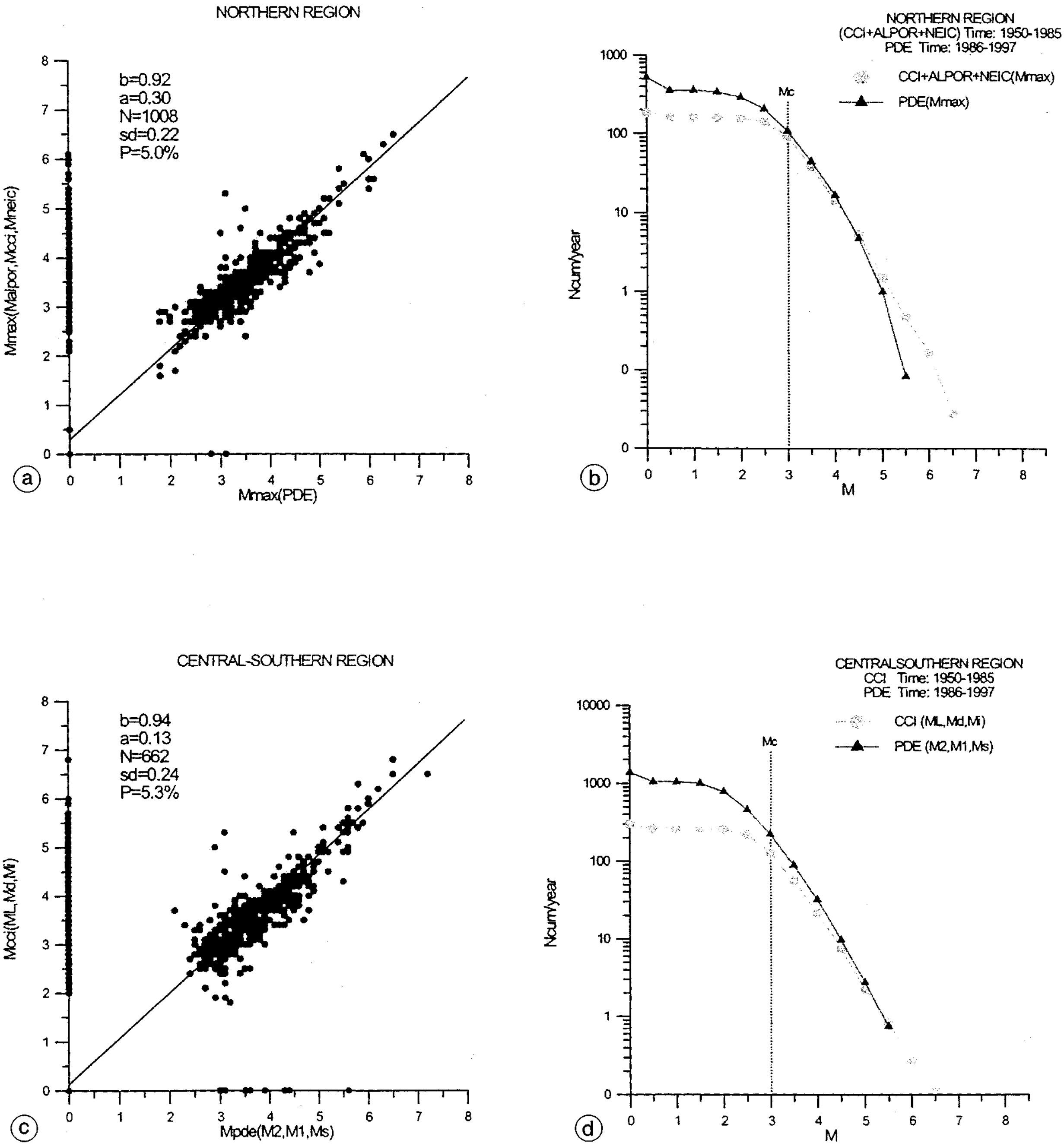

Fig. 4a-d. Diagrams considered to compare CCI and PDE catalogues, showing the distribution of $M_{priority}$ (CCI) *versus* $M_{priority}$ (PDE) for the common events and the Gutenberg-Richter relation for the consecutive intervals of time in which the different catalogues are used. The values reported 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_{priority}(CCI) *versus* M_{priority}(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

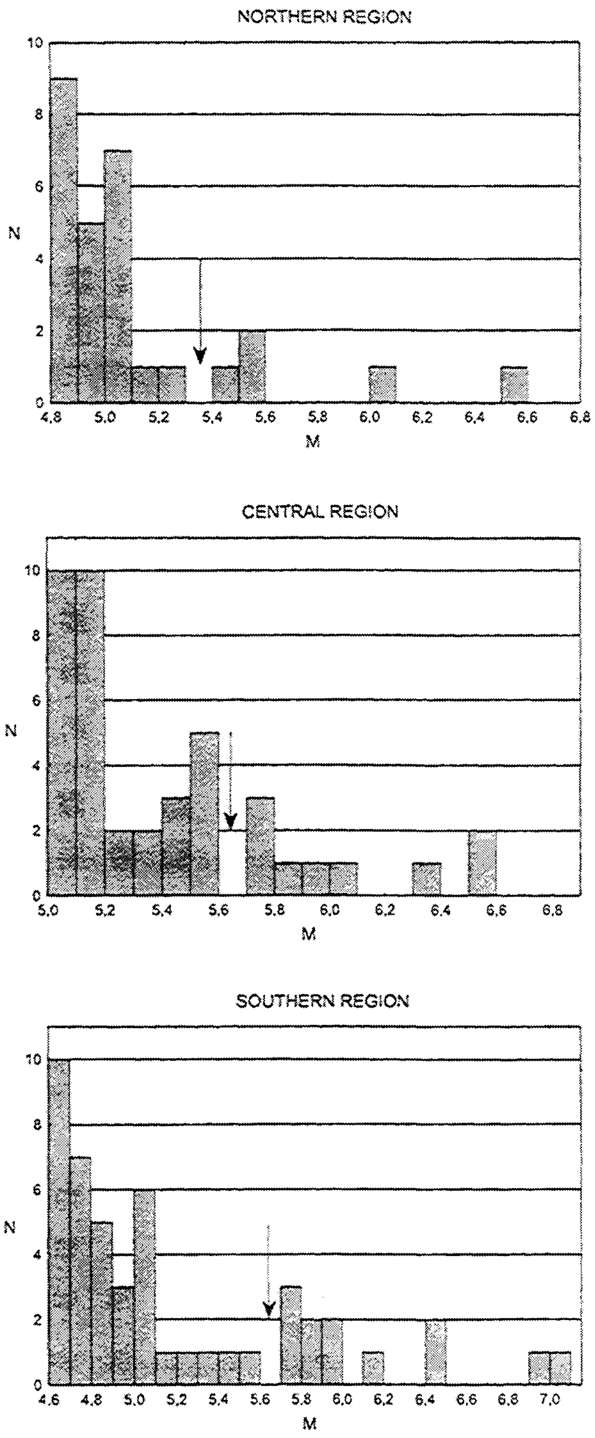

Fig. 5. Histograms of the number of events *versus* magnitude considered for the choice of the threshold M_0 for the definition of the events to be predicted. The arrows indicate the selected values in each of the three regions.

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	CC1	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

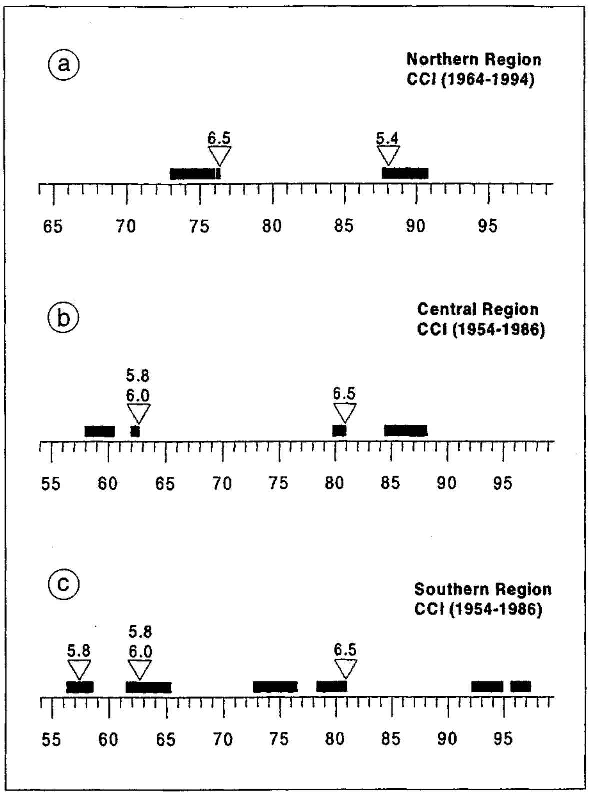

Fig. 6a-c. TIPs obtained with the CCI1996 catalogue, updated to July 1997, for the three regions shown in fig. 3a-c. The learning period is indicated in brackets, while the time of occurrence of a strong earthquake is indicated by a triangle with a number above it, giving the magnitude of the event (see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

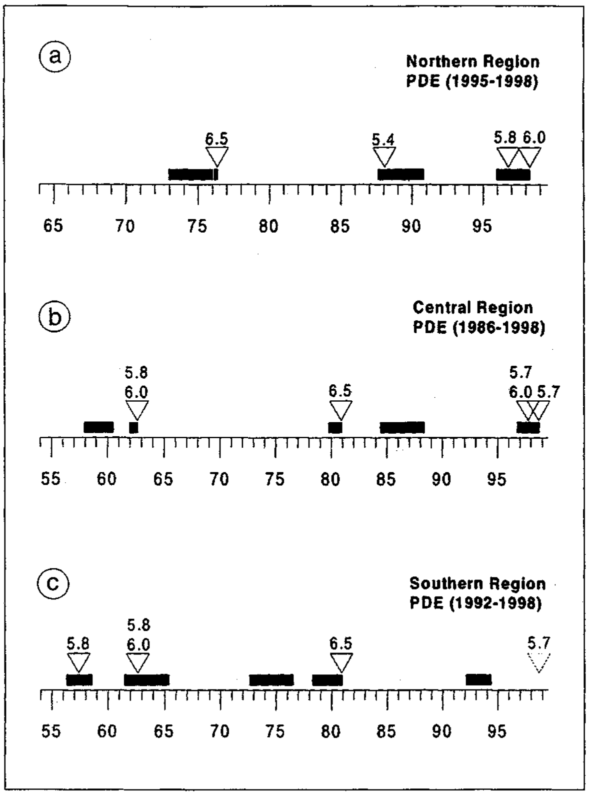

Fig. 7a-c. TIPs obtained using the PDE catalogue (see also tables I and II). The catalogue named CCIPDE is composed by the CCI1996 catalogue, for the learning period, and by the PDE determinations (NEIC) for the subsequent time interval. The time interval in which PDE data are used is given in brackets.

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 $M_{\mathrm{PDE}}(M_{\max})$, according to the analysis previously described, appears homogeneous to the maximum magnitude among $M_{\mathrm{ALPOR}}(M_L, M_l)$, $M_{\mathrm{CCI}}(M_L, M_d, M_l)$ and $M_{\mathrm{NEIC}}(M_L, M_s, m_b)$, 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_l. 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_l), 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_{CCI} (M_L, M_d, M_I), followed by the PDE (1992-1998), with the same priority M_{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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Pure and Applied Geophysics

Seismotectonic Model and CN Earthquake Prediction in Italy

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Abstract—The choice of the regions is essential in the application of the algorithm CN, therefore a seismotectonic criterion for their definition is tested. In order to take into account the geodynamic complexity characterising the Italian peninsula, we established to strictly follow the seismotectonic zones, including in each region only zones with similar seismogenic behaviour and the transitional zones connected to them. Three regions have been successfully defined in this way, corresponding approximately to the North, Centre and South of Italy. The reduction of the space-time uncertainty and the increase of the stability of prediction results obtained with this regionalisation, with respect to the previous applications of CN in Italy (KEILIS-BOROK *et al.*, 1990; COSTA *et al.*, 1995, 1996), can be interpreted as a validation of the seismotectonic model.

Key words: CN algorithm, earthquake prediction, Italy, seismotectonic model.

Introduction

The algorithm CN is structured according to a pattern recognition scheme to allow a diagnosis of the Time of Increased Probability (TIPs) for events with magnitude above a fixed threshold M_0. CN is based on the quantitative analysis of the premonitory phenomena, which can be detected in the seismic flow preceding the occurrence of strong earthquakes. The quantification of the seismicity patterns is obtained through a set of empirical functions of time, evaluated on the sequence of the main shocks which occurred in the analysed region. The seismicity traits considered are: level of seismic activity, quiescence, space-time clustering and space concentration of events. At each time, a vector formed by the values, coarsely discretized, assumed by the different functions, describes the seismic flow (KEILIS-BOROK, 1996). Although CN has been originally designed by retrospective analysis of seismicity in the California–Nevada region, the normalisation of its functions

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allows application of the algorithm, without any adjustment of parameters, even to regions with different dimensions and seismicity.

The first application of CN to the central part of the Italian territory was performed by KEILIS-BOROK *et al.* (1990), over a region chosen considering simply the completeness of the used catalogue. Subsequently COSTA *et al.* (1995) showed that seismological and tectonic arguments permit a narrowing of the region, leading at the same time to a reduction of failures to predict and of TIPs, while increasing the stability of the algorithm. In a further step the analysis has been extended to the whole Italian territory by COSTA *et al.* (1996), selecting three main regions, Northern, Central and Southern Italy, according both to the seismotectonic model (SCANDONE *et al.*, 1990) and to the spatial distribution of epicentres. These experiments evidence that the CN algorithm allows for dealing with the development of the regional geodynamic models, since it involves relationships between the structural features that control the seismicity and the selection of the optimal causative fault system for prediction purposes (RUNDKVIST and ROTWAIN, 1996).

In this work we want to advance one step further in this direction, testing the possibility of tracing the boundary of regions following closely the seismotectonic zones, independently defined by GNDT (SCANDONE *et al.*, 1990, 1994), to investigate the possibility of reducing the time-space uncertainty and the number of false alarms.

A new catalogue, the CCI1996 (COSTA *et al.*, 1997; PERESAN *et al.*, 1997) has been compiled which revises the PFGING catalogue (POSTPISCHL, 1985; COSTA *et al.*, 1995) to take into account recent information, mainly concerning historical seismicity, supplied by BOSCHI *et al.* (1995). In order to guarantee homogeneous and timely catalogue upgrading, monitoring is currently performed which updates the CCI1996 catalogue with the NEIC Preliminary Determinations of Epicentres; the procedure of data upgrading is fully described in PERESAN and ROTWAIN (1998).

The Regionalization

The choice of the region in which a strong earthquake must be predicted, is a relevant factor to obtain reliable results and to minimise the time-space uncertainty. Regions defined for prediction purposes have to be as small as possible, in order to reduce the space uncertainty, and must include the zones with higher seismicity level, where stronger earthquakes are likely to occur. Therefore, considering the fractal character of the spatial distribution of events (KAGAN and KNOPOFF, 1980; TURCOTTE, 1992), the region must contain the major clusters of epicentres, characterised by a high density of epicentres and by large magnitudes. This choice clearly affects the frequency-magnitude distribution for events which occurred within each region, because the log-linearity of the Gutenberg–Richter relation is preserved only on a global scale or, according to a multiscale approach (MOLCHAN *et al.*, 1996, 1997), within an area of the appropriate hierarchical scale, depending on the maximum magnitude considered. To reduce the spatial uncertainty of predictions, the area must be relatively small; therefore the frequency-magnitude distribution exhibits a good linearity only for lower magnitudes, with increasing fluctuations due to the small number of events for larger magnitudes. Generally an upward bend can be observed in this pattern, starting at a certain magnitude, depending both on the particular choice of the region that must include the more seismically active zones and on the possible occurrence of a characteristic earthquake for the major faults included in it (SCHWARTZ and COPPERSMITH, 1984). According to the standard procedure (MOLCHAN *et al.*, 1990), 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, and this guarantees the stability of the results (e.g., COSTA *et al.*, 1995). In other words, CN makes use of the information engendered by small and moderate earthquakes, registering good statistics, to predict the stronger earthquakes, which are rare events.

The area selected for predictions, using the algorithm CN, must satisfy three general rules: (1) its linear dimensions must be greater or equal to 5L–10L, where L is the length of the expected source; (2) on average, at least 3 events with magnitude exceeding the completeness threshold should occur inside the region each year; (3) the border of the region must correspond, as much as possible, to minima in the seismicity (KEILIS-BOROK *et al.*, 1996). This indicates that the detection level controls, to some extent, the time-space uncertainty of prediction (KEILIS-BOROK, 1996) and then the possibility of reducing the spatial uncertainty is limited by the difficulty of keeping a high level of detection, due to unavoidable logistic problems.

CN algorithm has been designed by the retrospective analysis of seismicity in the California–Nevada region, whose geodynamic can be related to a main driving mechanism, controlled by the relative displacement between the Pacific and the North-American plates. Compared to the California–Nevada, the Italian peninsula and the entire Mediterranean area exhibit a considerable heterogeneity in the tectonic regime, revealed by the coexistence of fragmented seismogenic structures of greatly differing kinds, where a very complex and apparently paradoxical kinematic evolution can be observed within very narrow regions (MELETTI *et al.*, 1998). Although the normalisation of CN functions guarantees the applicability of the algorithm to regions with a different level of seismic activity, we believe that this aspect should not be neglected. For instance, the number of aftershocks generated by an earthquake of a given magnitude is not independent from the fault mechanism, and consequently to mix sources of different kinds may compromise precursors based on the time cluster of events. More specifically, the selection of the region can influence the thresholds of discretisation of the function associated to the "bursts of aftershocks," even if this is a precursor observed in very diverse regions (MOLCHAN *et al.*, 1990).

Wishing to account for the seismotectonic complexity of the Italian area, we decided to test a new criterion for the definition of the regions, strictly based on the seismotectonic model. Considering the general rules and the sizes of the seismotectonic zones (Fig. 1), we establish to include in a single region adjacent zones with the same seismogenic characteristics (e.g., only compressive or only extensive) and zones with transitional properties. A transitional zone is included in a region if it is between zones of the same kind or if it separates two zones with different regimes and the space distribution of the aftershocks reveals a possible connection. For this purpose the selection of aftershocks is performed (MOLCHAN *et al.*, 1995) using the

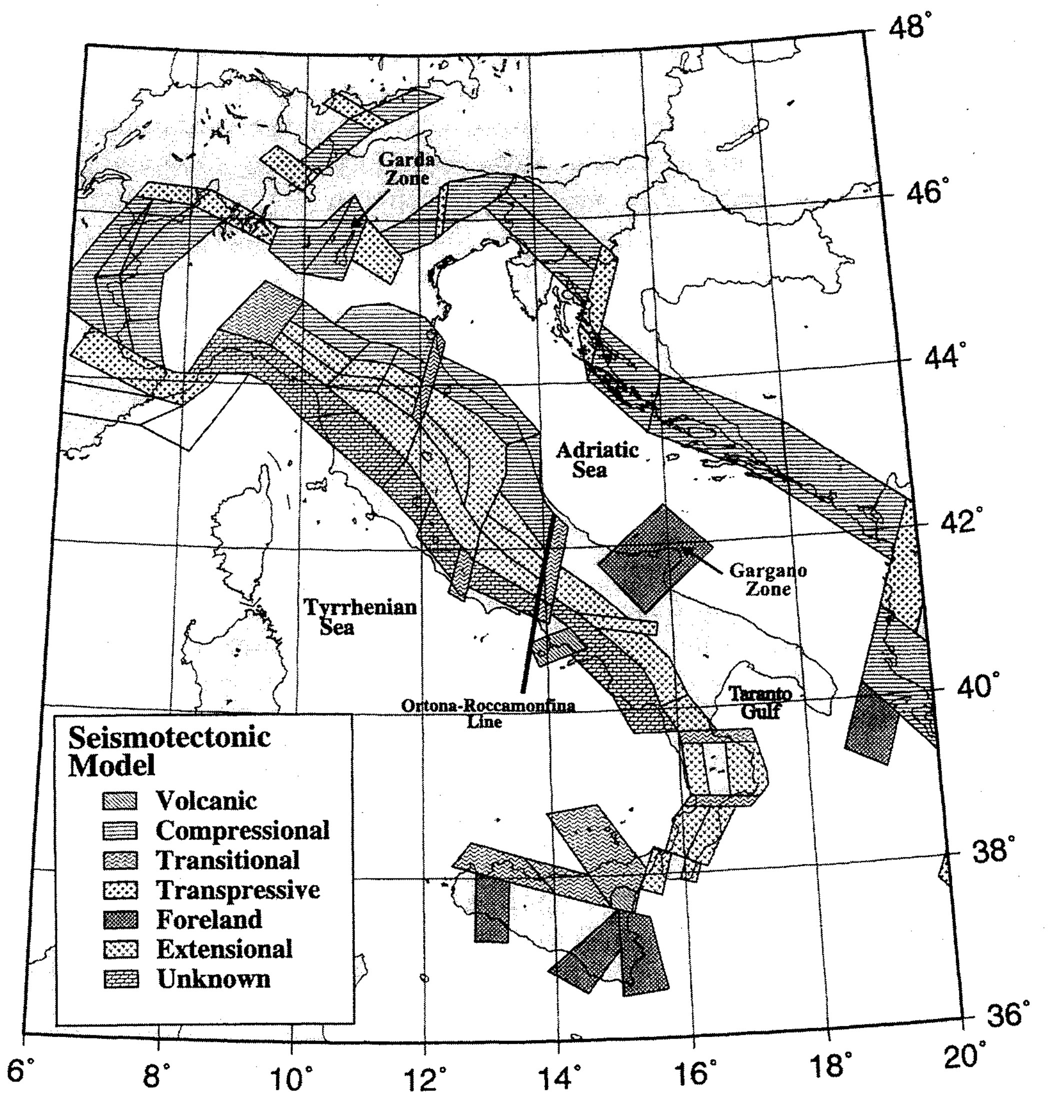

Figure 1
Seismotectonic model of Italy (SCANDONE *et al.*, 1994), revised version of the preliminary zoning described in SCANDONE *et al.* (1990).

"minimax" method proposed by MOLCHAN and DMITRIEVA (1992), since it allows a better spatial identification of aftershocks than the method proposed by KEILIS-BOROK *et al.* (1980), which is used in the selection of the subcatalogue of main shocks for prediction purposes.

Northern Italy

Northern Italy is characterised by the presence of a main structure, the Alpine arc, which is generally uplifting (MUELLER, 1982) with some westerly strike-slip motion (PAVONI *et al.*, 1992) and therefore the majority of focal mechanisms are compressive or transpressive.

The presence of many different political borders across the Alpine arc introduces two problems. Firstly the catalogue CCI1996 covers an area that, towards the North, follows the Italian border and consequently is fairly incomplete for our purposes; this problem has been solved (COSTA *et al.*, 1996) by filling the gap with data contained in two other catalogues, ALPOR (CATALOGO DELLE ALPI ORIENTALI, 1987) and NEIC (1992). The catalogue obtained for Northern Italy can be considered complete for $M \geq 3.0$ starting from 1960. The operating magnitude is selected as follows:

$$M = \mathrm{MAX} \left| \begin{array}{l} M_{\mathrm{ALPOR}}(M_L, M_I) \\ M_{\mathrm{CCI}}(M_L, M_d, M_I) \\ M_{\mathrm{NEIC}}(M_L, M_S, m_b) \end{array} \right. . \tag{1}$$

This means that the operating magnitude is the maximum of the three magnitudes selected for each catalogue, according to the priority order given in brackets. Magnitudes are indicated as follows: M_L is the local magnitude, M_d the duration magnitude, M_I is the magnitude from intensities, while M_S and m_b are the magnitudes from surface and body waves. Aftershocks are removed following the criteria proposed by KEILIS-BOROK *et al.* (1980) and, according to the general rules of the algorithm CN, the magnitude for the selection of the events to be predicted is fixed at $M_0 = 5.4$.

The second problem, due to the presence of political borders, arises from the necessity to use an adequate seismotectonic zoning for the neighbouring countries. Until recently, the available zones for the Slovenian–Croatian region were designed with different purposes and criteria (LAPAJNE *et al.*, 1995), consequently the easternmost border of the region could only be defined on the base of seismicity. Recently, following criteria quite similar to those used for Italy by SCANDONE *et al.* (1990, 1994), a seismotectonic zoning was proposed by ZIVCIC and POLJAK (1997) and consequently it became possible to redraw the boundaries of the northeastern part of the region closely following the seismogenic zones (Figs. 2c and 3).

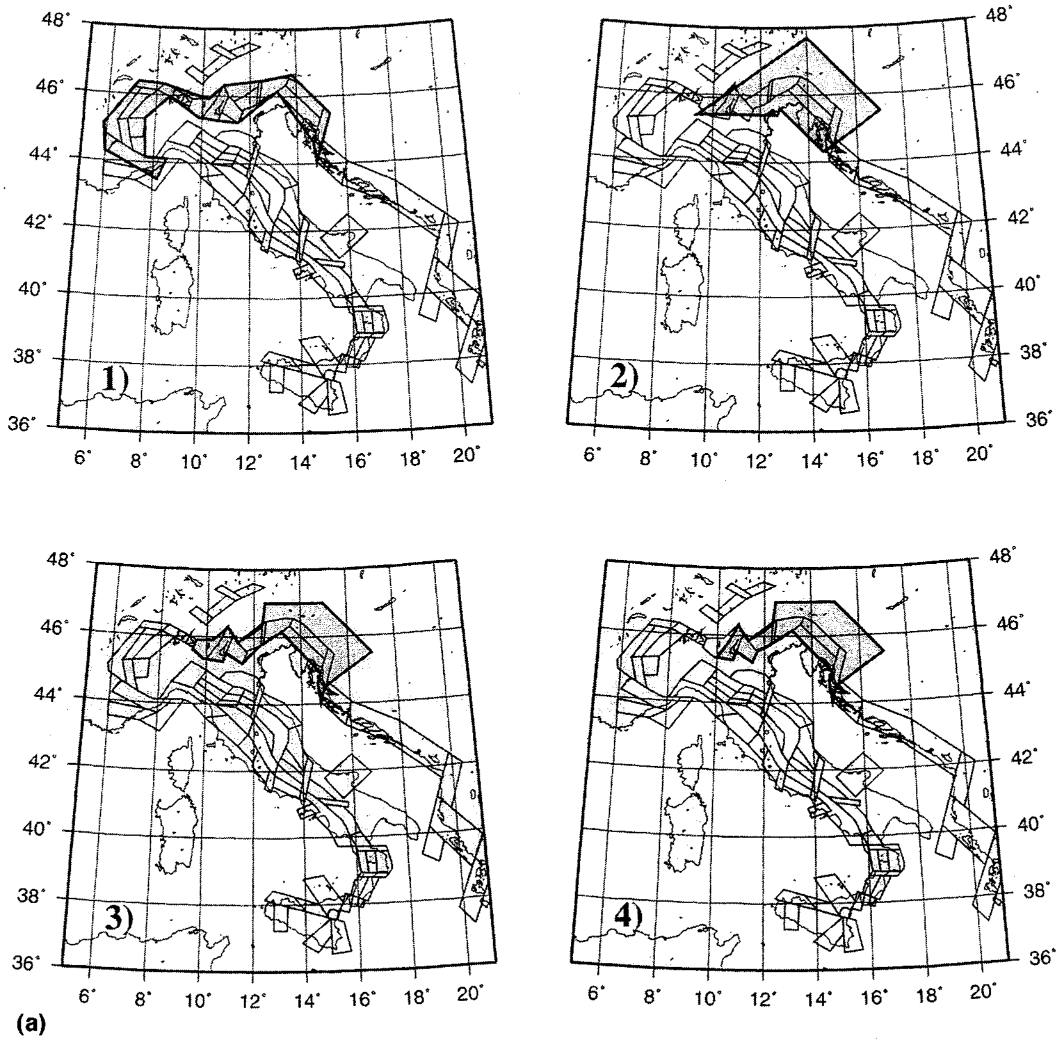

Figure 2a
Regionalisation for Northern Italy, considering simply connected seismogenic zones: (1) first variant based on the seismotectonic model, including the whole Alpine arc; (2) "small" region defined by Costa *et al.* (1996); (3) second variant, including the zone at the west of Garda's Lake (GZ); (4) third variant, excluding the GZ zone.

Our final choice of the region to be used with CN algorithm is based on the prediction experiments described below. When performing prediction experiments, with the aim to optimise the regionalisation, we must preserve the predictive power reached with the previous regionalisations. Therefore, since the old regionalisations allow us to predict all the strong earthquakes, in the following we define as successful only the experiments with no failures to predict.

Experiment 1. We consider the region formed by the compressional band and the adjacent transpressive zones that cover the entire Alpine arc, from the Istrian peninsula to Liguria (Fig. 2a-1 and Table 1). This experiment is unsuccessful, probably due to the different completeness of the catalogue (MOLCHAN *et al.*, 1995) and to the different level of seismic activity in different parts of the Alpine arc.

Experiment 2. Within the smaller region defined by COSTA *et al.* (1996) for Northern Italy (Fig. 2a-2) we keep only the compressional and transpressive adjacent zones in Italy, while in Austria, Slovenia and Croatia we keep the boundaries proposed by COSTA *et al.* (1996), except towards the North, where we follow the minimum of seismicity located in correspondence of the 47°N parallel. The seismogenic properties of the zone at the west side of Lake Garda (central part of Southern Alps) have been the subject of debate, as can be seen by recent

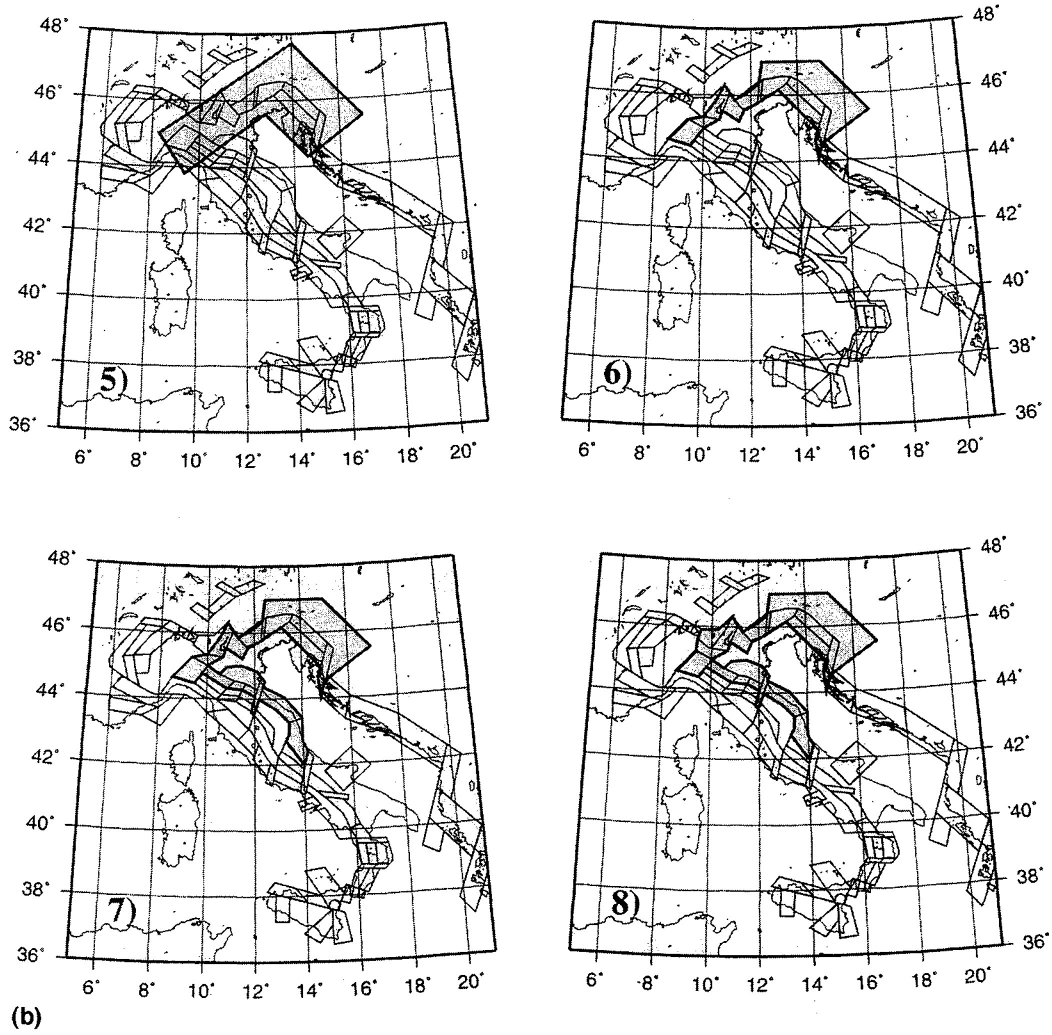

Figure 2b
Regionalisation for Northern Italy, considering also disconnected zones: (1) "extended" region defined by COSTA *et al.* (1996); (2) first variant based on the seismotectonic model, including the transitional zone at the northern edge of the Apennines; (3) second variant, including the whole compressional band, but without the GZ zone; (4) third variant, including also the GZ zone.

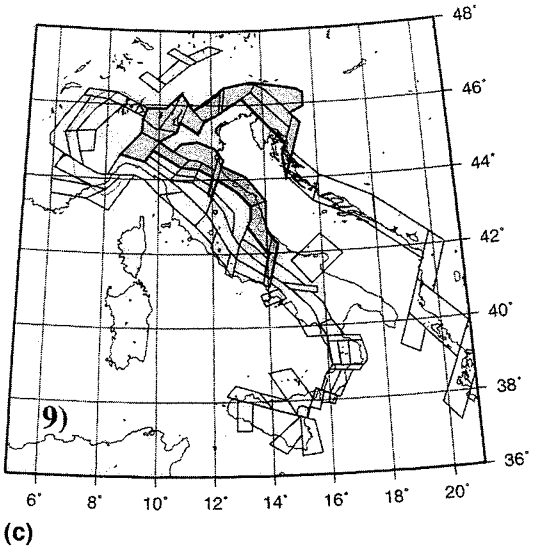

Figure 2c
Regionalisation for Northern Italy that takes into account the seismogenic zoning of the Slovenian–Croatian territory (ZIVCIC and POLJAK, 1997); the transition zones are included at both edges.

revisions of the seismotectonic model (SCANDONE *et al.*, 1990, 1994). Therefore we define two regions, one including and the other excluding the zone west of Garda (GZ), as shown respectively in Figures 2a-3 and 2a-4. The results obtained for these two regions are given in Table 1 and can be considered satisfactory only for the region shown in Figure 2a-4. Then we deduce that the seismicity contained in this small zone plays a critical role, revealing a certain instability with respect to the choice of the areas represented in Figures 2a-2, 3 and 4 (see also Fig. 4).

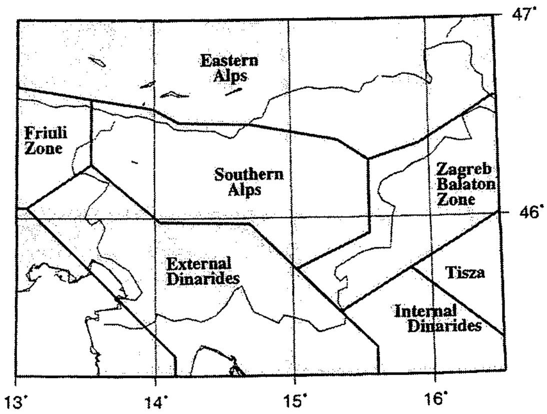

Figure 3
Preliminary seismogenic zoning of Slovenia and adjacent regions proposed by ZIVCIC and POLJAK (1997).

Table 1

Results obtained with the algorithm CN in Northern Italy, using the different regions represented in Figures 2a, 2b and 2c. For regions 2 and 5 the catalogue PFGING has been used by COSTA *et al. (1996). The last line indicates results updated on September 1, 1998, whose corresponding TIPs diagram is shown in Figure 10-a*

Northern Italy							
Region	Time	Learning period	M_0	Events predicted	Failure to predict	TIPs %	False alarms
1	1960–1995	1964–1995	5.4	0	2	32.5	6
2*	1960–1994	1964–1994	5.4	2	0	34	2
3	1960–1995	1964–1995	5.4	1	1	35.1	4
4	1960–1995	1964–1995	5.4	2	0	28.8	2
5*	1960–1994	1964–1994	5.4	2	0	27	1
6	1960–1995	1964–1995	5.4	2	0	24.7	2
7	1960–1995	1964–1995	5.4	2	0	24.7	3
8	1960–1995	1964–1995	5.4	2	0	20.5	2
9	1960–1995	1964–1995	5.4	2	0	19.9	2
9**	1960–1998	1964–1995	5.4	4	0	25.1	2

* Catalogue: PFGING.
** Updated Catalogue: CCI1996(1960–1994) + NEIC(1995–1998).

Experiment 3. For a deeper analysis of the instability detected with experiment 2, we remember the hypothesis that the seismicity at the northern edge of the Apennines may be related to the seismicity of the Alpine arc (COSTA *et al.*, 1996), which led to a definition of the region in Figure 2b-5. Therefore we extend the region of Figure 2a-4 to the transition seismogenic zone at the northern edge of the Apennines, even if it is not directly connected to the others (Fig. 2b-6). In such a way the percentage of total TIPs is reduced. Subsequently the area is further extended to the whole compressional band along the Adriatic coast (Fig. 2b-7). With this extension the destabilising effect of the zone at the west side of Lake Garda's zone is removed (Figs. 2a-3, 4 and Table 1).

Experiment 4. The northeastern border of the region shown in Figure 2b-8 is modified considering the seismotectonic zoning for the Slovenian–Croatian territory (ZIVCIC and POLJAK, 1997) and including only compressional and transpressive zones. Where there is an overlapping of the two zoning the priority is given to the model proposed by SCANDONE *et al.* (1994) (Figs. 2c and 3).

The results obtained for the area finally selected (Fig. 2c) can be summarised as follows: both events with $M \geq M_0$, which occurred in the period under analysis ($M = 6.5$, May 6, 1976 and $M = 5.4$, February 1, 1988) are predicted with 20% of the total time considered occupied by TIPs and 2 false alarms. The improvement with respect to the results obtained by COSTA *et al.* (1996) is a reduction in the percentage of TIPs (from 27% to 20%) and in the spatial uncertainty (around 38%).

These results are stable with respect to changes in the learning period and to the exclusion of the transition zone containing the Ortona–Roccamonfina line (Fig. 4).

The new regionalisation is compatible with the kinematic model of rotation and subduction of the Adriatic microplate and supports the hypothesis of a possible connection between the earthquakes that occur within the compressional band, marking the zone of subduction along the Southern Alps and Northern Apennines (WARD, 1994; ANDERSON and JACKSON, 1987).

The diagram of the time distribution of TIPs, obtained in the monitoring updated to September 1998, is presented in Figure 10-a. The catalogue for the monitoring in the Northern region is updated with the NEIC data since January

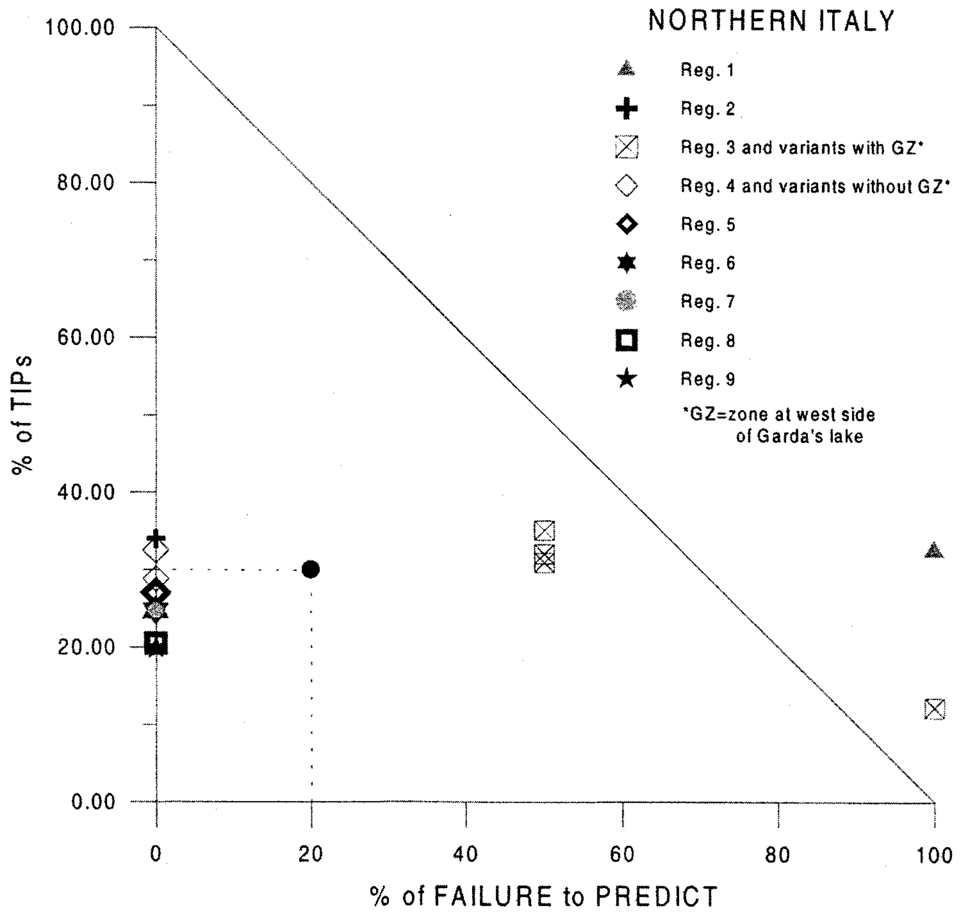

Figure 4

n-τ diagram of the percentage of total TIPs versus the percentage of failures to predict for the results obtained in Northern Italy for the different regions shown in Figures 2a, 2b and 2c. Other variants (not shown) including or not the GZ zone have been considered. All the regions with GZ (zone at west side of Lake Garda) correspond to unsuccessful experiments. The diagonal line indicates the results of a random guess (MOLCHAN, 1990). The large full dot represents the worldwide performance of CN.

1995. The operating magnitude from NEIC is chosen to be the maximum given in the Preliminary Determinations of Epicentres database (PERESAN and ROTWAIN, 1998). The results of the application of CN algorithm to this updated catalogue can be summarised as follows: all the four strong earthquakes with $M \geq M_0 = 5.4$ which took place within the region since 1964, are preceded by TIPs, with alarms (including two false alarms) covering about 25% of the total time. Only two strong events occurred during the learning period, while the two recent events ($M = 5.8$, October 15, 1996 and $M = 6.0$, April 12, 1998) are real predictions.

A common feature to the different successful regionalisation experiments performed is the persistence of a TIP in the time interval from 1972 to 1976. Starting in January 1973, remarkable tilt perturbations have been recorded by the horizontal pendulums of Grotta Gigante, near Trieste (ZADRO, 1978). These anomalies have been interpreted as a "slow earthquake" (DRAGONI *et al.*, 1985) and therefore it seems reasonable to formulate the hypothesis that the persisting TIP, from September 1972 to January 1976, is related to these creeping phenomena. A less clear-cut, but similar phenomenon, seems to characterise the false alarm following the $M \geq M_0 = 5.4$ event, correctly predicted in 1988. Long-term tilt variations, with periods of several years, have been detected for both the NS and EW components of the tiltmeters in the stations of Villanova and Cesclans, located in the Friuli region and working since 1977. Among them a strong anomalous deformation with a shorter period can be evidenced by the EW component of tilt in Cesclans (near Tolmezzo, Udine), from 1987 to 1991 (ROSSI and ZADRO, 1996). The occurrence of the $M = 5.4$ earthquake did not slow down the deformations nor the alarm. Therefore the symptoms of instability detected by the algorithm CN could reveal a stress accumulation, partially released seismically and not terminated with a strong earthquake, because of creep. This interpretation is an alternative to the explanation given within the framework of the dilatancy model, in which a volume increase is expected under the effect of tectonic stresses, due to fluid migration in a volume of cracked rocks; accordingly the anomalies can be seen as precursors, indicating accumulation rather than relaxation of stress.

Central Italy

The central part of the Italian peninsula along the Apennines is characterised by a band with tensional seismotectonic behaviour, with prevailing dip-slip focal mechanism. Two belts run parallel to it: the western belt comprises the extensional zones near the Tyrrhenian coast and the eastern consists of the compressional zones along the Adriatic Sea, from the Ortona–Roccamonfina line (Fig. 1) to the Po Plain. COSTA *et al.* (1996) evidenced that the central band may be considered individually and this fact seems to be supported by the model proposed by MELETTI *et al.* (1995) for the deep structure of the Northern Apennines. The model

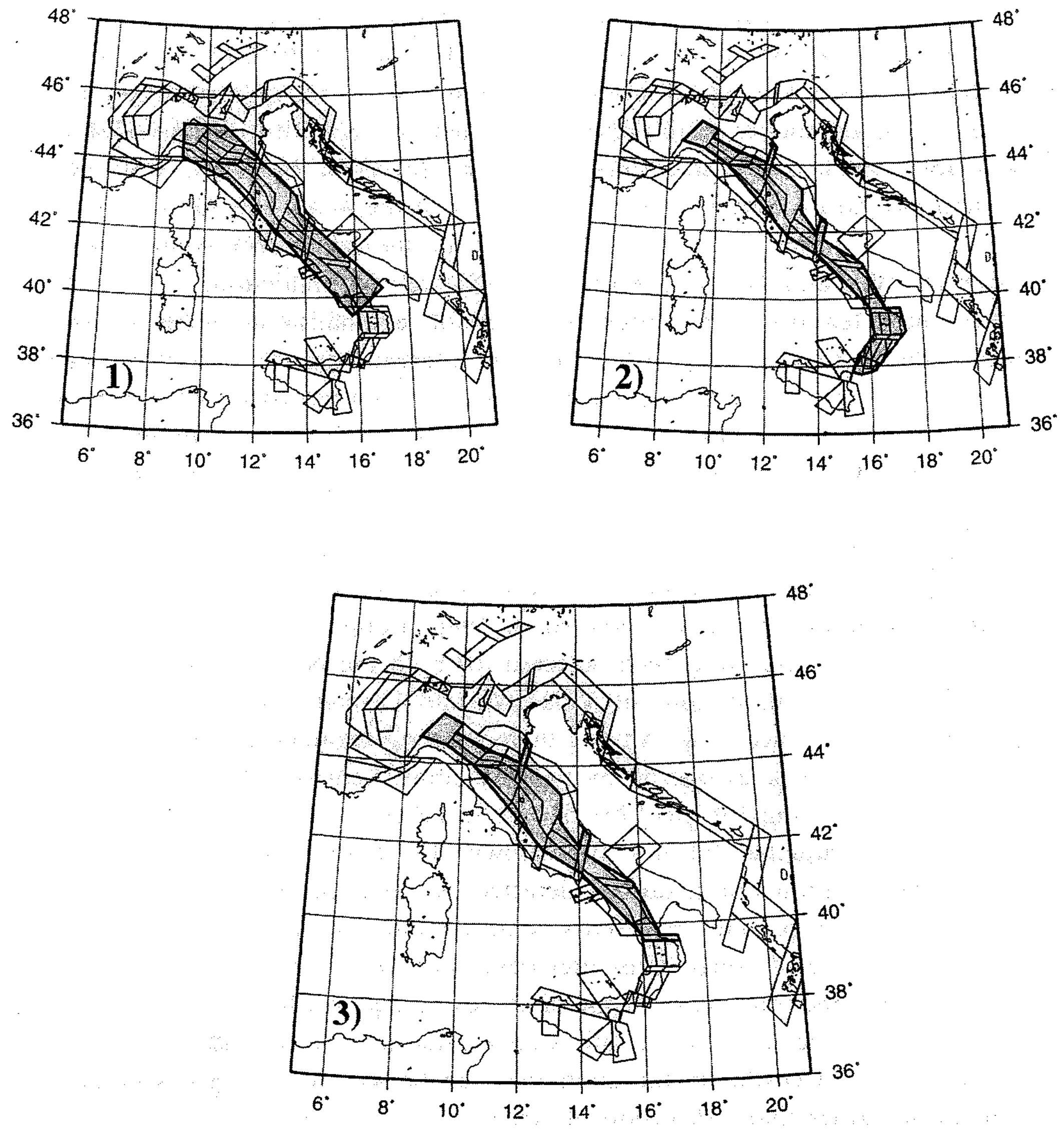

Figure 5
(1) Regionalisation for Central Italy defined by COSTA *et al.* (1996); (2) region including the whole extensional band; (3) region defined following the seismotectonic model, including the transition zones at the edges.

indicates a connection at depth between the Adriatic compressional front and the uplifting asthenosphere along the Tyrrhenian Sea, in agreement with the geometry of the lithosphere–asthenosphere system outlined by CALCAGNILE and PANZA (1981), DELLA VEDOVA *et al.* (1991) and MARSON *et al.* (1995) on the basis of the available relevant geophysical data (surface waves, body waves tomography, heat flow, gravity). According to the seismogenic zoning, the foreland Gargano region must be excluded from the region of Central Italy.

The region defined for Central Italy is presented in Figure 5-3. In this region the catalogue CCI1966, starting from 1950, can be considered complete for $M \geq 3.0$ (MOLCHAN *et al.*, 1995). The operating magnitude is chosen following the priority: M_L, M_d, M_I. Aftershocks are removed as in Northern Italy and, according to the general rules of the algorithm CN, only crustal earthquakes are considered, and the threshold for the selection of strong events is $M_0 = 5.6$. The events to be predicted inside this region (Fig. 5-3) are three: $M = 5.8$ and $M = 6.0$, both on August 21, 1962 and the Irpinia's earthquake, with $M = 6.5$, on November 23, 1980. All of them are predicted with TIPs covering 19% of the total time and with two false alarms (Table 2). The exclusion of the transition zones at both edges of the extensional band does not significantly affect the results, which are very stable over this area (COSTA *et al.*, 1995).

The entire extensional band, extending along the peninsula from the Po Plain to the Messina Strait, can be considered to form a single region (Fig. 5-2), although this leads only to an increase of the spatial uncertainty (Table 2 and Fig. 6). On the contrary, the attempt to divide this tensional band along the Ortona–Roccamonfina discontinuity demonstrates that a proper retrospective description of seismicity is impossible, because the strong Irpinia's earthquake and its precursors seem to significantly affect the activation in the entire peninsula.

Comparing the region defined in Figure 5-3 to that defined for Central Italy by COSTA *et al.* (1996) (Fig. 5-1), we observe that the new criteria allow us a reduction of the spatial uncertainty by about 30%.

The monitoring of seismicity in the Central region is currently performed using the CCI1966 catalogue updated with the NEIC data since January, 1986. The operating magnitude from NEIC is chosen according to the priority order: $M_{\mathrm{NEIC}}(M2, M1, M_S)$, where M_S is the magnitude from surface waves, while $M1$ and $M2$ are two estimations contributed from different agencies, mainly local and

Table 2

Results obtained over the regions defined for Central Italy and shown in Figure 5. The first line indicates the results given by COSTA et al. *(1996), using the PFGING catalogue. The diagram of TIPs for the updated catalogue and with the new region is shown in Figure 10-b*

Central Italy							
Region	Time	Learning period	M_0	Events predicted	Failure to predict	TIPs %	False alarms
1*	1950–1994	1950–1986	5.6	3	0	23	2
2	1950–1995	1950–1986	5.6	3	0	22.3	3
3	1950–1995	1950–1986	5.6	3	0	18.7	2
3**	1950–1998	1950–1986	5.6	5	0	22.2	2

* Catalogue: PFGING.

** Updated Catalogue: CCI1996(1960–1985) + NEIC(1996–1998).

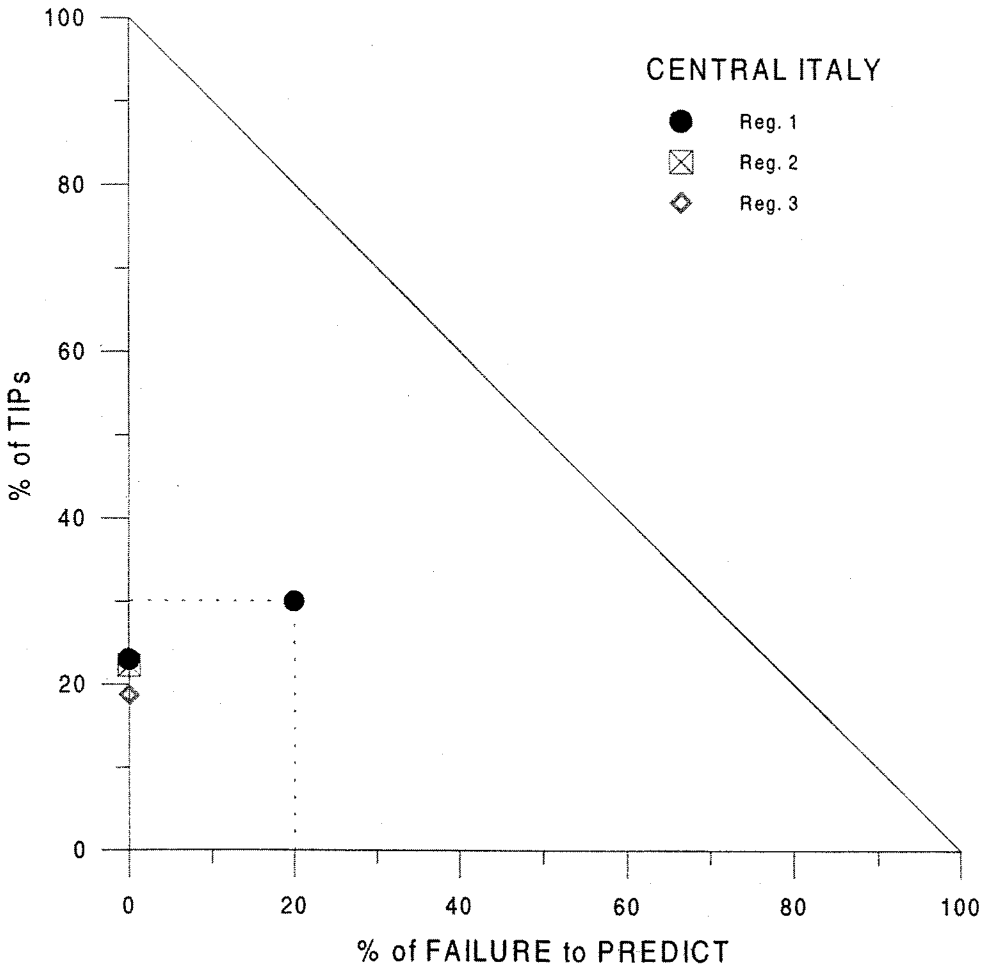

Figure 6
n-τ diagram for the results obtained in Central Italy considering the different regions shown in Figure 5. The large full dot represents the worldwide performance of CN.

duration magnitude (PERESAN and ROTWAIN, 1998). The results obtained with this catalogue are the following: all five strong earthquakes with $M \geq M_0 = 5.6$ which occurred within the region since 1954, are identified by TIPs covering about 22% of the total time, including two false alarms. The forward monitoring updated to September 1998 indicates a current alarm for this region continuing to September 1999. The distribution of TIPs is shown in Figure 10-b.

The results obtained using different regionalisations for Central Italy (KEILIS-BOROK *et al.*, 1990; COSTA *et al.*, 1996), all show the persistence of a false alarm which spans a period from July 1984 to March 1988. Similar to the case observed in Northern Italy, anomalous deformations, modelled as aseismic dislocation processes (DRAGONI, 1988), have been recorded in this region during 1985 (BELLA *et al.*, 1987).

Southern Italy

The extremity of the Italian peninsula, together with Sicily, is characterised by a seismotectonic connected with the sinking of the Adriatic–Ionic plate under the Southern Apennines and the Calabrian arc. The kinematic model proposed by SCANDONE *et al.* (1990, 1994) for Southern Italy seems to indicate a possible relation among the events occurring along the arc which reaches from the Ortona–Roccamonfina discontinuity to the western edge of Sicily. This hypothesis is supported by the unsuccessful CN-prediction experiment reported by COSTA *et al.* (1996) for the region that excludes the Irpinia's area (Fig. 7-2 and Table 3).

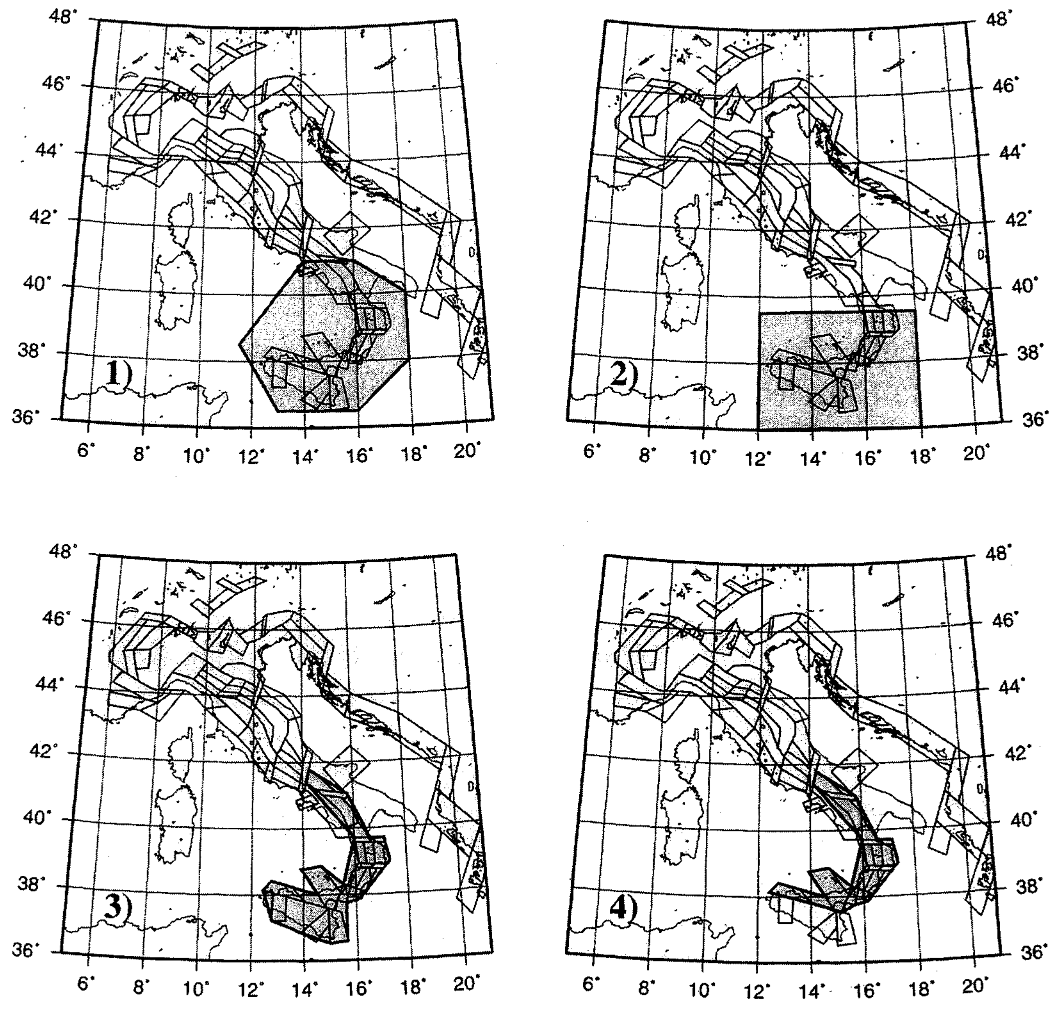

Figure 7
(1) Region defined for Southern Italy by COSTA *et al.* (1996); (2) region tested by COSTA *et al.* (1995); (3) region defined following the seismotectonic model and including the foreland zones of Sicily; (4) region defined for Southern Italy, excluding all the foreland zones.

Table 3

Results obtained for the four variants of the Southern Italy region shown in Figure 7. The results given by Costa *et al. (1996) for regions 1 and 2 were obtained using the PFGING catalogue, including deep events and considering their maximum magnitude. Updated predictions (September 1, 1998) for the new region are represented with a TIPs diagram in Figure 10-c*

Southern Italy							
Region	Time	Learning period	M_0	Events predicted	Failure to predict	TIPs %	False alarms
1*	1950–1994	1954–1994	6.5	3	0	33	5
2*	1950–1994	1954–1994	6.5	1	1	25	2
3	1948–1995	1952–1995	6.5	0	1	42.6	7
4	1950–1995	1954–1986	5.6	4	0	34.6	5
4**	1950–1998	1954–1986	5.6	4	0	30.8	5

* Magnitude = MAX. Catalogue: CCI1996. Also deep events are included.
** Updated Catalogue: CCI1996(1960–1991) + NEIC(1992–1998).

The role played by foreland zones is particularly critical in Southern Italy, because their inclusion in the analysis leads to unsuccessful or very unstable experiments. When they are excluded, both in the Gargano region and in Sicily, the experiments are successful (Figs. 7-3, 4 and Table 3).

The transition zone corresponding to the Ortona–Roccamonfina line is not included in the South-Italy region, though it is adjacent to the region, since the distribution of the aftershocks of the strong events which occurred over this area (Molchan *et al.*, 1995) does not indicate a connection between the transition zone and the southward part of the tensional band (Fig. 9).

Following the standard priority (M_L, M_d, M_I) for the operating magnitude in the region shown in Figure 7-4, we can fix the completeness threshold for the catalogue CCI1996, starting from 1950, at $M = 3.0$ and choose $M_0 = 5.6$. All four events ($M = 5.8$, May 20, 1957; $M = 5.8$ and $M = 6.0$ in August, 1962; $M = 6.5$ on November 23, 1980) with $M \geq M_0$ are predicted with TIPs occupying about 34% of the total time interval and 5 false alarms. With respect to the region defined by Costa *et al.* (1996) and shown in Figure 7-1, the reduction of the spatial uncertainty can be estimated around 72%, although it is necessary to consider that the threshold M_0 has been lowered.

The updated catalogue for Southern Italy has been compiled using the CCI1996 for the period: 1954–1991, followed by the NEIC (1992–1998), with priority $M_{\mathrm{NEIC}}(M2, M1, M_s)$. Results of the monitoring, updated to September 1, 1998, indicate that all four strong events are correctly identified by the retrospective analysis, with TIPs covering about 31% of total time, including 5 false alarms. The time distribution of alarm periods and the time of occurrence of strong events are represented in Figure 10-c. Particular attention must be paid, however, to the forward monitoring in the Southern region, where the lower completeness level of NEIC data increases the probability of failures to predict (Peresan and Rotwain, 1998).

Evaluation of the Results

To reduce the spatial uncertainty of predictions, the area indicated as the place where a strong event is expected to occur, must be as small as possible. Therefore, even if on a global scale strong earthquakes are not infrequent, within such small regions they are rare events, with long interevents time. Since the compilation of reliable catalogues started quite recently, on a regional scale the statistical properties of the sequence of strong earthquakes remain undefined and therefore alternative approaches must be used for predictions.

A crucial problem that generally arises with empirical methods, such as CN and *M*8 (KEILIS-BOROK, 1996), is the evaluation and comparison of results together with the estimation of the reliability of forward predictions.

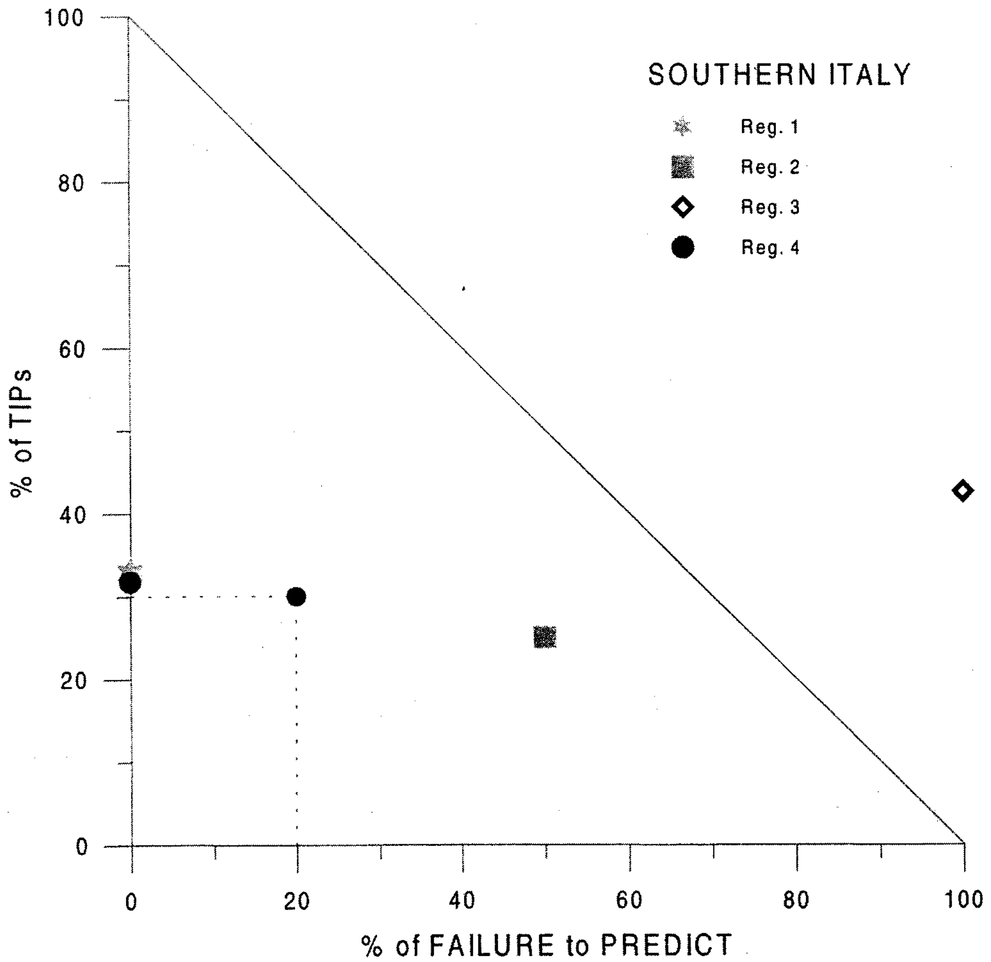

Figure 8

η-τ diagram of the results, obtained using algorithm CN, for the different regions tested for Southern Italy and shown in Figure 7. The large full dot represents the worldwide performance of CN.

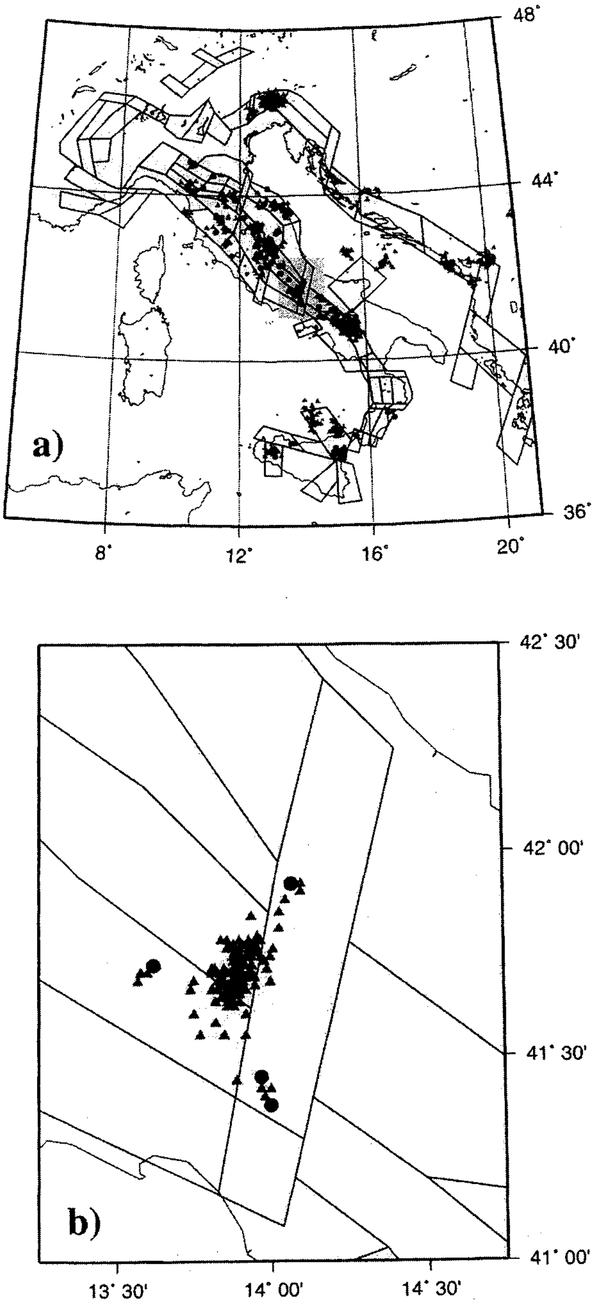

Figure 9
(a) Map of the main shocks (dots) and corresponding aftershocks (triangles) selected with the "minimax" method proposed by MOLCHAN *et al.* (1995). Only events with at least 10 aftershocks and which occurred in the time span 1900–1993 are considered. The small box indicates the area shown in detail in part (b) centred around the transitional zone corresponding to the Ortona–Roccamonfina line. Aftershocks indicate a possible connection only with the northward part of the extensional band.

In the previous paragraphs we have compared the results obtained with different choices of the regional boundaries. Particularly in Northern Italy we performed a series of experiments, defining as successful only those which provided an indication of the occurrence of all the strong events. This is not a general rule for evaluation however, but simply represents the choice to preserve the predictive power of the algorithm with respect to the regionalisation used by COSTA *et al.* (1996). Obviously declaring an alarm covering 100% of the time all the events are predicted, while if no alarm is indicated there are only failures to predict. Therefore

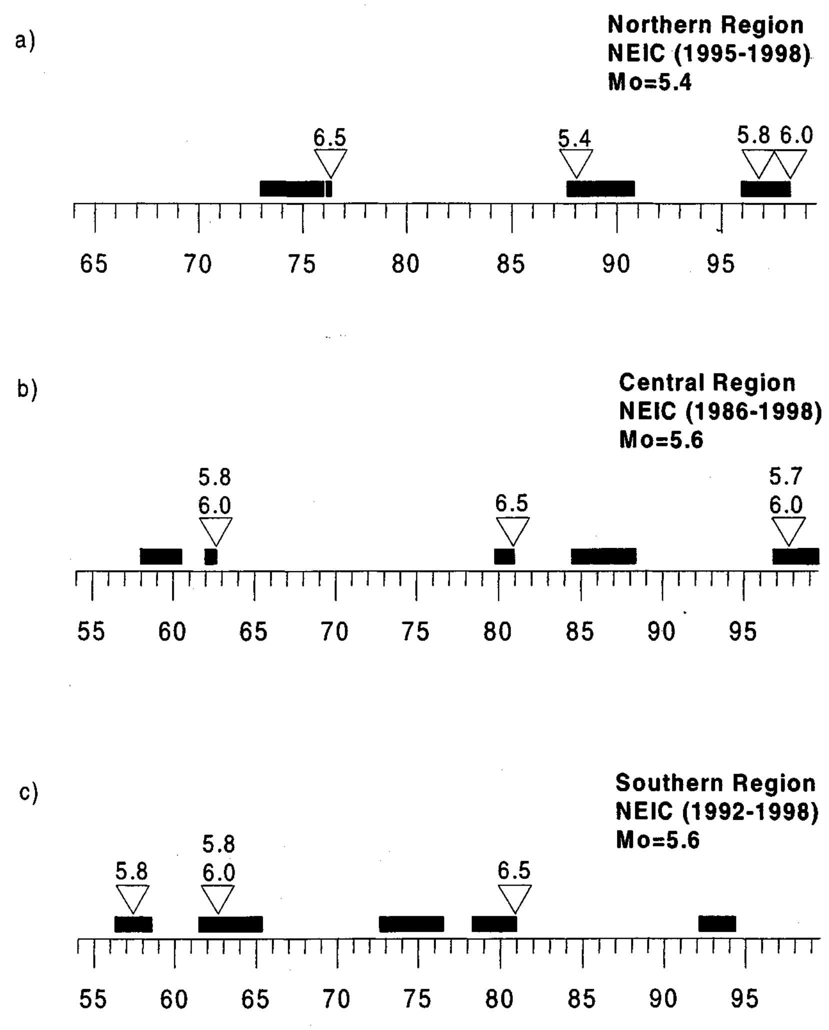

Figure 10
Diagrams of the TIPs obtained with the updated catalogue: CCI1996 + NEIC (up to September 1, 1998), over the regions defined for: (a) Northern (Fig. 2c-9), (b) Central (Fig. 5-3) and (c) Southern Italy (Fig. 6-4). NEIC data are used for the period of time indicated in brackets. The time of occurrence of a strong earthquake is indicated by a triangle with a number above giving its magnitude. These diagrams correspond to the results indicated in Tables 1, 2 and 3, respectively. On a global scale, about 50% of the TIPs continuing after strong events become false alarms.

an algorithm must trade between these extremes, trying to minimise both the time uncertainty and the number of failures to predict. The condition can be properly described through the so called n-τ error diagrams (MOLCHAN, 1996), representing the percentage of failures to predict versus the percentage of total alarm duration (Figs. 4, 6 and 8). The diagonal line between the extreme points (0, 1) and (1, 0) represents the results of a random guess, therefore we expect that the results associated with a useful prediction method will lie below this line. Once chosen the set of information to be used for prediction, for instance earthquake catalogues, the set of errors corresponding to the different possible strategies will lay in the portion of plane between the diagonal line and a convex downward monotonic curve. This curve represents the set of optimal prediction strategies and is characteristic of the set of information itself. Once a loss function is defined, taking into account both the costs of possible false alarms and of failures to predict, the n-τ diagram allows us to evaluate the quality of results. The best result, and therefore the best prediction strategy, corresponds to the first point (for increasing n and τ errors) that lies on the convex upward, monotonic curve corresponding to a contour of the loss function (MOLCHAN, 1996).

Figures 4, 6 and 8 represent the empirical results obtained for Northern, Central and Southern Italy, respectively. The diagram corresponding to the Northern regions shows the evident instability of the results when slight variations of region 3 (including Garda's zone) are considered, while for the other regionalisation the results lie on the τ axis. For all three regions the results obtained with the new regionalisation appear to be the best, as their τ has been reduced, and there is still no failure to predict. Nevertheless the small number of events to be predicted limits the statistical significance of the description with the n-τ diagram, whose proper use would require a multitude of predictions.

We now describe the problem of the evaluation CN results and of the reliability of forward predictions from a slightly different point of view, simply showing on the basis of the concept of "base-rate effect," the consequences which the chances of occurrence of an event have on the ability to predict it. This effect is characteristic of rare phenomena and, in the case of earthquakes, it determines innumerable false alarms, in spite of the great accuracy that a prediction method may reach (MATTEWS, 1996).

From the global retrospective tests performed, it results that the algorithm CN is able to indicate the occurrence of some 80% of the strong events, with TIPs occupying, on average, about 30% of the total time (KEILIS-BOROK, 1996). When dangerous conditions are recognised by CN an earthquake is expected to occur within one year and a TIP is declared. In practice alarms may be longer or shorter than one year, due to the merging of consecutive TIPs or to the occurrence of a strong earthquake. Nevertheless, for an average description, it appears appropriate to use for TIPs the value of 1 year, neglecting their possible correlation in time. Once a region is fixed, according to the general rules for the application of the

Table 4

Contingency table for the algorithm CN, for a time period of 100 years. The yearly base-rate of earthquakes is the probability of occurrence of a strong event during one year, and it is obtained considering the average return period of six years (condition for the applicability of the algorithm). The accuracy in the prediction of earthquakes and the percentage of total alarm are drawn from global results in retrospective and forward analysis, while the other quantities have been calculated in the hypothesis of the yearly duration of TIPs. The accuracy here refers to prediction within a single class of objects (dangerous or non-dangerous) and gives a measure of their predictability with algorithm CN. The conditional probability of predictions is given by the ratios: "true alarms/total alarms" and "true no alarm/total no alarm"

	Prediction of earthquake	Prediction of no earthquake	Total	Accuracy of predictions
Years with earthquake	12	3	15	80%
Years with no earthquake	18	67	85	79%
Total	30	70	100	
Conditional probability of predictions	40%	96%		

Yearly base-rate of earthquakes: 15% (one earthquake every 6 years, on average, within the considered region).

Average performance (forward and retrospective) in intermediate-term prediction of earthquakes: 80%.

Average percentage of total TIPs: 30%.

algorithm CN, the events with magnitude $M \geq M_0$ must have an average recurrence time of about six years and the probability of occurrence of a strong earthquake during one year (base-rate) is around 15%. Therefore, considering a period of 100 years, 15 years are expected to contain an event with $M \geq M_0$, while during the remaining 85 no strong earthquake will occur (Table 4). According to global results, 12 out of the 15 earthquakes will be correctly forecasted, with 3 failures to predict and alarms will occupy about 30 years. Because there are only 12 strong events, we can expect that at least 18 TIPs will correspond to false alarms. Consequently, if we try to evaluate the accuracy in recognition of non-dangerous years, we ascertain that it is about 79% (18 out of 85 years are identified as dangerous by mistake) and then 80% seems a reasonable measure of CN performance. From Table 4 it is possible to see that only 12 of the 30 predictions of an incoming earthquake are correct, therefore the conditional probability for a TIP can be estimated at roundly 40%. This percentage increases to about 96% when the conditional probability for predictions of no earthquake is considered (67 successes out of 70 forecasts). These estimations, in any case, must be viewed as approximate and averaged values, because they are based on global results, both forward and retrospective, and on the assumption of a yearly duration of alarms. The values given in Table 4 have been calculated neglecting the properties of the time distribution of TIPs and earthquakes, such as possible correlation or periodicity, which can be very different from region to region. A proper evaluation of the reliability of the monitoring for a single region must take into account these specific properties and a similar table must be compiled which considers the real time distribution of the true and false alarms. Regretfully, the small number of events to be predicted in all three regions defined for Italy, and particularly for the Northern region, compromises the statistical significance of this type of evaluation, just as it occurs with the n-τ diagrams. Therefore the real predictive power of CN algorithm and the reliability of its predictions within a fixed region could be evaluated only on the basis of future results. Approximately, however, it is possible to deduce from Table 4 that when a TIP is declared, it has a 60% probability of being a false alarm. Conversely, if no TIP is indicated, at 96% no strong earthquake will occur.

Conclusions

The new regionalisation of the Italian territory, based on the seismotectonic zoning, allows us to both improve the predictions and to validate the seismotectonic model.

Three regions have been selected for Northern, Central and Southern Italy respectively, strictly following the boundaries of the seismogenic zones; each region contains only adjacent zones with the same characteristics or with transitional properties.

The Northern Italy region appears compatible with the kinematic model of rotation and subduction of the Adriatic microplate, and the results of the analysis with the CN algorithm support the hypothesis of the connection between earthquakes that occur within the compressional band along the subduction zone in the Southern Alps and Northern Apennines. Similarly, the Southern Italy region is defined by the seismotectonic structures associated with the sinking of the Adriatic–Ionian plate under the Calabrian Arc. The choice of the Central region, instead, is related to the deep structure of the Northern Apennines, characterised by the subduction of the Adria plate and by the uplifting of the asthenosphere along the Tyrrhenian rim.

The results obtained for the three regions exhibit a general reduction of time and space uncertainty of the predictions of strong events, with respect to the regionalisations that do not closely follow the seismotectonic zones (COSTA *et al.*, 1996). The border of the regions defined according to the tested criterion might appear too complex and the regions too tiny. However the hypothesis, derived by this regionalisation, that precursors can be found inside seismogenically homogeneous areas associated with a dominating geodynamic process, seems supported by the corresponding improvement of results.

The results of the forward monitoring (Fig. 11), show that the strong earthquakes which occurred in the Northern and Central regions can be correctly predicted using this regionalisation. Nevertheless only a statistically significant number of forward predictions can firmly validate the regionalisation and the method itself.

Earthquake catalogues, as complete and homogeneous as possible, are essential for intermediate-term predictions. For this reason we have used a revised version of the PFGING catalogue, named CCI1996 (PERESAN *et al.*, 1997), obtained considering the most recently available revisions of source parameters of individual events (BOSCHI *et al.*, 1995; ICS, 1976–1990). Nevertheless, it appears particularly difficult to compile a suitable updated catalogue, especially when the studied area is crossed by political boundaries, and this calls for a strengthening of data collection at the European level. For the time being we have bypassed this shortcoming using the NEIC global catalogue, which guarantees the space homogeneity and the timely upgrading of the catalogue necessary for CN application in the three Italian regions.

The discretisation of the functions which describe the seismic flow, however, makes the algorithm CN quite robust with respect to the small, sporadic errors that

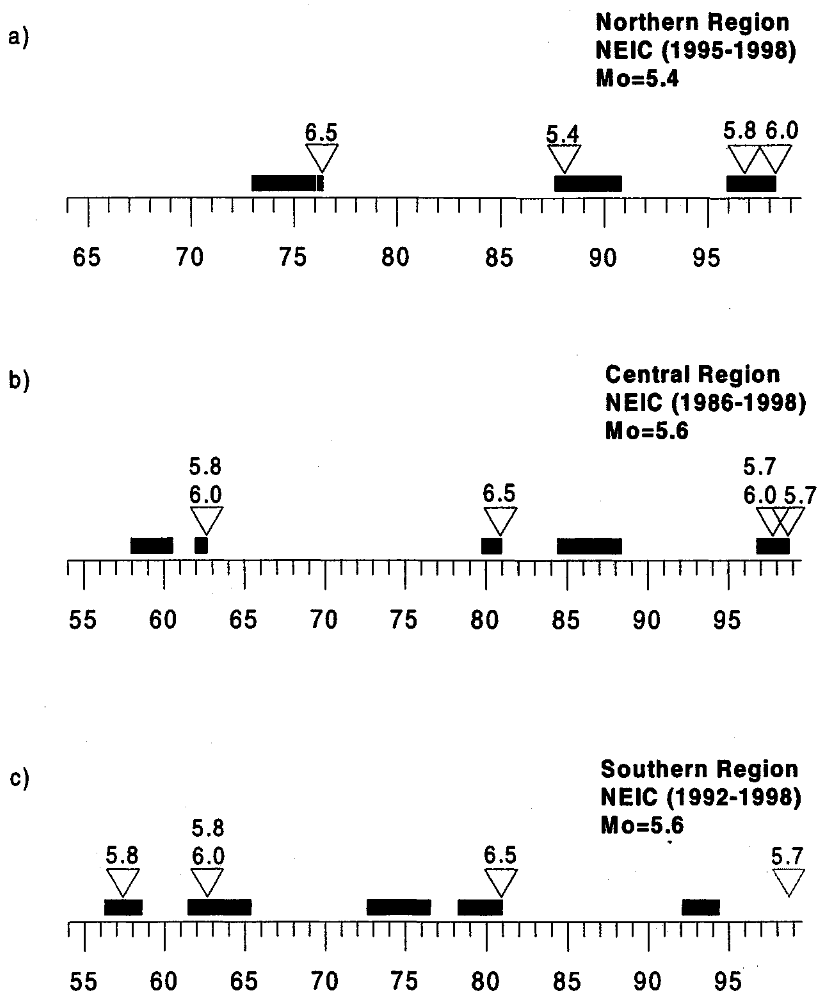

Figure 11

(Information added during the revision of the proofs in January 1999). Prediction results updated to January 1, 1999. On September 9, 1998 an earthquake with $M = 5.7$ occurred within the area common to the Central (Fig. 5-3) and Southern (Fig. 7-4) regions. The TIPs diagram shows that the event is predicted. The event terminates an alarm that continued after the Umbria-Marche events, occurred on September, 26 1998 (see Fig. 10). The failure to predict when considering the Southern region is not a surprise, due to the lower completeness level of the data (see text for more details).

inevitably affect earthquake catalogues. For instance, the inadvertent increase in magnitude indicated by ZUNIGA and WYSS (1995) for the Italian catalogue, from 1980 to 1981, does not seem to affect the results of predictions (during this period there are alarms of different length in Central and Southern Italy and no alarm in Northern Italy).

From this work emerges the necessity to integrate and compare the data contained in earthquake catalogues with the available information pertinent to deformations and silent earthquakes, in order to analyse whether aseismic processes can affect the precursory patterns. Indeed, even if a direct connection between TIPs and creeping phenomena must still be verified, some similarities can be detected, analysing the functions of seismic flow (GABRIELOV *et al.*, 1986) for Northern and Central Italy during the false alarms associated with angular deformations. In both cases there is a relatively high space-time clustering of events (triggering the TIPs), while the release of seismic energy throughout minor events is small, if compared to that of a strong earthquake, and therefore insufficient to stop the alarm.

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CN algorithm and long-lasting changes in reported magnitudes: the case of Italy

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SUMMARY

Prediction methods based on seismic precursors, and hence assuming that catalogues contain the necessary information to predict earthquakes, are sometimes criticised for their sensitivity to the unavoidable catalogue errors and possible undeclared variations in the evaluation of reported magnitudes. We consider a real example and we discuss the effect, on CN predictions, of a long-lasting underestimation of the reported magnitudes.

Starting approximately in 1988, the CN functions in Central Italy evidence an anomalous behaviour, not associated with TIPs, that indicates an unusual absence of moderate events. To investigate this phenomenon, the magnitudes given in the catalogue used, which since 1980 is defined by the ING bulletins, are compared to the magnitudes reported by the global catalogue NEIC (National Earthquake Information Centre, USGS, USA) and by the regional LDG bulletins issued at the Laboratoire de Detection et de Geophysique, Bruyeres-le-Chatel, France.

The comparison is performed between the ING bulletins and the NEIC catalogue, considering the local, M_L, and duration, M_d, magnitudes, first within the Central region, and then extended to the whole Italian territory. To check the consistency of the conclusions drawn from ING and NEIC data, the comparison of local magnitudes is extended to a third data set, the LDG bulletins.

The differences between duration magnitudes M_d that are reported by ING and NEIC since 1983 appear quite constant with time. Starting in 1987, an average underestimation of about 0.5 can be attributed to M_L reported by ING for the Central region; this difference decreases to about 0.2 when the whole Italian territory is considered. The anomalous behaviour of the CN functions disappears if a magnitude correction of $+0.5$ is applied to M_L reported in the ING bulletins. However, such a simple magnitude shift cannot restore the real features of the seismic flow, and ING bulletins are not suitable for CN algorithm application.

Key words: earthquake catalogues, earthquake prediction, Italy, regionalization.

INTRODUCTION

CN is an intermediate-term earthquake prediction algorithm based on the quantitative analysis of premonitory phenomena, which can be detected in the seismic flow preceding the occurrence of strong earthquakes (Gabrielov *et al.* 1986; Keilis-Borok & Rotwain 1990). The quantification of the properties of the seismic flow is performed by means of a set of functions of time (Table 1), which evaluate variations in the seismic activity, seismic quiescence and space–time clustering of events. The normalization of the functions allows us to apply CN to regions with different seismic activity (Keilis-Borok 1996; Rotwain & Novikova 1999).

The CN algorithm has been applied to the monitoring of seismicity in Central Italy since 1990 (Keilis-Borok *et al.* 1990; Costa *et al.* 1996; Peresan *et al.* 1998a). The analysis of the time behaviour of CN functions for the different regionalizations defined for Central Italy (Fig. 1) allowed us to observe the common anomalous flat values of some functions (see Z_{max}, S_{max}, Sigma, K and G in Fig. 2), starting approximately in 1988. The flat trend of the functions, never observed before, indicates the absence of moderate events and hence evidences an unusual decrease in the seismicity rate, suggesting the need to check for possible changes in the magnitudes reported by the catalogue used.

Until July 1997 the catalogue used for CN monitoring in Italy was the CCI1996 (Peresan *et al.* 1997). This catalogue is composed of the revised PFG catalogue (Postpischl 1985) for the period 1000–1979, and since 1980 we have updated it with the bulletins distributed by the Istituto Nazionale di

Table 1. Definition of the time functions used in the CN algorithm for the quantification of the properties of the seismic flow (from Keilis-Borok *et al.* 1990). The magnitude thresholds m_1, m_2, m_3 that allow the normalization of the functions are fixed according to the average yearly frequency of the main shocks that occurred within the region during the learning period (1954–1986). For the Central region (in dark grey in Fig. 1) $m_1 = 4.2$, $m_2 = 4.5$, $m_3 = 5.0$, corresponding to the standard yearly average frequencies $n_1 = 3.0$, $n_2 = 1.4$, $n_3 = 0.4$.

$N_2(t)$	Number of main shocks with $M \geq m_3$ that occurred in the time interval $(t-3\ \mathrm{yr}, t)$.
$K(t)$	$K(t) = K_1 - K_2$, where K_i is the number of main shocks with $M_i \geq m_2$ and origin time $(t - 2j\ \mathrm{yr}) \leq t_i \leq [t - 2(j-1)\ \mathrm{yr}]$.
$G(t)$	$G(t) = 1 - P$, where P is the ratio between the number of the main shocks with $M_j \geq m_2 (m_2 > m_1)$ and the number of the main shocks with $M_j \geq m_1$. Only main shocks with origin time t_j in the interval $(t - 1\ \mathrm{yr}) \leq t_j \leq t$ are considered.
Sigma(t)	Sigma$(t) = \Sigma\, 10^{\beta(M_i - \alpha)}$; the main shocks with $m_1 \leq M_i \leq M_0 - 0.1$ and origin time $(t - 3\ \text{years}) \leq t_i \leq t$ are included in the summation; $\alpha = 4.5$, $\beta = 1.00$.
$S_{\max}(t)$	$S_{\max}(t) = \max\{S_1/N_1, S_2/N_2, S_3/N_3\}$, where S_j is calculated as Sigma(t) for the events with origin time $(t - j\ \mathrm{yr}) \leq t_i \leq [t - (j-1)\ \text{years}]$, 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 $\beta = 0.5$ and N_j is the number of earthquakes in the sum.
$N_3(t)$	Number of main shocks with $M \geq m_2$, which occurred in the time interval (t-10 years, t-7 years)
$q(t)$	$q(t) = \Sigma_{j=1}^{6} \max\{0{,}6a_2 - n_j\}$, where a_2 is the average annual number of main shocks with $M_j \geq m_2$, n_j is the number of main shocks with $M_j \geq m_2$ and origin time $[t - (8+j)\ \mathrm{yr}] \leq t_i \leq [t - (2+j)\ \mathrm{yr}]$.
$B_{\max}(t)$	Maximum number of aftershocks for each main shock counted within a radius of 50 km for the first 2 days after the main shock.

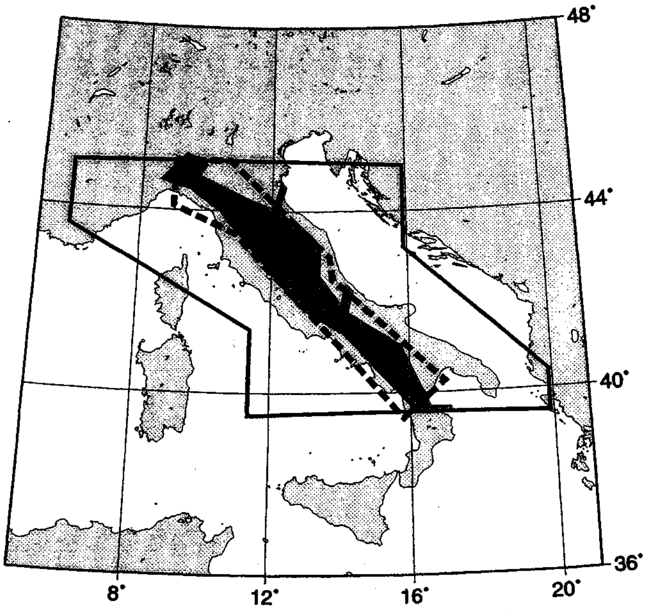


Figure 1. Different regionalizations defined for CN application to Central Italy. The continuous line delimits the region defined by Keilis-Borok *et al.* (1990), while the dotted line shows the region proposed by Costa *et al.* (1995). The region currently used for CN monitoring, defined strictly following the seismotectonic model (Peresan *et al.* 1998a), corresponds to the dark grey area.

Geofisica (ING). For the years 1980–1985 we use the ING paper bulletins, while from 1986 the upgrading is performed with the digital ING bulletins made available via ftp until July 1997. In order to check a possible change in reported magnitudes, the ING data are compared with the following catalogues (Table 2):

the Preliminary Determinations of Epicentres (PDE) distributed by NEIC, USGS, for the time period 1980–1997;

the Bulletins compiled at the Laboratoire de Detection et de Geophysique (CEA, Bruyeres-le-Chatel, France), referred to as LDG in the following, from January 1980 to December 1996.

We do not use the ISC catalogue since it does not provide revised M_L and M_d.

Table 2. Data set used for the catalogue comparison. For each agency the following are indicated: the period of time, the kind of catalogue and how the data are made available.

ING: Istituto Nazionale di Geofisica		
1980–1984	Revised ING bulletins	printed
1985–1986	Digital ING bulletins	floppy disk
1987–1997	Digital ING bulletins	ftp
LDG: Laboratoire de Detection et de Geophysique		
1980–1996	LDG Bulletins	Auto DRM
NEIC: National Earthquake Information Centre, USGS		
1980–1989	Global Hypocentres Data Base	cd-rom
1990–1997	Earthquake Hypocentres Data Files	ftp

The ING bulletins contain two estimations of magnitude: the local magnitude M_L and, since 1983, the duration magnitude M_d. The NEIC global catalogue reports the magnitudes m_b and M_S, both computed by NEIC, plus two values, $M1$ and $M2$, that correspond to magnitudes of a different kind contributed by different agencies. From a previous analysis of the NEIC catalogue (Peresan & Rotwain 1998) we observed that, for the Italian area, both $M1$ and $M2$ are mainly M_d and M_L, and that M_L is 10 times more frequent than M_d. Furthermore, ING is among the contributors to the PDE, and it supplied information for more than 600 events, from 1987 to 1997, as can be observed by listing the events with network code ROM reported in the PDE catalogue. Most of these events have magnitudes below 4.0, especially when M_d is considered, while about 100 of them have $M_L > 4.0$. The bulletins distributed by LDG contain two magnitude values, mainly corresponding to M_L and M_d.

In order to perform the magnitude comparison, the events common to the different catalogues are identified according to the following rules: (a) time difference $\Delta t \leq 1$ min; (b) epicentral distance $\Delta\mathrm{Lat} = \Delta\mathrm{Lon} \leq 1°$ for the comparison with the global catalogue (Storchak *et al.* 1998). No limitation is imposed on magnitude or depth differences.

The analysis is performed by evaluating, for a fixed type of magnitude, the quantities

$$\Delta M = M(\mathrm{C1}) - M(\mathrm{C2}), \qquad (1)$$

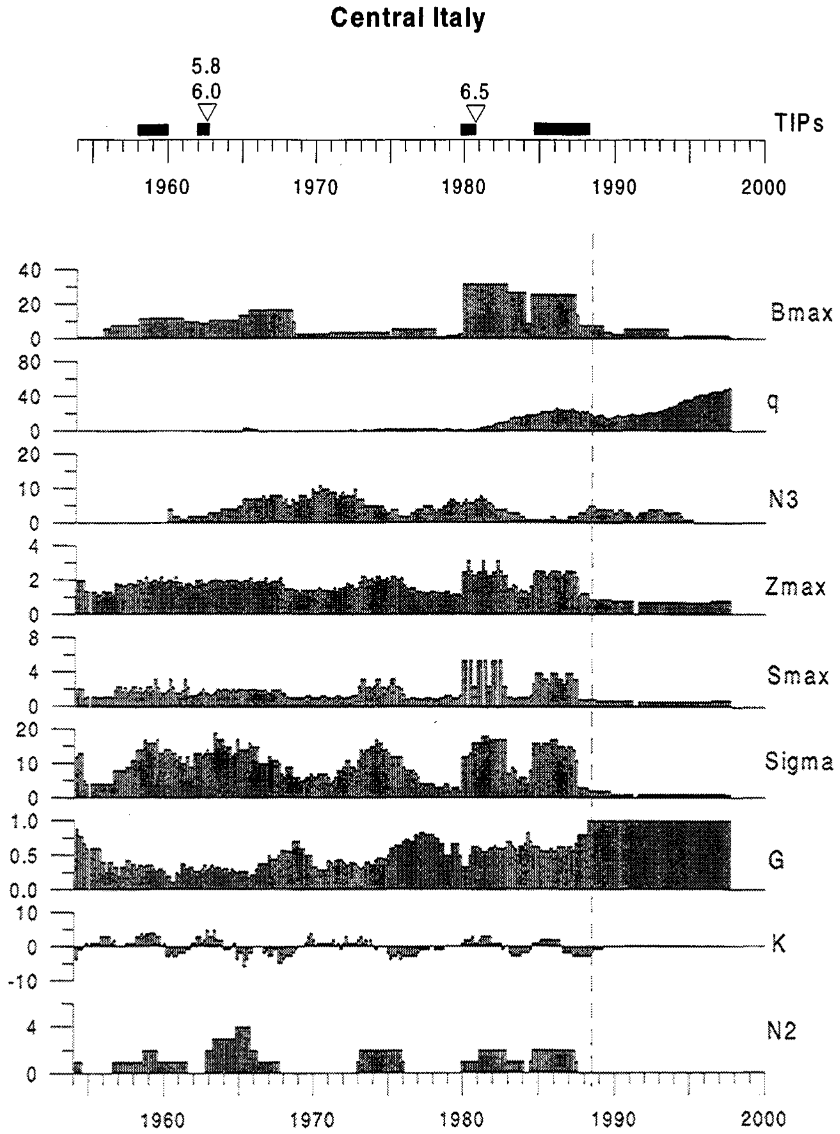


Figure 2. Time diagrams of the standard CN functions obtained for the Central region shown in Fig. 1. Functions Sigma, $S_{\max}$ and $Z_{\max}$ are evaluated for $4.2 \le M \le 4.6$, functions K, G, N_3, q for $M \ge 4.5$ and function N_2 for $M \ge 5.0$; magnitude thresholds have been selected according to the general rules for normalization of functions (Keilis-Borok & Rotwain 1990). The corresponding diagram of TIPs (times of increased probabilities) obtained using the CCI1996 catalogue is given at the top of the figure (triangles indicate the occurrence of strong events). The dotted line indicates the beginning of the anomalous behaviour of functions.

which are the differences between magnitudes of the same type reported in the catalogues C1 and C2 for each of the common earthquakes.

The comparison between ING and NEIC estimations is performed considering M_L and M_d separately among the events for which M_L and M_d are reported in both the catalogues. The events contributed to NEIC by ING, which represent a relatively small fraction of the set of common events (less than 10 per cent), are obviously excluded from the analysis. Initially, the comparison is focused on the Central region (Fig. 1) and the yearly average values ΔM_L and ΔM_d are evaluated from the common events contained in the area monitored using the CN algorithm. Subsequently, the comparison between the ING and NEIC catalogues is enlarged to the whole Italian territory and its surroundings, as shown in Fig. 9.

To check the consistency of the conclusions drawn from ING and NEIC data, the comparison of M_L is extended to a third catalogue, and the ING and NEIC M_L are compared directly with the M_L reported by the LDG bulletins. Since the LDG is among the NEIC contributors for the area analysed, the NEIC events with magnitude code LDG are obviously excluded when performing the comparison between LDG and NEIC data.

CHANGES IN REPORTED MAGNITUDES FOR CENTRAL ITALY

The analysis of the behaviour of CN functions in Central Italy allows us to identify the anomalous flat trend of some of the functions (Fig. 2), starting approximately in 1988. Such a flat trend indicates an unusual absence of moderate events.

To look for an explanation for this anomaly we focus our attention on the magnitude variations within the Central region currently used for the monitoring of seismicity (in dark grey in Fig. 1). The subcatalogue of earthquakes common to ING and NEIC contains about 800 events. The operating magnitude for CN monitoring is chosen from the Italian catalogue CCI1996, and hence from ING bulletins, according to the priority order M_L, M_d (Costa *et al.* 1996; Peresan *et al.* 1998a); therefore, local magnitudes play a relevant role in the CN analysis of seismicity. Hence, as a first stage, we study the discrepancies among the M_L values reported in the two catalogues, i.e. the quantity

$$\Delta M_L = M_L(\mathrm{NEIC}) - M_L(\mathrm{ING}). \qquad (2)$$

The histograms of ΔM_L are plotted for three contiguous ranges of magnitude (Fig. 3), chosen to correspond to the CN magnitude thresholds for Central Italy. The events with $M_L < 3$ are not used by CN, the events with $3.0 \le M_L < 4.2$ are included only in the counting of aftershocks, and those with $M_L \ge 4.2$ can enter into the calculation of functions. For most of the events, $\Delta M_L > 0$, while a secondary peak around $\Delta M_L = 0$ can be seen in Fig. 3 for the smaller events.

In order to detect a possible undeclared long-lasting change in the estimation of the reported M_L, the time behaviour of the yearly average of ΔM_L is analysed considering only earthquakes with $M_L(\mathrm{NEIC}) \ge 3.0$. The yearly number of such events is around 20–25, with two exceptions: there were 83 earthquakes in 1980 (mainly associated with the Irpinia event of 1980 November 23) and only four events in 1987.

The time distribution of ΔM_L yearly averages, shown in Fig. 4(a), indicates the presence of a major discontinuity in 1987. The average ΔM_L, estimated using eq. (2) for two

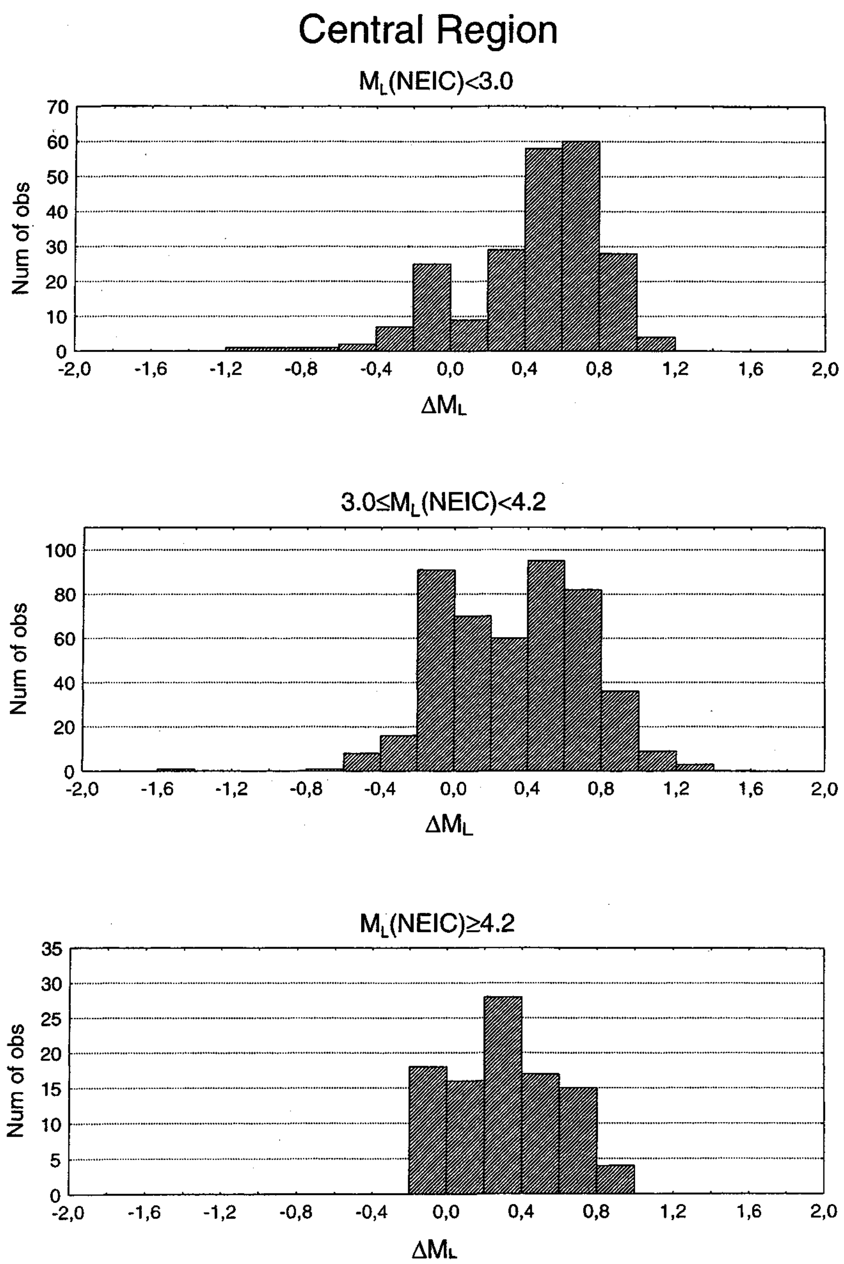
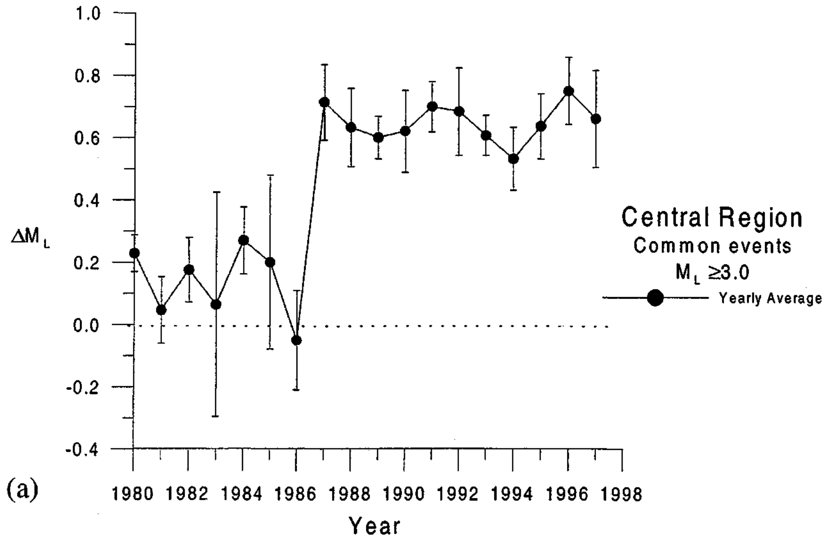


Figure 3. Histograms of the number of events versus ΔM_L for three contiguous ranges of magnitude in the Central region (dark grey area in Fig. 1).

(a)



(b)

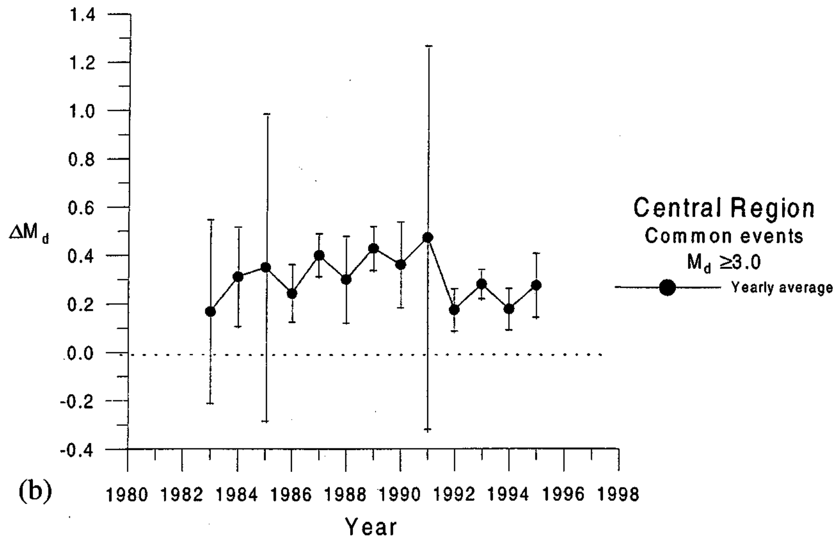


Figure 4. Yearly average of (a) ΔM_L and (b) ΔM_d obtained for the NEIC and ING catalogues, considering the common events that occurred within the Central region (Fig. 1). Error bars correspond to the 95 per cent confidence interval of the mean.

subsequent periods of time, excluding the year of transition, 1987, are as follows (the error corresponds to the 95 per cent confidence interval of the mean):

$$(1980\text{–}1986) \quad \Delta M_L = 0.13 \pm 0.05,$$
$$(1988\text{–}1997) \quad \Delta M_L = 0.64 \pm 0.04.$$

According to these average results, assuming M_L(NEIC) as a uniform reference value, an underestimation of about 0.5 can be assigned to the M_L values reported by ING since 1987.

A similar analysis, performed by replacing M_L with M_d in eq. (2), does not evidence a significant change for M_d(ING). The relevant uncertainty associated with the value of ΔM_d (Fig. 4b) for the years 1985 and 1991 is mainly due to the reduced sample size (only two events in 1985 and four in 1991). The average magnitude difference for the whole period 1983–1995 for which the sample is available is estimated to be $\Delta M_d = 0.30 \pm 0.04$.

CN: A DETECTOR OF ANOMALOUS VARIATIONS IN REPORTED MAGNITUDES

In order to understand whether the variations found in reported magnitudes can account for the anomalous behaviour of the CN functions observed in the Central region, the quantity $D = 0.5$ is added to the M_L reported by the ING bulletins, beginning in 1987. M_d values do not need to be modified because no significant time variation has been detected. CN is then applied to the Central region using the 'corrected' catalogue and following the standard procedure of forward monitoring of seismicity: learning is not repeated and the parameters are kept unchanged. The time diagram obtained is shown in Fig. 5 and clearly indicates that the anomalous behaviour of some CN functions, shown in Fig. 2, is no longer present.

Obviously, this magnitude transformation cannot be used to correct the catalogue and the magnitude revision must be

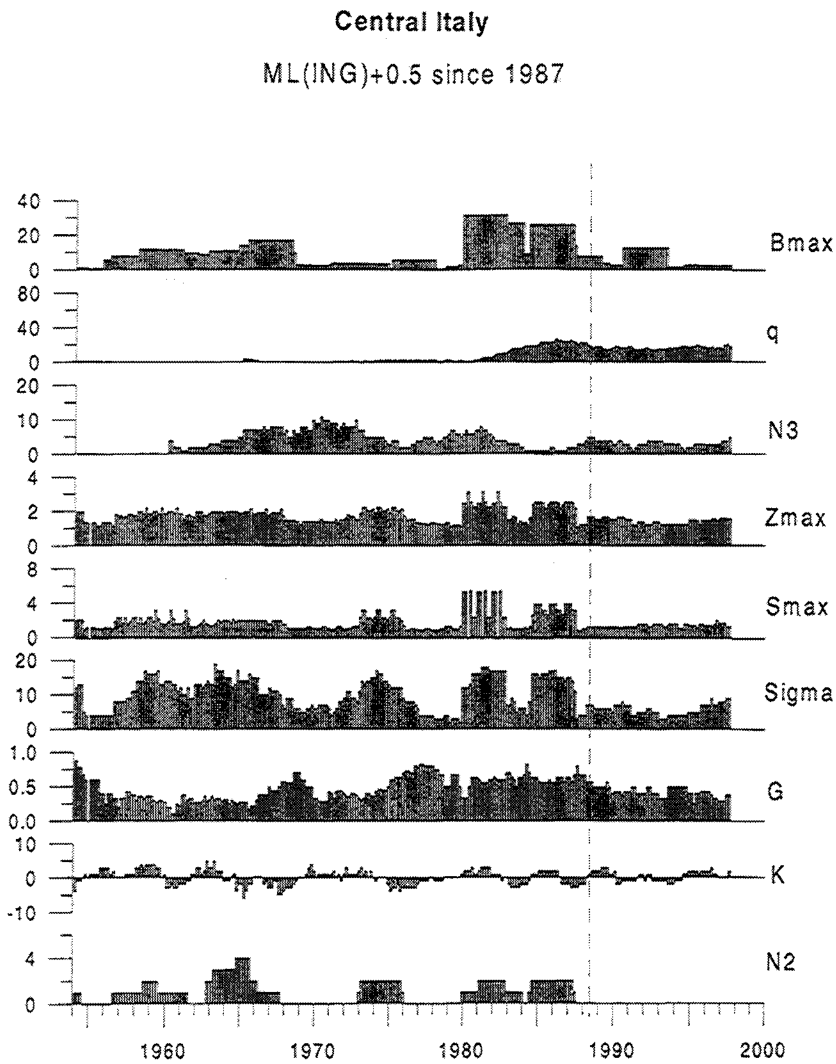


Figure 5. Time diagrams of the CN functions obtained for the Central region using the 'corrected' catalogue, in which the quantity $D=0.5$ is added to M_L(ING) beginning in 1987.

performed using all the available information (especially concerning variations in the acquisition system), not only that provided by the catalogue itself. Furthermore, a simple magnitude shift, estimated from a limited sample, cannot restore all the properties of the real seismic sequence.

Several tests performed by systematically increasing or decreasing the operating magnitude in the catalogue used for CN monitoring (Peresan & Rotwain 1998) show that the functions G, Sigma, Z_{max} and S_{max} (Table 1) are sensitive to long-lasting major magnitude underestimations of about half a magnitude unit: they became abnormally constant for relatively long periods of time, while the function q keeps very high values, but do not cause any TIP activation. On the other end, magnitude overestimations lead to unusually high values, especially for the functions N_2 and N_3, that can be used to identify and therefore discard possible TIPs declared by CN.

EXTENSION OF THE ANALYSIS TO THE WHOLE ITALIAN REGION

The magnitude differences have also been analysed within the Northern and Southern regions defined for the application of CN to the Italian territory (Peresan *et al.* 1998a). In the Northern region, the results are in very good agreement with those obtained for the Central region and, on average, an increase of $+0.5$ is observed for ΔM_L in 1987. The variation in reported M_L does not affect the CN functions in the Northern region as clearly as in the Central region because the Italian catalogue (Postpischl 1985) covers an area that, towards the north, follows the Italian border and consequently is incomplete for CN application. This incompleteness has been filled in by Costa *et al.* (1996) and Peresan *et al.* (1998a) with data provided by two other catalogues: ALPOR (Catalogo delle Alpi Orientali) (1987) and NEIC, thus reducing the influence of M_L(ING) in the computation of CN functions in the Northern region. The small number of common events, and hence the insufficient sample size, does not allow any conclusive analysis in the Southern region.

The analysis of the NEIC catalogue performed by Peresan & Rotwain (1998) for the Italian area showed that for the magnitudes M_d and M_L contributed to NEIC by other agencies, M_L is 10 times more frequent than M_d. From Fig. 6 it is seen that the total yearly number of common events varies quite significantly with time. The number of common events

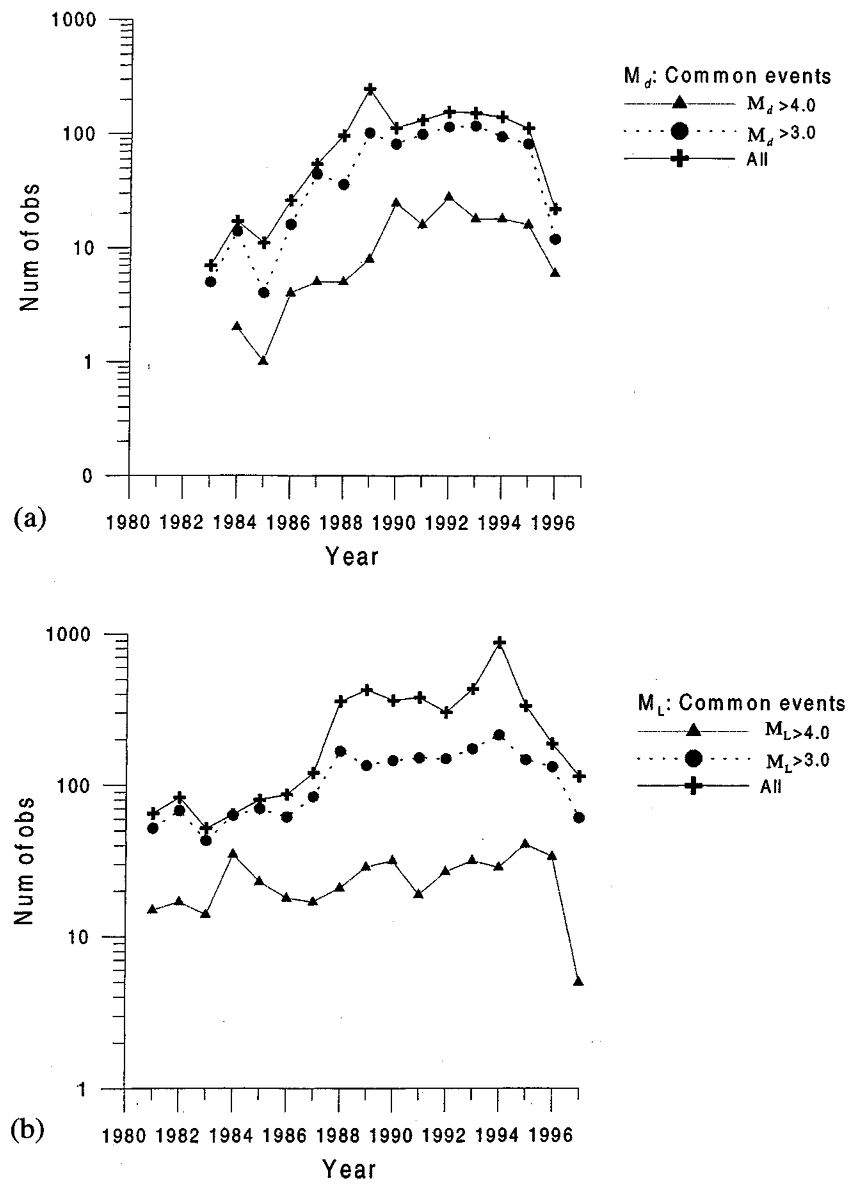


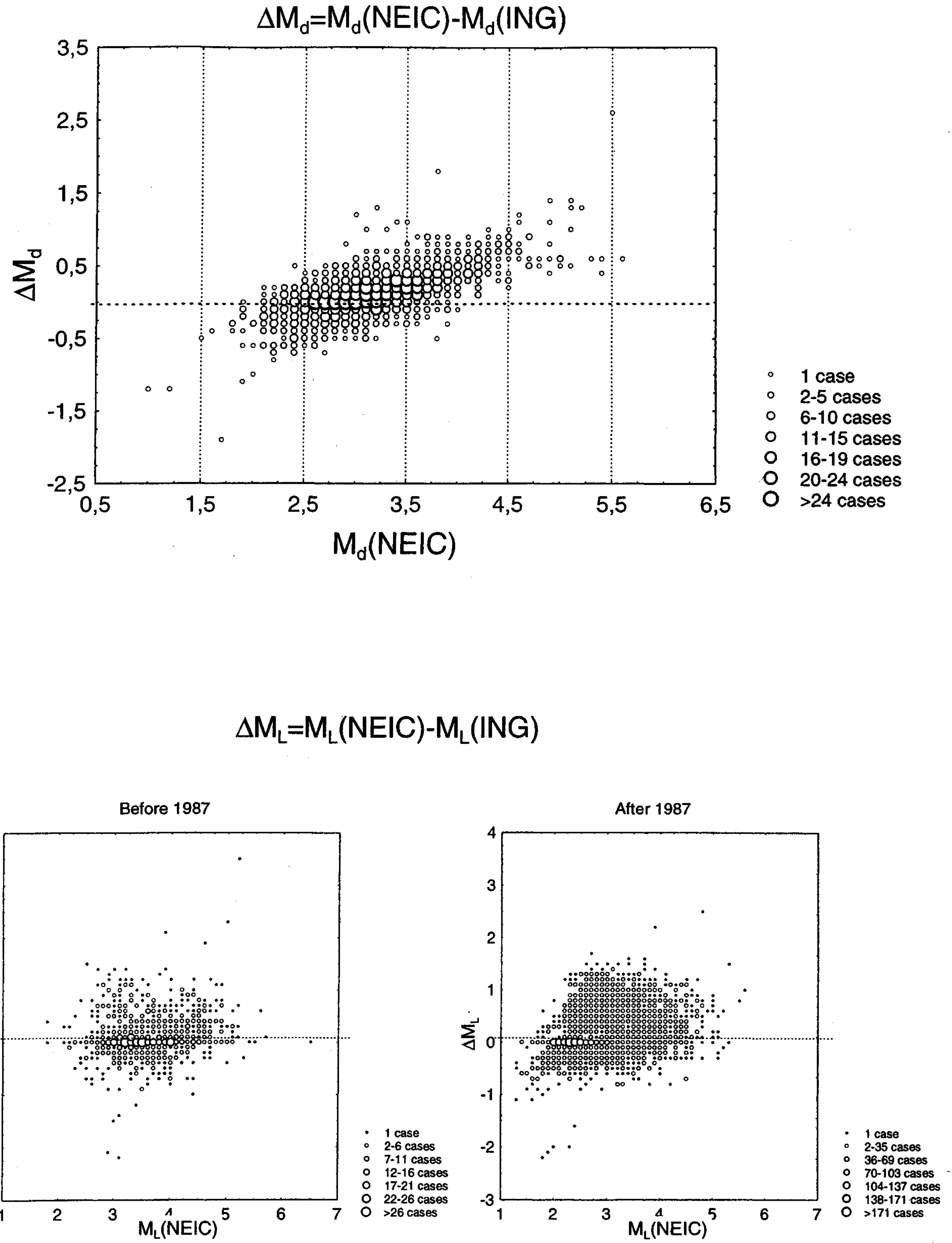
Figure 6. Yearly number of common events used for the comparison between the ING and NEIC catalogues. (a) Events used for M_d analysis; (b) events used for M_L analysis.

considerably increases after 1988, for both M_L and M_d, especially when the smaller earthquakes are considered.

The frequency distributions of ΔM_L and ΔM_d versus NEIC magnitude are analysed to evaluate their possible correlation with the earthquakes size (Fig. 7). The linear correlation between ΔM_L and M_L(NEIC) appears quite weak, while the correlation is significant for ΔM_d versus M_d(NEIC), the correlation coefficient being about 0.7 (significant at $P < 0.05$). The distributions of ΔM_L and ΔM_d are rather different, as can easily be seen from their histograms constructed for three contiguous intervals of magnitude (Fig. 8). The values of ΔM_d appear normally distributed around mean values increasing with M_d. However, the histograms of ΔM_L are centred around $\Delta M_L = 0$, with a tail towards positive values. It seems that the set of common events can be divided into two subsets: (a) events with ΔM_L distributed around zero; and (b) events with ΔM_L distributed around 0.5.

A detailed analysis, suggested by the bimodal distribution of ΔM_L, shows that the events giving $\Delta M_L \equiv 0$ are fairly localized in space (Fig. 9). The peak in the ΔM_L histograms is due to the coincidence of M_L(ING) with the M_L contributed to NEIC by some local networks, mainly from GEN (IGG network, Dipartimento Scienze della Terra, Università di Genova, Italy), LDG (Laboratoire de Detection et de Geophysique, Bruyeres-le-Chatel, France), TTG (Seismological Institute of Montenegro, Podgorica, Yugoslavia) and TRI (OGS, Osservatorio Geofisico Sperimentale, Trieste, Italy), following the standard station codes used by NEIC. Indeed, the data reported by some local networks are used by ING to integrate the information collected by the Italian network (Fig. 8).

Fig. 6 indicates that the size of the sample becomes relatively stable for magnitudes larger than 3.0, although the yearly number of common events generally increases in 1988. Hence, in this step of the analysis also, the time behaviour of the



(a)

(b)

Figure 7. Frequency scatter plots of (a) ΔM_d and (b) ΔM_L versus the corresponding NEIC magnitude.

yearly average of ΔM_L and ΔM_d is evaluated using only earthquakes with NEIC magnitude larger than 3.0.

The yearly average values of ΔM_L and ΔM_d are shown in Fig. 10. The remarkable uncertainties on the average value of ΔM_L during the year 1983 and, similarly, of ΔM_d in 1985 are due to the large dispersion of the reported values rather than to the sample size. For the whole period 1983–1997, the yearly average of ΔM_d appears almost constant around a mean value

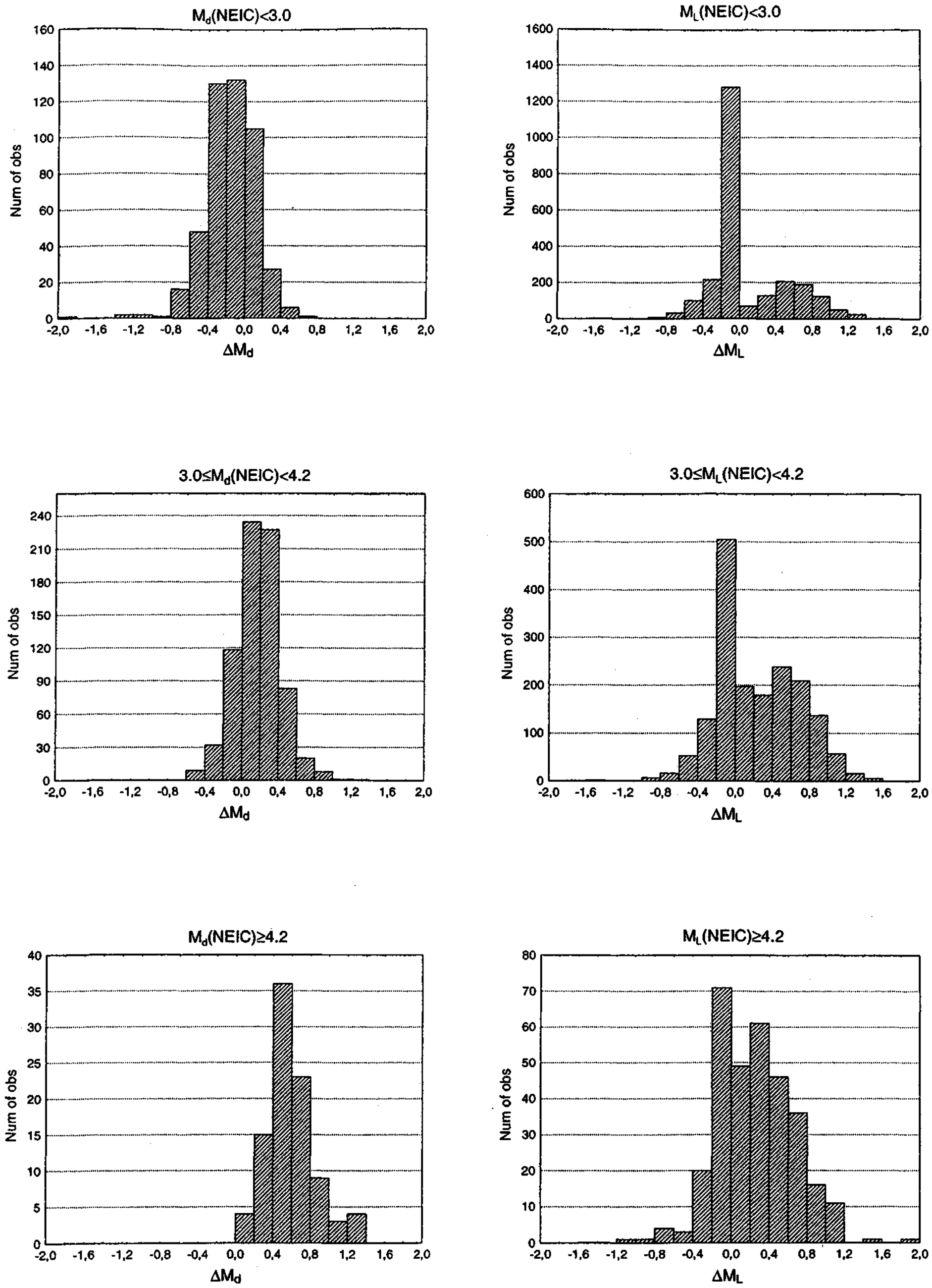


Figure 8. Histograms of the number of events versus ΔM for three contiguous ranges of magnitude for (a) ΔM_d and (b) ΔM_L. Events with ΔM lower than or equal to the upper boundary are counted in each interval.

of 0.30 ± 0.02 (Fig. 10a), in very good agreement with the results obtained for the Central region. Therefore, this analysis seems to confirm that since 1983, when they started to be reported, there have been no changes in the M_d values provided by ING. A linear relation between the M_d reported by the two agencies can be estimated by orthogonal regression of M_d(ING) versus M_d(NEIC) using the set of common events, as follows:

$$M_d(\mathrm{ING}) = 0.7 M_d(\mathrm{NEIC}) + 0.8\,. \qquad (3)$$

According to this relation, the events with $M_d(\mathrm{ING}) \geq 3.0$ are on average underestimated with respect to M_d(NEIC), while smaller events are overestimated.

The diagram of the yearly average ΔM_L (Fig. 10b), however, seems to indicate the presence of two main discontinuities: the first in 1987 and the second in 1994. The average ΔM_L, estimated for the three contiguous periods of time, are as follows (the error corresponds to the 95 per cent confidence interval of the mean):

$$(1980\text{–}1986) \quad \Delta M_L = 0.08 \pm 0.05,$$
$$(1988\text{–}1993) \quad \Delta M_L = 0.30 \pm 0.04,$$
$$(1995\text{–}1997) \quad \Delta M_L = 0.77 \pm 0.06.$$

The ΔM_L increase observed during 1987 appears less relevant within the whole Italian area than for the Central region

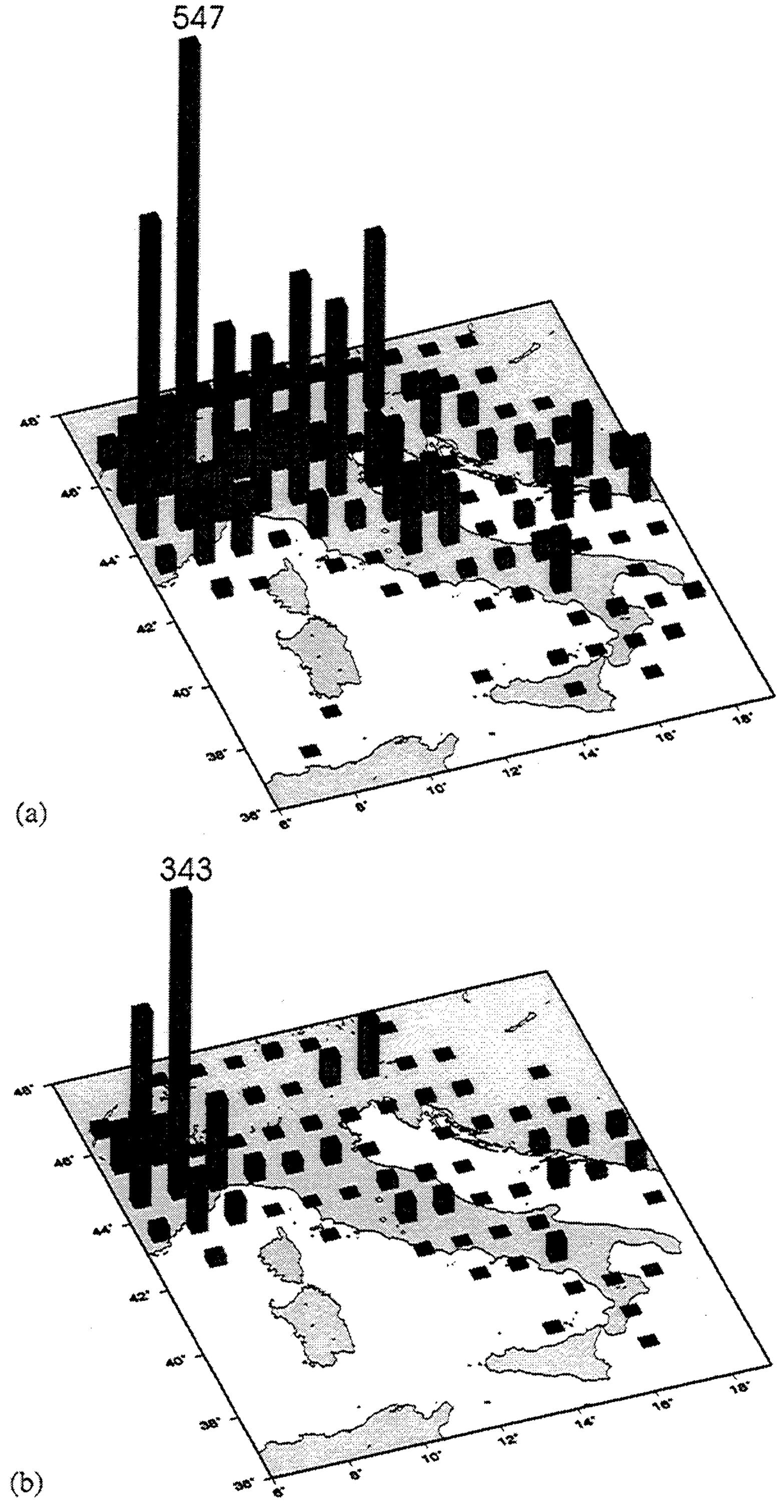


Figure 9. (a) Space histogram of the number of common events used for ΔM_L evaluation. (b) Space distribution of events with $\Delta M_L = 0$. The two histograms are plotted using the same linear scale. The maximum number of common events is indicated as a reference.

(Figs 10b and 4b). This reduction of ΔM_L can be explained by the inclusion of the M_L values contributed to both NEIC and ING by some of the neighbouring local networks, located near to the French and Slovenian borders and along the Croatian coast.

COMPARISON WITH MAGNITUDES FROM LDG BULLETINS

The use of eq. (2) for M_L reported by the catalogues ING and NEIC gives positive values for ΔM_L. To check the conclusions

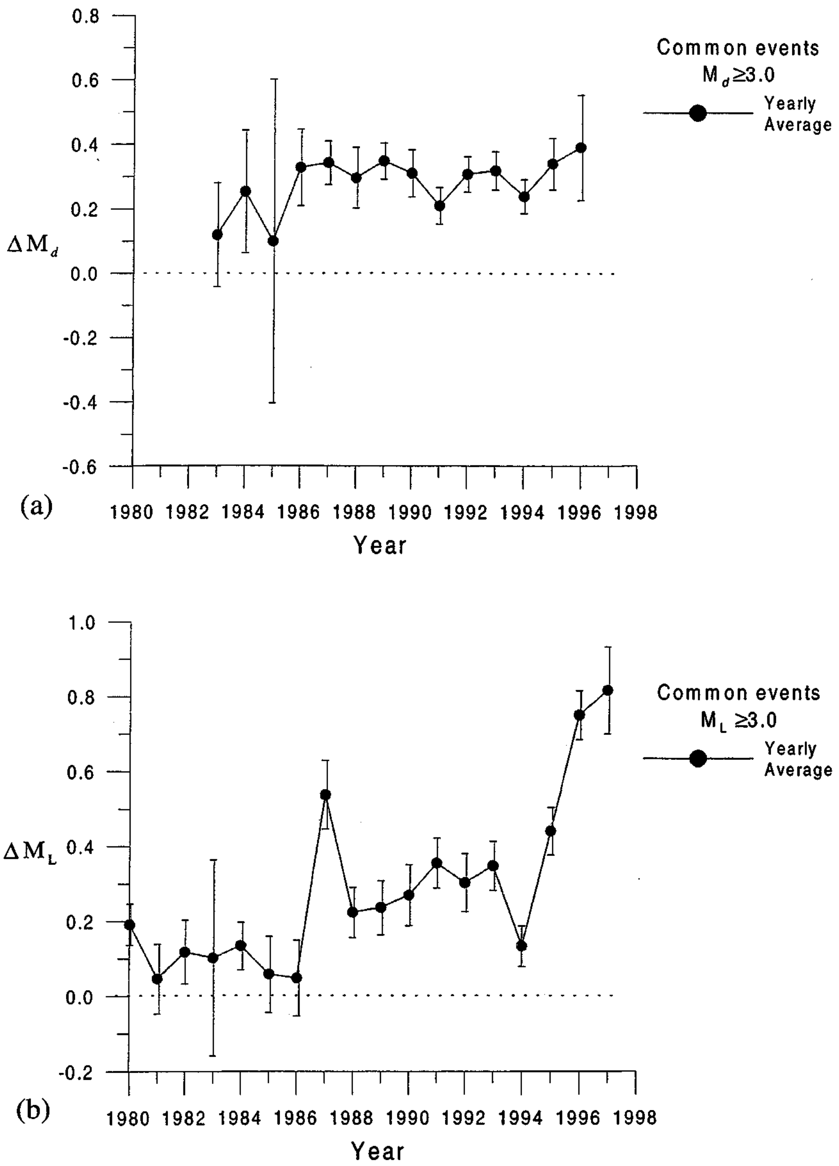


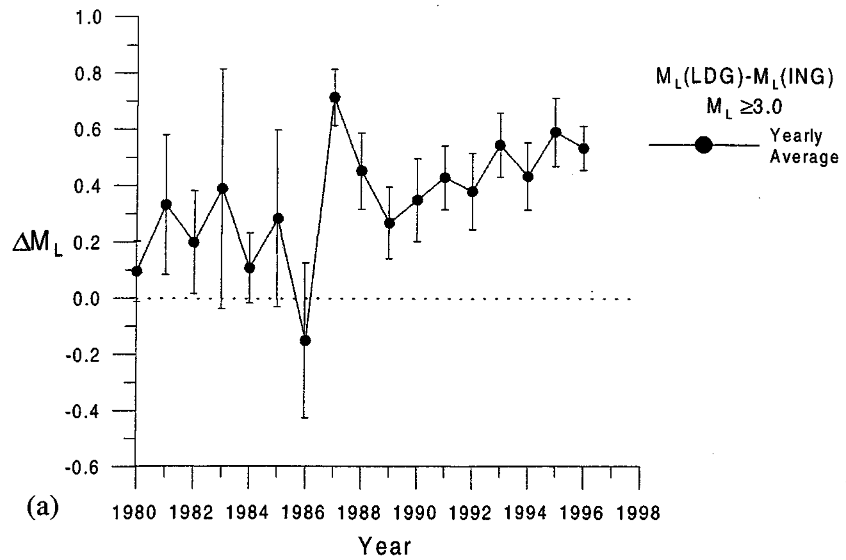
Figure 10. Yearly average of (a) ΔM_d and (b) ΔM_L for the NEIC and ING catalogues. Only events with magnitude greater than 3.0 have been considered. Error bars correspond to a 95 per cent confidence range on the calculated average. The ΔM_L minimum in 1994 is explained by the very large number of events with magnitudes coinciding with those provided by the local networks, mainly the IGG network.

drawn from the analysis of ING and NEIC data, the comparison of M_L is extended to the LDG bulletins.

The comparison between ING local magnitudes and those reported by LDG bulletins is performed within the time interval 1980–1996. About 1000 common events are selected from these regional catalogues according to the following rules: (a) time difference $\Delta t \leq 1$ min; (b) epicentral distance $\Delta\text{Lat} = \Delta\text{Lon} \leq 0.1$.

The bimodal distribution of ΔM_L observed in the comparison with the NEIC catalogue (Fig. 8) becomes even more marked when the ING and LDG magnitudes are considered. Nevertheless, most of the events with $\Delta M_L \equiv 0$ have $M_L(\text{LDG})$ lower than 3.0. Hence, considering only events with magnitude larger than 3.0 allows us to exclude a large part of such events, whose magnitudes have very probably been provided by the same agency, while permitting us to keep events for which magnitude determinations can be considered quite reliable in regional catalogues.

The yearly average values of ΔM_L for the pairs of catalogues LDG–ING and NEIC–LDG have been estimated and are plotted in Fig. 11. The number of common events used for such estimations increases in time from about 10–15 events per year up to 30–40 events per year, and this is also apparent from the corresponding reduction of uncertainties. The average values obtained from eq. (2) for the pair of catalogues LDG–ING is always significantly greater than zero, even



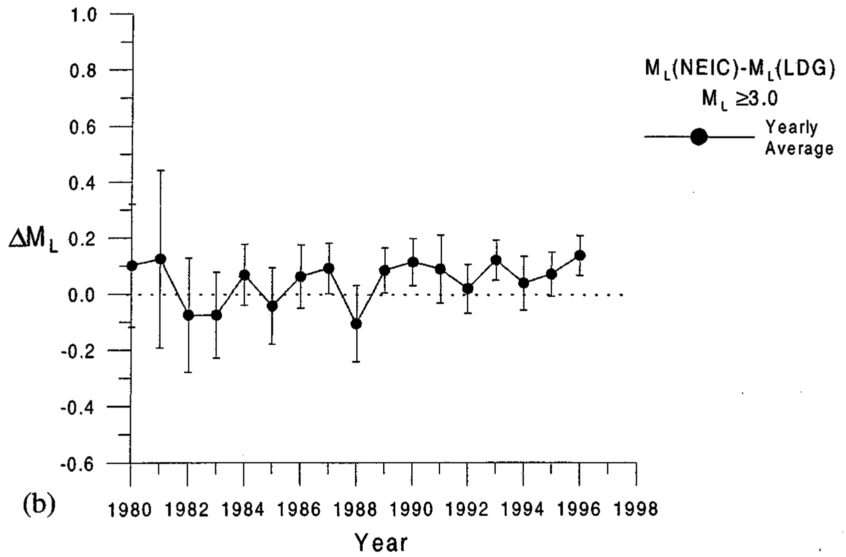


Figure 11. Yearly average of ΔM_L for (a) LDG and ING bulletins and (b) for the NEIC catalogue and LDG bulletins. Error bars indicate the 95 per cent confidence interval of the average.

with fluctuations in time (Fig. 11a). The differences ΔM_L estimated for the pair of catalogues LDG–ING and for the two intervals of time indicated in brackets give the following average values:

(1980–1986) $\Delta M_L = 0.18 \pm 0.08$,
(1988–1996) $\Delta M_L = 0.44 \pm 0.04$.

These values are in good agreement with those computed, for the whole Italian territory, comparing M_L from the NEIC and ING catalogues.

The average values ΔM_L calculated for the global catalogue NEIC and the regional bulletins LDG (about 1200 common events) are always close to zero (Fig. 11b) and, on average, are

(1980–1986) $\Delta M_L = 0.03 \pm 0.06$,
(1988–1996) $\Delta M_L = 0.08 \pm 0.03$.

This comparison seems to confirm the relative uniformity of the reference catalogues NEIC and LDG, despite the heterogeneous origin of M_L(NEIC).

A series of magnitude comparisons focused on the Central region, excluding from NEIC the events contributed by LDG or comparing directly ING and LDG, essentially confirms observations made comparing the ING and NEIC catalogues.

According to Bath (1973), we have to expect errors as large as ± 0.3 units in a calculated magnitude; nevertheless, the differences ΔM_L between the ING and the two catalogues considered have been, even after averaging, equal to or larger than $+0.3$ since 1987. Giardini *et al.* (1997) stated that local magnitudes are generally of poor quality with respect to the seismic moment, and this study indicates that they can even be inhomogeneous within the same bulletins. Unfortunately, M_L is the basic instrumental magnitude in the Italian catalogue, while M_d has only been reported since 1983.

CONCLUSIONS

Prediction methods based on seismic precursors are sometimes criticised for their sensitivity to the unavoidable catalogue errors and undeclared changes in the evaluation of the reported magnitudes (Habermann 1991; Habermann & Creamer 1994; Peresan *et al.* 1998b). This study provides a real example, showing the effect of a long-lasting systematic magnitude underestimation on CN predictions.

The absence of moderate events detected by CN functions and consequently the unusual decrease of the seismicity rate within the Central region used for the CN monitoring in Italy lead us to check for possible systematic errors in the reported magnitudes.

A detailed comparative analysis, focused on M_L and M_d, has been performed between ING and NEIC catalogues, within the area corresponding to the Central region. The magnitude differences ΔM_d appear quite stable in time and small, while a variation of about 0.5 has been found in ΔM_L, starting in 1987. This difference decreases to about 0.2 when the analysis is extended to a wider area including the whole Italian territory, but there is always an underestimation of the M_L values given by ING with respect to NEIC. The comparison extended to a third catalogue, the LDG bulletins, confirms such underestimation.

The robustness of the CN algorithm has been successfully tested with respect to the partial replacements in the catalogue, provided the homogeneity of data is preserved (Peresan & Rotwain 1998), and with respect to the short-term inadvertent increase in reported magnitude indicated by Zuniga & Wyss (1995) for the Italian catalogue, which does not seem to affect the results of predictions (Peresan *et al.* 1998a).

Therefore, our study indicates that a careful analysis of CN functions allows us to find major long-lasting undeclared changes in the reported magnitudes and may permit us to separate such effects from the anomalies in the seismic flow that define the times of increased probability (TIPs) for the occurrence of a strong event. The results of our analysis cannot be used for catalogue correction; therefore, the ING catalogue cannot be used for CN monitoring and one has to make use of a different data set such as the NEIC catalogue.

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