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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 follow strictly 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 regionalization, with respect to the previous applications of CN in Italy (Keilis-Borok et al., 1990; Costa et al., 1995; Costa et al., 1996), can be interpreted as a validation of the seismotectonic model.

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Introduction

Algorithm CN has been originally designed by retrospective analysis of seismicity in the California-Nevada region to diagnose the Time of Increased Probability (TIPs) for events with magnitude above a fixed threshold M_0 . Thanks to the normalisation of the functions used by the algorithm, CN can be applied without any adjustment of parameters to regions with different dimensions and seismicity.

The first application of CN in Italy has been 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 to narrow 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, accordingly both to the seismotectonic model (Scandone et al., 1990) and to the spatial distribution of epicenters. These experiments evidenced that the CN algorithm permits to deal with the development of regional geodynamic models, involving relationships between the structural features that control the seismicity and the selection of the optimal causative fault system for prediction purposes (Costa et al., 1996; Panza et al., 1997).

In this work we want to go one step further in this direction, testing the possibility to trace the boundary of regions following closely the seismotectonic zones, independently defined by GNDT (Scandone et al., 1990 and 1994), to check if it's possible to reduce 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 revising and updating 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).

The regionalization

The choice of the region where a strong earthquake has to 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 and must include the zones with higher seismicity level, where stronger earthquakes are likely to occur, therefore, considered the fractal character of their spatial distribution (Kagan and Knopoff, 1980; Turcotte, 1992), they must contain the major clusters of epicenters. This choice affects clearly the frequency-magnitude distribution for events 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 and 1997), within an area of the appropriate hierarchical scale, depending on the maximum magnitude considered. To reduce the spatial uncertainty of prediction, the area

has to 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, 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 given by small and moderate earthquakes, having a quite good statistic, 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 over 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 to reduce the spatial uncertainty is limited by the difficulty to keep a high level of detection, due to unavoidable logistic problems.

The Italian peninsula and the whole Mediterranean area are characterised by a very complex geodynamic behaviour (fig. 1), as revealed by the coexistence of fragmented seismogenic structures of greatly different kind. Even if the normalisation of its functions guarantees the applicability of the algorithm CN to regions with a different level of seismic activity, it was designed by the retrospective analysis of the seismicity in a region quite homogeneous, from the seismogenic point of view. Compared to the California-Nevada region, which is dominated by a strike-slip regime, Italy exhibits a considerable heterogeneity in the tectonic regime and this aspect should not be neglected. As an example, the number of aftershocks generated by an earthquake is not independent from the fault mechanism; therefore mixing sources of different kind may alter the time clustering of events (bursts of aftershocks). Wishing to take into account the seismotectonic complexity, we propose a new criterion for the definition of the regions. Considering the general rules and the sizes of the seismotectonic zones, a preliminary grouping appears necessary, so we established to include in each region only adjacent zones with the same seismotectonic characteristics or with transitional properties. A transitional zone is included in a region 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 selection of aftershocks is performed (Molchan et al., 1995) using the "minimax" method proposed by Molchan and Dmitrieva (1992).

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. First of all the catalogue CCI1996 covers an area that, toward to the North, follows the Italian border and consequently it's fairly incomplete for our purposes; this problem has been solved (Costa et al., 1996) 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:

$$M = \max \begin{cases} M_{\text{ALPOR}}(M_L, M_I) \\ M_{\text{CCI}}(M_L, M_d, M_I) \\ M_{\text{NEIC}}(M_L, M_s, m_b) \end{cases} \quad (1)$$

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. Till 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 and 1994), a seismotectonic zoning has been proposed by Zivcic and Poljak (1997) and consequently it is possible to redraw the boundaries of the north-eastern part of the region closely following the seismogenic zones (fig. 2c and fig. 3).

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 regionalization, we must preserve the predictive power reached with the previous regionalizations. Therefore, since the old regionalizations allow us to predict all the strong earthquakes, in the following we define 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 whole Alpine arc, from the Istrian peninsula to Liguria (fig.2a-1 and tab. 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 Garda's lake (central part of Southern Alps) have been subject of debate, as can be seen by recent revisions of the seismotectonic model (Scandone et al., 1990 and 1994). Therefore we define two regions, one including and the other excluding the zone west of Garda (GZ), as shown respectively in fig. 2a-3 and fig. 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 fig. 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 fig. 2a-2, 3 and 4 (see also fig.4).

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), that led to define the region in fig. 2b-5. Therefore we extend the region of fig. 2a-4 to the transition seismogenic zone at the northern edge of the Apennines, even if it's 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 destabilizing effect of the zone at the west side of Garda's lake zone is removed (fig. 2a-3, 4 and tab. 1).

Experiment 4. The northeastern border of the region shown in fig. 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) (fig. 2c and fig. 3).

The results obtained for the area finally selected (fig. 2c) can be summarised as follows: both events with $M \geq M_0$, 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%). The diagram of the time distribution of TIPs, obtained in the monitoring with the

catalogue updated to July 1997, is shown in fig. 10-a. 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 regionalization 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).

A common feature to the different successful regionalization 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 characterize 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 does not end with a strong earthquake, because of creep. This interpretation is an alternative to the explanation given in the framework of the dilatancy model, where 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 one is composed by the extensional zones near to the Tyrrhenian coast and the eastern one by 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 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 base 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 fig. 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 $M_0 \geq 5.6$. 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 (tab. 2). The distribution of TIPs is shown in fig. 10-b. The exclusion of the transition zones at both edges of the extensional band doesn't affect significantly the results, that are very stable over this area (Costa et al., 1995).

The whole extensional band, running along the peninsula, from the Po plain to the Messina strait, can be considered to form a single region (fig. 5-2), but this leads only to an increase of the spatial uncertainty (tab.2 and fig. 6). On the contrary, the attempt to divide this tensional band along the Ortona-Roccamonfina discontinuity shows that a proper retrospective description of seismicity is impossible, because the strong Irpinia's earthquake and its precursors seem to affect significantly the activation in the whole peninsula.

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

The results obtained using different regionalizations for Central Italy (Keilis-Borok et al., 1990; Costa et al., 1996), all show the persistence of a false alarm within a period that goes from July 1984 to March 1988. Similarly to the case observed in Northern Italy, anomalous deformations, modelled as aseismic dislocations processes (Dragonì, 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 that goes from 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 tab. 3).

The role played by foreland zones is particularly critical in the south of 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 (fig. 7-3,4 and tab. 3).

The transition zone corresponding to the Ortona-Roccamonfina line is not included in South-Italy region, though it is adjacent to the region, since the distribution of the aftershocks of the strong events 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 the four events ($M=5.8$, May 20, 1957; $M=5.8$ and $M=6.0$ on August, 1962; $M=6.5$ on November 23, 1980) with $M \geq M_0$ are predicted with TIPs occupying 32% of the total time interval and 3 false alarms. With respect to the region defined by Costa et al. (1996) and shown in fig. 7-1, the reduction of the spatial uncertainty can be estimated around 72%.

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 inter-events time. Since the compilation of reliable catalogues started quite recently, on a regional scale the statistical properties of the sequence of strong earthquakes remain still undefined and therefore alternative approaches must be used for predictions.

A crucial problem that generally arises with empirical methods, like CN and M8 (Keilis-Borok, 1996), is the evaluation and comparison of results together with the estimation of the reliability of forward predictions.

In the previous paragraphs we have compared the results obtained with different choices of the region boundaries. Particularly, in Northern Italy we performed a series of experiments, defining successful only those who allowed to indicate 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 regionalization 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 an algorithm must trade between these extremes, trying to minimise both the time uncertainty and the number of failures to predict. The situation 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 (figures 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 to a useful prediction method will lay below this line. Once fixed 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).

In figures 4, 6 and 8 the empirical results obtained for Northern, Central and Southern Italy, respectively, are represented. 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 regionalization the results lay on the τ axis. For all the three regions the results obtained with the new regionalization 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 quite large number of predictions.

Let us 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 that 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 a great number of false alarms, in spite of the great accuracy that a prediction method may reach (Matthews, 1997).

From the global retrospective tests performed, it turns out that the algorithm CN is able to indicate the occurrence of about 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 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 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 (tab. 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 find out that it's about 79% (18 out of 85 years are identified as dangerous by mistake) and then 80% seems a reasonable measure of CN performance. From tab. 4 it is possible to see that only 12 out of the 30 predictions of incoming earthquakes are correct, therefore the conditional probability for a TIP can be estimated around 40%. This percentage increases to about 96% when the conditional probability for predictions of no earthquake is considered (67 success 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 tab. 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 considering the real time distribution of the true and false alarms. Regretfully, the small number of events to be predicted in all the three regions defined for Italy, and particularly for the Northern region, compromise the statistical significance of such kind of evaluations, just like it happens 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 the future results. Approximately, however, it is possible to deduce from tab. 4 that when a TIP is declared, it has 60% of probability to be a false alarm; on the other side, if no TIP is indicated, at 96% no strong earthquake will occur.

Conclusions

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

Three regions have been selected, for Northern, Central and Southern Italy respectively, following strictly 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 algorithm CN is designed, thanks to the discretization of the values of its functions, to be quite robust with respect to the small, sporadic errors that 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, doesn't 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). Nevertheless earthquake catalogues, as complete and homogeneous as possible, are essential for intermediate-term prediction based on the representation of the lithosphere as a non-linear system. Therefore we have used a revised version of the PFGING catalogue, named CCI1996 (Peresan et al., 1997), obtained considering the most recent available revisions of source parameters of individual events (Boschi et al, 1995; ISC, 1976-1990). It appears particularly relevant the problem of completeness and homogeneity of catalogues when the studied area is crossed by political boundaries and this calls for the strengthening of data collection at European level.

The results obtained for the three regions show a general reduction of time and space uncertainty of the predictions of strong events, with respect to the regionalizations that do not follow the seismotectonic zones (Costa et al., 1996). The new regionalization, based on the seismotectonic model appears adequate for the forward monitoring since the results of the retrospective analysis reach a score very close to the one obtained globally.

It appears from this work the necessity to integrate and compare the data contained in earthquake catalogues with the available information about deformations and silent earthquakes, in order to analyse if aseismic processes can affect the precursory patterns. In fact, even if a direct connection between TIPs and creeping phenomena still needs to 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 to angular deformations. In both cases there is a relatively high space-time clustering of events (triggering the TIPs), while the release of seismic energy through minor events is small, if compared to that of a strong earthquake, and therefore insufficient to stop the alarm.

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Table captions

Tab. 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 PFGING catalogue has been used by Costa et al. (1996). The last line indicates results updated at July 1, 1997, whose corresponding TIPs diagram is shown in fig. 10-a.

Tab. 2 - Results obtained over the regions defined for Central Italy and shown in fig. 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 fig. 10-b.

Tab. 3 - Results obtained for the four variants of the Southern Italy region shown in fig. 7. The results given by Costa et al. (1996) for the regions 1 and 2 were obtained using the PFGING catalogue, including deep events and considering their maximum magnitude. Updated predictions (July 1, 1997) for the new region are represented with a TIPs diagram in fig. 10-c.

Tab. 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 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 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".

Northern Italy							
Region	Time	Learning Period	Mo	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**	1960-1997	1964-1995	5.4	2	0	19.3	2
* Catalogue: PFGING				** Updated Catalogue			

tab. 1

Central Italy							
Region	Time	Learning Period	Mo	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**	1950-1997	1950-1986	5.6	3	0	18.4	2
* Catalogue: PFGING				** Updated Catalogue			

tab. 2

Southern Italy							
Region	Time	Learning Period	Mo	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	1954-1995	5.6	4	0	31.8	3
4**	1950-1997	1954-1995	5.6	4	0	31.7	3
* Magnitude=MAX Catalogue: PFGING Also deep events are included							
** Updated Catalogue							

tab. 3

	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%		
<p>Yearly base-rate of earthquakes: 15% (one earthquake every 6 years, on average, within the considered region)</p> <p>Average performance (forward and retrospective) in intermediate-term prediction of earthquakes: 80%</p> <p>Average percentage of total TIPS: 30%</p>				

tab. 4

Figure captions

Fig. 1 - Seismotectonic model of Italy (Scandone et al., 1994), revised version of the preliminary zoning described in Scandone et al. (1990).

Fig. 2a - Regionalization 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.

Fig. 2b - Regionalization 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 Appennines; 3) second variant, including the whole compressional band, but without the GZ zone; 4) third variant, including also the GZ zone.

Fig. 2c - Regionalization 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.

Fig. 3 - Preliminary seismogenic zoning of Slovenia and adjacent regions proposed by Zivcic and Poljak (1997).

Fig. 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 fig. 2a, 2b and 2c. Some other variants (not shown) including or not the GZ zone have been considered. All the regions with GZ (zone at west side of Garda's Lake) 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.

Fig. 5 - 1) Regionalization 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.

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

Fig. 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.

Fig. 8 - n - τ of the results, obtained using algorithm CN, for the different regions tested for Southern Italy and shown in fig. 7. The large full dot represents the worldwide performance of CN.

Fig. 9 - a) Map of the mainshocks (dots) and corresponding aftershocks (triangles) selected with the "minimax" method proposed by Molchan et al. (1995). Only events with at least 10 aftershocks and occurred in the period of time 1900-1993 are considered. The small box indicates the area shown in detail in part b) centered around the transitional zone corresponding to the Ortona-Roccamonfina line. Aftershocks indicate a possible connection only with the northward part of the extensional band.

Fig. 10 - Diagrams of the TIPs obtained with the updated catalogue (up to July 1 1997), over the regions defined for: a) Northern (fig. 2c-9), b) Central (fig. 5-3) and c) Southern Italy (fig. 6-4). The learning period is indicated in brackets, while the times 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.

fig. 1

fig. 2a

fig. 2b

fig. 2c

fig. 3

fig. 4

fig. 5

fig. 6

fig. 7

fig. 8

fig. 9

a)

b)

c)

fig. 10