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A Seismicity study of the Northern Apennine Region

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Sismologia. — *A Seismicity study of the Northern Apennine Region.* Nota (*) di STEFANO TINTI, GIUSEPPE LENZI e FRANCESCO MULARGIA, presentata dal Corrisp. E. BOSCHI.

RIASSUNTO. — Scopo della Nota è di calcolare la probabilità di verificarsi di un terremoto di magnitudo superiore ad un valore prefissato nell'Appennino Settentrionale. I dati utilizzati nello studio sono gli eventi contenuti in una versione aggiornata del catalogo ENEL estesa fino al 31 dicembre 1979. Effettuata preventivamente un'accurata analisi di completezza del catalogo, vengono stimate le probabilità e tracciate le relative mappe. I risultati evidenziano nei dintorni del Forlivese la zona dell'Appennino Settentrionale in cui è massima la densità di probabilità che si verifichi un terremoto di magnitudo M > 4.2.

1. INTRODUCTION

In recent years the seismicity of Italian territory has been studied by several authors with the ultimate goal of performing detailed analysis of seismic risk. Unfortunately lack of information about the seismogenetic structures, the attenuation of the seismic waves along their propagation path and the elastic properties of the surface layers has so far interposed serious obstacles to obtaining detailed and reliable maps of seismic risk. Since we believe that at the state of the art further investigation is particularly needed on the last two points, in the present note we limit ourselves to studying the seismic potential of a given region. Here we choose the Northern Apennine region. As a measure of seismic potential (or intrinsic seismicity) we take the occurrence probability of earthquakes of greater size than a given magnitude M. In the paper we will show maps relative to three different threshold values, i.e. M > 5.4, M > 4.8 and M > 4.2.

We stress that our index of seismicity differs somewhat from other ones used in the literature, either in the definition or in the computational procedure. We may e.g. recall the seismic activity introduced by Riznichenko (1959) and computed for Italian regions by Riznichenko *et al.* (1969), by Carrozzo *et al.* (1974) and by Barbano *et al.* (1984), the tectonic flux, evaluated by Cattaneo *et al.* (1981) and Cattaneo *et al.* (1983), and eventually the seismicity simply defined as the number of earthquakes per unit area, computed by Caputo *et al.* (1984). We point out further that the seismic potential differs from shakea-

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bility (see Riznichenko *et al.*, 1969; Shenkareva, 1971; Petrini *et al.*, 1980) in that the latter takes into account also the propagation law of the seismic energy along the travelling path away from the earthquake source. The attenuation law however, is generally so poorly known (Iaccarino, 1973; Caputo *et al.*, 1973; Caputo *et al.*, 1974; Petrini *et al.*, 1980) that shakeability, although in principle more valuable, in practice is far less useful than seismic potential.

The data base we have used in the paper is a catalogue of the Italian earthquakes counting more than 23,000 events. It has been obtained by adding to the ENEL catalogue (1000–1975) about 3,000 more earthquakes occurred in the period 1976–1979. (Gasperini and Postpischl, 1981). Though our catalogue set contains more events than the catalogues so far used in similar statistical analysis, it suffers from incompleteness which is known to be a factor distorting the data dishomogeneously in space and time. Since for a correct study of the seismic potential of a region incompleteness effects must be removed from the data, we perform first a completeness analysis. As a result we obtain a catalogue partitioned into intervals, differing from each other as regards the value assumed by relative completeness index γ or equivalently by the absolute completeness index c. As will be explained in the next sections, the indexes γ or c, being a measure of completeness, may be incorporated in a weighting scheme that establishes the mutual importance of the catalogue intervals, to compute the maps of seismicity. We have applied the procedure to the Northern Apennine, to be more precise to the region delimited by $43^0 10'$ N-45^0 N and by 10^0 E-14^0 E. It is identified as one of the five Italian regions with the highest concentration of earthquakes as may be deduced from the work of Caputo and Postpischl (1974) and has been recently stressed by Mulargia and Tinti (1985) in a paper to determine the area of the Italian territory most suitable to be the site of an intensified program of seismic research.

2. Completeness Analysis

The procedure we used to measure the completeness of the catalogue is here only briefly outlined since it is described in full detail elsewhere (see Tinti and Mulargia, 1985a; Tinti and Mulargia, 1985b). The procedure applies only to a catalogue of independent events, and therefore the data set is first passed through a phase of aftershock removal. Since we assume that the sequence of the independent events is a Poisson process with a " true " occurrence rate σ constant in time, we basically take the departure of the " apparent " time-dependent occurrence rate ρ from σ as a measure of incompleteness. To estimate ρ as a function of time, the data set enters a segmentation-aggregation process which at the end results in a partition of the catalogue in segments (or time intervals) which are units both homogeneous as regards Poissonian behaviour and dishomogeneous (i.e. significantly different in a statistical sense) from the contiguous ones. On plotting the resulting ρ versus time, a typical histogram-like curve is obtained. Since ρ is expected to depend greatly on magnitude, the analysis must be performed separately for different magnitude classes. If we denote with $\tilde{\rho}_j$ the maximum value of the "apparent" occurrence rate of the j–th class and with ρ_{ij} the "apparent" rate of its i–th time interval, we may introduce the ratio $\gamma_{ij} = \frac{\rho_{ij}}{\tilde{\rho}_j}$, which we call the index of relative completeness, since it measures the completeness of the i–th interval with respect to the interval of the same class with the highest completeness degree. Analogously, we designate with c_{ij} the ratio $\frac{\rho_{ij}}{\sigma_j}$ where σ_j is the "true" occurrence rate of the j–th class. The ratio c_{ij} measures, of course, the absolute completeness of the i–th time interval in the j–th class. In figure 1 we show the

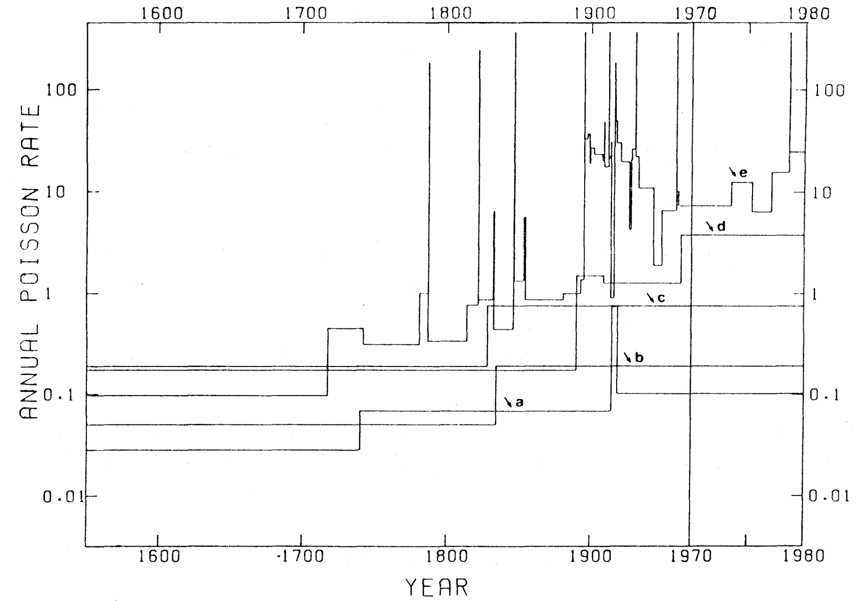

Fig. 1. – Annual apparent rate ρ vs. time for different magnitude classes: *a*) $5.4 < M$ class 1; *b*) $4.8 < M \leq 5.4$ class 2; *c*) $4.2 < M \leq 4.8$ class 3; *d*) $3.6 < M \leq 4.2$ class 4; *e*) $M \leq 3.6$ class 5 (figure from Tinti and Mulargia, 1985c).

results of the completeness analysis as obtained in a previous study where the true occurrence rate of the earthquakes in the Northern Apennine region as well as in the Central and Southern Apennine regions has been estimated (Tinti and Mulargia, 1985c). The magnitude classes considered are as follows:

class 1 $5.4 < M$

class 2 $4.8 < M \leq 5.4$

class 3 $4.2 < M \leq 4.8$

class 4 $3.6 < M \leq 4.2$

class 5 $M \leq 3.6$.

The problem of evaluating σ from the apparent rate ρ, is solved by taking into account the empirical frequency-magnitude relationship of Gutenberg-Richter. At the end of the analysis, we know not only the relative completeness γ_{ij} of any time interval, but also the absolute completeness c_{ij}. The classes that in our terminology are complete are those where there is at least one time interval where " true " and " apparent " occurrence rates coincide. This means

TABLE I

Completeness intervals and true occurrence rate estimates for the classes that are complete.

Magnitude band	Completeness interval	Estimated rate $\hat{\sigma}_j$
$5.4 < M$	1740-1979	0.075
$4.8 < M \leq 5.4$	1834-1979	0.206
$4.2 < M \leq 4.8$	1828-1979	0.717
$3.6 < M \leq 4.2$	1962-1979	2.50

that $\gamma_{ij} = c_{ij}$ for complete classes. Table I lists the magnitude classes which resulted complete for the Northern Apennine region, together with the related completeness intervals. For a complete discussion of these result, the reader is referred to the already quoted paper of Tinti and Mulargia (1985c).

3. Seismicity Maps

In order to compute the seismicity over a given region, it is usual to divide the region into regular cells that are supposed to be fully homogeneous. If the cells are all the same size, the mean number of earthquakes α_j with magnitude in the j–th class occurring in the cell centered in the point (x , y) and with sides $\Delta x , \Delta y$ respectively, may be expressed by (see Tinti and Mulargia, 1985a):

$$\alpha_j (x , \Delta x ; y , \Delta y) = \sigma_j P_{j,xy} (x , \Delta x ; y , \Delta y) \tag{1}$$

where σ_j is the mean number of earthquakes, i.e. the " true " occurrence rate of the whole region and $P_{j,xy}$ is the occurrence probability inside the cell. The estimates $\hat{\sigma}_j$ of σ_j are obtained from the completeness analysis. The evaluated Gutenberg-Richter empirical line for the Northern Apennine region was given by Tinti and Mulargia (1985c):

$$\text{Log } \hat{\sigma} = 4.12 - .90 \text{ M} \tag{2}$$

and the values $\hat{\sigma}_j$ may be easily computed by:

$$\hat{\sigma}_j = \int_{M_j}^{M_j + \Delta M_j} \hat{\sigma}(M)\, dM \tag{3}$$

where ΔM_j is the width of the j–th class and M_j its lower boundary. Since we consider as significant for the present seismicity analysis, only the classes with the greatest earthquakes, we restrict hereafter our computations to the first three magnitude classes (i.e. $j = 1, 2, 3$). Moreover, we notice that all these classes are complete, as appears from Table I where the resulting estimates of $\hat{\sigma}_1$, $\check{\sigma}_2$ and $\hat{\sigma}_3$ are also given. As regards the evaluation of the space distribution function $P_{j,xy}$, we follow a procedure introduced by Tinti and Mulargia (1985a) in studying the seismicity in Calabria and Sicily. It consists essentially in associating to each earthquake an influence region accounting both for uncertainty in epicentre location and for the surface extension of the seismic source. Given the i–th time interval of the j–th class, we evaluate the related space density function simply by first associating to each grid point the number of the influence regions that contain the point, and then by normalizing properly. The function $P_{j,xy}$ is eventually obtained by a weighted superposition of all the partial maps, the weights being a function of the number of the earthquakes observed in the i–th time interval N_{ij} and of the absolute completeness index c_{ij}, as follows

$$W_{ij} = N_{ij} \sqrt{c_{ij}} \; . \tag{4}$$

Although it is not worthwhile to discuss the procedure in detail in the present note, nevertheless, we stress that we use a weighted average evaluation, since we cannot rely on a map based only on the earthquakes of the complete intervals, which, in our case, coincide with the last time intervals. In fact, the number of these earthquakes is generally too small to avoid the distortion due to statistical fluctuations. So, past intervals must intervene in the computational method and their contribution must of course be weighted even according to their absolute completeness, since we know that completeness is another factor introducing distortion in the space distribution of seismicity. In fig. 2, we show the map computed following equations (1)-(4) for the class 1, with earthquakes $M > 5.4$. Isolines indicate the mean number of earthquakes per year and per $10' \times 10'$ cell in 0,001 units. Cumulative maps may easily be obtained by simply adding the mean numbers due to the additivity property of the rates of two or more independent Poisson processes. Therefore, if we introduce the cumulative mean number $\tilde{\alpha}$, by means of the following expressions:

$$\begin{aligned} \tilde{\alpha}_2 &= \alpha_1 + \alpha_2 \\ \tilde{\alpha}_3 &= \alpha_1 + \alpha_2 + \alpha_3 \end{aligned} \tag{5}$$

we readily compute the maps of the expected earthquakes per year with $M >$ > 4.8 and with $M > 4.2$, which are shown in figs. 3 and 4 respectively. We

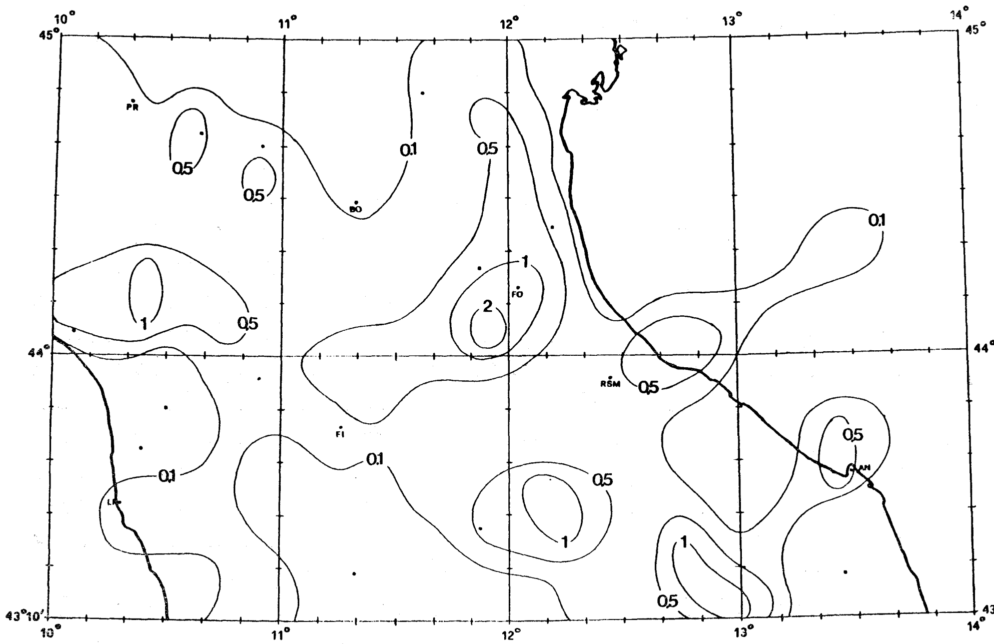

Fig. 2. – Mean number of earthquakes per year and per $10' \times 10'$ cell with $M > 5.4$. Isoline values are in 0.001 units.

notice that the mean numbers of earthquakes per year computed in (1) or (5), may be equally well interpreted as probabilities of occurrence of at least one earthquake in the next year, inasmuch as the inequality $\tilde{\alpha} \ll 1$ holds (with $\tilde{\alpha}$ measured in events per year), as happens in our analysis. Therefore, we shall indifferently refer to our seismicity index as the mean number of earthquakes and as the occurrence probability of earthquakes.

4. Discussion and Conclusions

The seismicity map relative to largest earthquakes (see fig. 2) indicates quite clearly the presence of poles. One of them centered South of Forlì is rather significant both for i oline values and for extension since it embraces southwestward the Mugello area and northward part of Ravenna-Ferrara provinces. Other poles are located in Garfagnana-Lunigiana at the Northern end of the Apennine chain and in S. Sepolcro-Fabriano zone in the southernmost portion of the chain shown on the map. The seismicity map in fig. 3 is a little more complex. Poles close to Forlì-Faenza and close to S. Sepolcro survive, but others (Garfagnana-Lunigiana, Fabriano) disappear. A sort of seismicity axis may be identified, which is aligned to the Apennine chain in direction northwest-southwest, and extends from Parma down to Forlì. Seismicity for $M > 4.2$ earthquakes is mapped in fig. 4. Its most striking feature is a well defined high

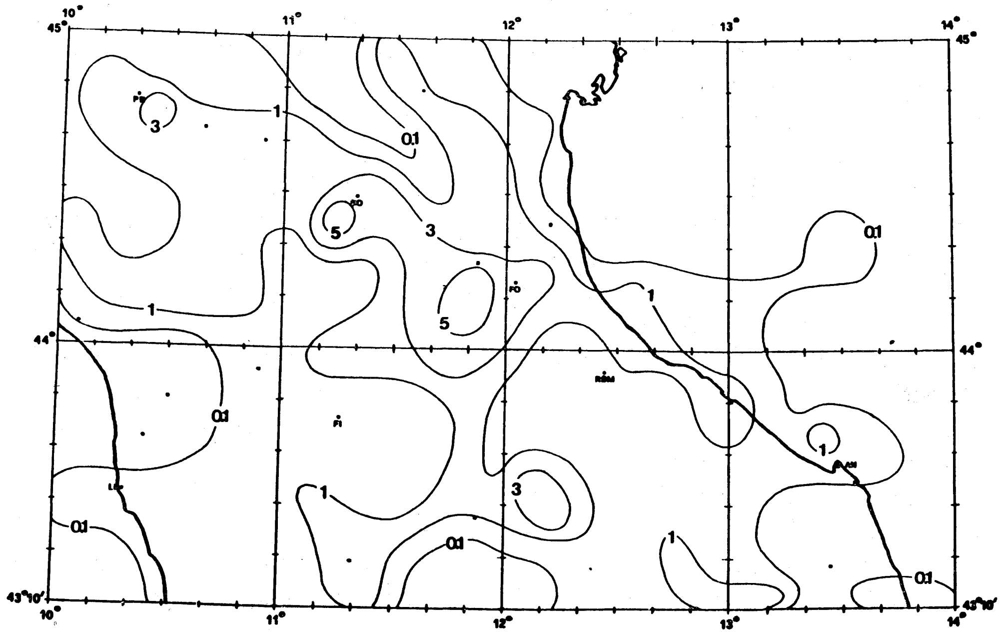

Fig. 3. – Mean number of earthquakes per year and per 10′ × 10′ cell with M > 4.8. Isoline values are in 0.001 units.

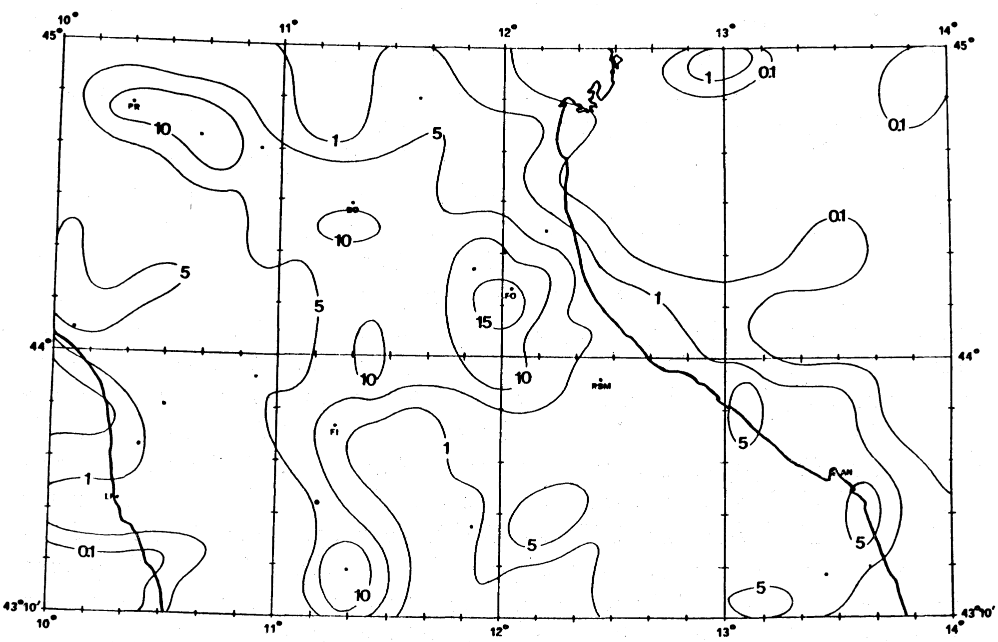

Fig. 4. – Mean number of earthquakes per year and per 10′ × 10′ cell with M > 4.2. Isoline values are in 0.001 units.

seismicity belt, paralleling to the Apennine chain from Parma to Forlì which may be extended to the southeast to embrace S. Sepolcro and to the South through Florence until reaching Siena. Inside the belt the highest estimated values of seismicity are found near Parma-Reggio Emilia, near Bologna, in the Mugello zone, in the Siena area and especially around Forlì-Faenza.

For a correct interpretation of the maps, we remark that our results should be seen in the framework of the theory of Poisson processes. The isoline values given in the maps express the expected number of independent earthquakes per year and per $10' \times 10'$ cell in 0.001 units or, equivalently, the expected number of independent earthquakes per one thousand years in normal units. Earthquakes occur randomly in time and inter-event times obey a long-tailed exponential distribution. We should also bear in mind that only independent events are used in computing the maps, according to the strict requirements of the Poisson processes that are also used in the completeness analysis. Addition of aftershock sequences would no doubt increase the mean number of observed frequencies and modify the space distribution of the earthquakes by perhaps strengthening the poles of seismicity. However, since so far no satisfactory statistical model including aftershocks has been proposed, the practical value of maps taking into account all events is uncertain especially for future extrapolations.

As we have seen, the space distribution of the computed seismicity in the three maps is somewhat different. This may be attributed to a number of reasons which may even act concurrently. First, it could be simply a consequence of undesired statistical fluctuations; if this were the case, then we would obtain a more reliable seismicity map by taking a proper average of the space distribution we have instead separately computed. Second, the assumed Gutenberg-Richter law between frequency and magnitude is violated locally. Third, though Gutenberg-Richter law holds everywhere, b-values are quite different from place to place; this latter interpretation seems, however, the most likely to be true, since it is quite well known that b-values tend to change in moving through areas of different tectonic history, as is the case for the wide region considered in our work. There is in fact evidence, even recently collected (see e.g. Nardi and Nardi (1975), Pieri and Groppi (1975), Eva *et al.* (1978), Bartolini *et al.* (1982)) that the region may be seen as divided in a number of zones, mostly paralleling to the Apennine chain with different present-day seismotectonic regimes. In this respect, the parameters computed in (2) are mean values valid for the whole region of interest, but not applicable to the single sub-regions. Among the examples of unequal distribution of great and intermediate size earthquakes we choose two: Garfagnana is affected by a pole of large magnitude seismicity (see fig. 2) that has no counterpart in other maps including smaller event contributions. On the contrary, the zone around Siena seems to be the site of solely intermediate earthquake activity (see fig. 4), greater events being rather unlikely to occur. What appears in any case very clear by inspecting the maps, is the permanence of a concentration of seismic potential for all magnitude bands in a zone including Forlì and Faenza as the most important urban centres. In an area with an extension hardly reaching 2%

of the total region, more than 10% of the events are expected to occur. In a 1000-year period, the mean numbers of M > 5.4, of M > 4.8 and of M > 4.2 earthquakes are estimated to be in the order 8.2, 36.9 and 95.4. The maximum activity is estimated to be localized slightly to South-Southwest of Forlì in an area ranging between Brisighella, Galeata and S. Sofia, well known to be a site of historical seismicity. The greatest shocks recorded in our data set occurred in 1279, 1661, 1688 and 1781. The most recent heavy earthquake dates back to 1918 with epicentre localized near Galeata.

Our results confirm that the continuous monitoring of the Faenza-Forlì area could be very valuable for a deeper investigation of the local seismicity, and indicate that scientific programs such as the installation of a local seismic network (Bollini *et al.*, 1984) should be encouraged and supported adequately.

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REFERENCES

BARBANO M.S., CARROZZO M.T., CHIRENTI A., COSENTINO M., LOMBARDO G. and RIUSCETTI M. (1984) – *Seismic zoning of Calabria and Sicily (South Italy)*, « Boll. Geof. Teor. e Appl. », *101-102*, 39-58.

BARTOLINI C., BERNINI M., CARLONI G.C., COSTANTINI A., FEDERICI P.B., GASPERI G., LAZZAROTTO A., MARCHETTI G., MAZZANTI R., PAPANI G., PRANZINI G., RAU A., SANDRELLI F., VERCESI P.L., CASTALDINI D. and FRANCAVILLA F. (1982) – *Carta neotettonica dell'Appennino Settentrionale.* Note illustrative, « Boll. Soc. Geol. It. », *10*, 523-549.

BOLLINI D., GASPERINI M., GASPERINI P., MONTANARI P. and TINTI S. (1984) – *Sviluppo di un sistema intelligente per l'acquisizione digitale di segnali sismici,* Atti 2° Conv. Naz. GNGTS, CNR, Roma, 575–584.

CAPUTO M., KEILIS-BOROK V., KRONROD T., MOLCHAN G., PANZA G.F., PIVA A., PODGAEZKAYA V.M. and POSTPISCHL D. (1973) – *Models of earthquake occurrence and isoseismals in Italy,* « Annali di Geofisica », *26*, 421-444.

CAPUTO M., KEILIS-BOROK V., KRONROD T., MOLCHAN G., PANZA G.F., PIVA A., PODGAEZKAYA V.M. and POSTPISCHL D. (1974) – *The estimation of seismic risk for central Italy,* « Annali di Geofisica », *27*, 349-365.

CAPUTO M. and POSTPISCHL D. (1974) – *Contour mapping of seismic areas by numerical filtering and geological implications,* « Annali di Geofisica », *27*, 619-640.

CAPUTO M., MILANA G. and RAYHORN J. (1984) – *Topography and its isostatic compensation as a cause of seismicity in the Apennines,* « Tectonophysics », *102*, 333-342.

CARROZZO M.T., VISINTINI G., GIORGETTI F. and SPRINGER M. (1974) – *Seismic Activity and Specific Seismicity in Italy,* « Boll. Geofis. Teor. Appl. », *61*, 3-21.

CATTANEO M., EVA C. and MERLANTI F. (1981) – *Seismicity of Northern Italy : a statistical Approach,* « Boll. Geofis. Teor. Appl. », *89*, 31-42.

CATTANEO M., EVA C., GIGLIA G. and MERLANTI F. (1983) – *Seismic Hazard in the Northwestern Apennines,* « Pure and Applied Geophys », *121*, 221-245.

ELMI C., SELLI R. and ZECCHI R. (1981) – *Sismotettonica dell'Emilia Romagna*, « Rend. Soc. Geol. It. », 4, 617-622.

EVA C., GIGLIA G., GRAZIANO F. and MERLANTI F. (1978) – *Seismicity and its relation with surface structures in the North-Western Apennines*, « Boll. Geofis. Teor. Appl. », *79*, 263-277.

GASPERINI P. and POSTPISCHL D. (1981) – *Extension of the ENEL catalog of December 1979*, unpublished.

IACCARINO E. (1973) – *Probabilità della scossa di IX grado in Italia*, CNEN, RT/PROT (73), *40*, Roma.

MULARGIA F. and TINTI S. (1985) – *Seismic sample areas defined from incomplete catalogues : an application to the Italian territory*, « Physics of the Earth and Planet. Int. », submitted.

NARDI L.D. and NARDI R. (1975) – *Structural pattern of the Northern Apennines*, Quaderni de « La Ricerca Scientifica », CNR (Roma), *90*, 203-256.

PIERI M. and GROPPI G. (1975) – *The structure of the Pliocene-Quaternary sequence in the subsurface of the Po and Veneto Plains, the Pedeapennine Basin and the Adriatic Sea*, Quaderni de « La Ricerca Scientifica », CNR-Roma, *90*, 409-416.

RIZNICHENKO Y.V. (1959) – *On quantitative determination and mapping of seismic activity*. « Annali di Geofisica », *12*, 227-237.

RIZNICHENKO Y.V., ZAKHAROVA A.I. and SEIDNZOVA S.S. (1969) – *Seismic Activity and Shakeability of the Apenninian Region*, « Boll. Geofis. Teor. Appl. », *43-44*, 227-238.

SHENKAREVA G.A. (1971) – *Seismicity of Italy*, « Boll. Geofis. Teor. Appl. », *51-52*, 271-297.

TINTI S. and MULARGIA F. (1985a) – *Completeness Analysis of a Seismic Catalog*, « Annales Geophysicae », in press.

TINTI S. and MULARGIA F. (1985b) – *An improved method for the analysis of the completeness of a seismic catalog.*, « Lettere al Nuovo Cimento », *42*, 21–27.

TINTI S. and MULARGIA F. (1985c) – *A note on the true occurrence rate of the earthquakes in the Apennine*, « Boll. Geofis. Teor. e Appl. », in press.