STATISTICAL ANALYSIS OF SEISMICITY 
AND HAZARD ESTIMATION FOR ITALY (MIXED APPROACH)

Statistical parameters of main shocks and aftershocks
in the Italian region

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MIRAMARE - TRIESTE
March 1995

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Contents.

1. Introduction
2. Seismicity model
3. Aftershock identification
   3.1. Algorithm
   3.2. Summary of aftershock information
   3.3. Conclusions
   3.4. Discussion
4. Estimation of long-term parameters of seismicity (methodology)
   4.1. General principles of (a,b, M ) estimation
   4.2. Statistical approach to estimation and comparison of seismicity parameters
5. Initial data
   5.1. Comparison of the catalog with the previous version.
   5.2. Time periods of catalog homogeneity
   5.3. Operating magnitude
   5.4. Magnitude grouping
   5.5. Completeness of data
6. Regional analysis of parameters of seismicity
   6.1. Maximum magnitude
   6.2. "a" and "b" zones
   6.3. Parameters (a,b)
7. Conclusion and problems
References
8. Appendix
   8.1. Probabilistic Seismic Hazard
   8.2. Minimax aftershock data (table)
   8.3. Seismogenic zones: operating map
   8.4. Analysis of data completeness (a set of figures)
Figure captions
Figures 1-25
Summary

The catalog of earthquakes of Italy (1900-1993) is analyzed in the present work. The following problems have been considered: 1) a choice of the operating magnitude, 2) an analysis of data completeness, and 3) a grouping (in time and in space). The catalog has been separated into main shocks and aftershocks. Statistical estimations of seismicity parameters (a,b) are performed for the seismogenetic zones defined by GNDT.

The non-standard elements of the analysis performed are: (a) statistical estimation and comparison of seismicity parameters under the condition of arbitrary data grouping in magnitude, time and space; (b) use of a not conventional statistical method for the aftershock identification; the method is based on the idea of optimizing two kinds of errors in the aftershock identification process; (c) use of the aftershock zones to reveal seismically- interrelated seismogenic zones. This procedure contributes to the stability of the estimation of the "b-value".

Foreword

This paper is summarizing the research activity carried on at the ICTP for the Consiglio Nazionale delle Ricerche - Gruppo Nazionale per la Difesa dai Terremoti project: "Statistical analysis of the seismicity and hazard estimation of Italy", directed by Giuliano F. Panza in the framework of the ICTP research activity "The structure and non-linear dynamics of the Earth".
1. Introduction.

Seismic risk is determined by the probability distribution of the expected losses produced by earthquakes on a given territory for a given time period. Losses may be considered as a vector variable containing both economic and population factors. Many examples of estimation of seismic risk are considered in the cycle of papers by Keilis-Borok & Molchan & Kronrod (KMK) in the time interval 1970-1985, see [1-12]. The calculations were related to the insurance problems (KMK [8]), to the optimization of the antiseismic measures for railway track (1000 km) for the seismic region of East Siberia (KMK [1]), and to Seismic Hazard Analysis (SHA) for the cities with population > 1 mln. in the framework of a UNESCO Project (KMK [9-10]). All the examples show that the problem of seismic risk estimation for a non-single point object cannot be solved by means of given distribution functions of strong motion in each point of the object:

\[ \text{Prob} \text{ (magnitude of strong motion in point } g \text{ for time } T < a) = F_g(a) \]  \hspace{1cm} (1)

(Magnitude is expressed in terms of acceleration, velocity, displacement or by Macroseismic intensity). In fact, functions (1) are related to one-dimensional ground motion field distribution, which do not characterize the mutual dependence of the field values in various points. The information on the dependence vanishes in the process of integration of the initial data (for instance, for calculating (1)). By this reason seismic hazard analysis, being the basis of seismic risk, has to include, first of all, visualization and/or modeling of any data which characterize the seismic hazard of the territory with its economic objects.

The main problems of SHA are the following:

i) statistical modeling of the seismic regime based on the earthquake catalogue analysis,

ii) statistical or theoretical modeling of the strong ground motion field,

iii) modeling of the Damage Probability Matrix and soil condition analysis (the problem of engineering seismology).

Models (i-iii) are sufficient for the calculation of many types of engineering seismic risk problem, in particular, for the estimation of (1). In the present report we solve the problems (i) and partially (ii) for the territory of Italy.

The problem (i) includes:
- earthquake catalogues analysis (both historical and instrumental data): completeness, grouping of data in magnitude and time, earthquake distribution with depth, estimation of $M_{\text{max}}$, etc;
- earthquake catalogue separation in main shocks and aftershocks;
- statistical estimation and comparison of Gutenberg-Richter parameters of seismicity $(a, b)$ for different seismogenetic zones;
- statistical analysis of macroseismic data and modeling of isoseismal zones for macroseismic intensities $I > 5$.

Besides, we discuss the general algorithm for the calculation of (1) for synthetic peak ground acceleration field.

### 2. Seismicity model.

The simplest seismicity model used for the purpose of seismic hazard analysis is based on the following assumptions:
- earthquakes are subdivided into main shocks and clustered events;
- main shocks form stationary Poissonian flow in the volume time-space-magnitude $(t, g, M)$. Thus main shocks are characterized by the rate of occurrence (i.e. number of events per 1 year, 1 area unit and 1 magnitude unit):

\[ \lambda(t, g, M) = 10^{a(g)-b(g)(M-M^*)}, \quad M_c < M < M_u(g) \quad (2) \]

where $M^*$ is some fixed magnitude and $M_c$ is a threshold of catalog completeness. The parameterization of $\lambda(t, g, M)$ is dictated by the Gutenberg-Richter magnitude-frequency law. Alternative parameterizations may be connected, for example, with the notion of characteristic earthquakes \cite{Coppershmith, 1991}. But in practice they are of local experimental applications because of their hypothetical nature. Events clustering is mostly connected with aftershock activity. Losses caused by aftershocks should be modeled differently from main shock losses. That is the reason why main shock and aftershock flows are considered separately in SHA problems. To solve the problem of aftershock separation we suppose that aftershocks of a main shock $x = (t_0, g_0, M_0)$ form a nonstationary Poissonian flow described by the conditional rate of occurrence.

\[ \lambda(t, g, M|x) = \Lambda_x \phi(t-t_0) f(g|x) \quad (3) \]

where $\Lambda_x$ is the parameter describing the number of events in the aftershock sequence,

\[ \phi(t) = t^{-p}, \quad t > \varepsilon \quad \text{is Omori law,} \]

\[ f(g|x) = c^{-1} \exp(-1/2 r^2 (g-g^0)), \quad c = 2\pi (\det B_x)^{1/2} \]
describes the space aftershock scattering with Gaussian shape, where $g^*$ is the scattering center, $B_x$ is the space covariance matrix of the aftershocks epicenters,

$$r(g) = (g' B g)^{1/2}$$

is the dimensionless elliptical distance between an epicenter $g$ and the scattering center $g^* = 0$. (Epicenter $g$ is considered here as a 2-dimensional vector, $g'$ is the transposed of vector $g$). Aftershock scattering matrix is individual for each main shock and is determined by observed data. By definition the elliptical zone of the type

$$S_k = \{ g: r(g - g^*) < r_0 \}$$

is called below as aftershock zone of confidence level

$p = \text{Prob}(g \in S_k)$.

When $g^*$ and $B_x$ are known

$$r_0^2 = -2 \ln(1-p);$$

but if $g$ and $B$ are based on "n" observations, this relationship should be corrected [Molchan & Dmitrieva, 1992]:

$$r = (1-p)^{-2/(n-1)} (n-1)^2 / (n-2).$$

There are alternative models of seismicity clustering, self-exciting model [Ogata 1988, Kagan & Knopoff 1973] being the most interesting one. However it is still not of wide application in SHA since it does not allow to divide the catalogue into main shocks and clustered events, while clustering complicates the problem of the detailed estimation of function (2). Thus, the formulated model leads to the following statistical problems:

I. aftershock identification;

II. estimation of main shock parameters of seismicity

$a(g), b(g), M_u(g)$.

The approach developed by Molchan & Dmitrieva [1991] is applied to the first problem. The idea of the method is to optimize two kinds of errors in the aftershock identification process (see below).

The estimation of $(a(g), b(g))$ is based on the statistical methods of parameter estimation and on seismotectonic regionalization. The completeness of the data and magnitude accuracy in Italian earthquake catalogs vary in time and space. Therefore the statistical problems of the estimation and comparison of parameters $(a, b)$ for a set of regions should be considered under the conditions of arbitrary data grouping in space, magnitude, and time (KMK [3]). The importance of the correct solutions of these problems is usually underestimated, while the solutions combined with seismogenetic zoning allow us to get more stable estimates of seismicity parameters.
3. Aftershock identification.

3.1. Algorithm.

To give the idea on the aftershock identification method used here, let us consider the time-space volume $T\times G$ containing a superposition of main shock background seismicity and an aftershock sequence related to a unique main shock. Two kinds of errors are possible for any aftershock identification algorithm:

- $N^-$: the number of aftershocks identified as background events
- $N^+$: the number of background events marked as aftershocks.

Then expected values

$$\Lambda^\pm(\mu) = E[N^\pm]$$

characterize aftershock identification method $\mu$. Thus the problem arises: to find an aftershock identification method optimizing the fixed quality function $\Phi(\Lambda^+, \Lambda^-)$. The method which minimizes the maximum of the errors

$$\Phi = \max \{\Lambda^+, \Lambda^-, \Lambda^-(\mu)\}$$

is naturally called minimax method. It has the property:

$$\Lambda^+ = \Lambda^- = \min \{\Lambda^+ \text{ under condition } \Lambda^+(\mu) = \Lambda^-(\mu)\}$$

i.e. the average numbers of missed and falsely identified aftershocks are equal and minimal. Thus the total number of identified aftershocks on the average coincides with the true value.

Under condition (2,3) the optimization rule for the function $\Phi(\Lambda^+, \Lambda^-)$ identifies the earthquake $(t,g)$ from space $T\times G$ as an aftershock if $(t,g)$ satisfies the inequality:

$$1/2 r^2 (g-g^*) + p \ln \left(\frac{(t-t_0)/\varepsilon}{c_\Phi} \right) < c_\Phi, \ t > t_0 + \varepsilon, \ p = 1.1 \ (\text{Omori parameter})$$

where the threshold $c_\Phi$ depends on the choice of the quality function $\Phi$.

The examples of identified aftershock sequences are presented in fig.1 and 2 respectively for two strong Italian earthquakes: Irpinia, 1980, $M=6.5$ and Friuli, 1976, $M=6.1$. Practical aspects of the aftershock identification method are given in [Molchan & Dmitrieva 1992]. Here we remark only that main shocks are considered sequentially: the strongest event in the catalogue is considered to be a main shock. After its fore- and aftershocks have been identified and eliminated from the catalogue, the procedure is repeated for the next strongest event, and so on.
The following criteria is used to identify foreshocks. Let us consider all events with magnitudes $M < M_0$ which precede a main shock $M_0$ by not more than 10 days, and are localized within 90% of the aftershock zone. If the total number of events is significant with confidence level = 95% with respect to the stationary seismicity flow, then the sequence of events is named foreshock sequence. In other words, the probability of correct decision in the absence of foreshocks in a given space-time volume is equal to 0.95.

Statistical estimation of aftershock scattering is impossible for scant aftershock sequences ($N_{aft} < 10$). Such a situation usually arises for main shocks from the magnitude range ($M_c, M_c + 2$) where $M_c$ is the magnitude threshold of the catalog completeness. In the case of $N_{aft} < 10$ minimax aftershock identification procedure is substituted by the simplest window procedure, i.e. all events $(t, g, M)$ are identified as aftershocks of a main shock if:

$$|g - g_0| < R(M_0), \quad t - t_0 < T(M_0), \quad M < M_0$$

(4)

Additionally, $t < t^*$ if window (4) contains an event $(t^*, g^*, M^*)$ with $M^* > M_0$. Space thresholds used here

$$R(M) = 5 M [\text{km}]$$

are near average size of the aftershock area and are in agreement with the statistics of aftershock sequences identified by minimax procedure for Italy (see fig. 3a). On the average $R(M)$, is equal to the size of the largest semiaxis of the 95% elliptical aftershock zone for $M$ in the range from 4 to 6 (fig.3); but $R(M)$ is smaller than the thresholds which are used for prediction purposes [Keilis-Borok & Rotwain, 1990]. Diminishing of the window size may lead to:
- subdivision of some sequences on subsequences, that is not so important for the purposes of SHA;
- increasing of the number of main shocks, and this may cause the increasing of the rate of occurrence of main shocks.

Time thresholds $T(M)$ are taken from earthquake prediction practice [Keilis-Borok & Rotwain, 1990]

<table>
<thead>
<tr>
<th>$M$</th>
<th>$3.5$</th>
<th>$3.5-4$</th>
<th>$4-4.5$</th>
<th>$4.5-5.5$</th>
<th>$5.5-6.5$</th>
<th>$&gt;6.5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T[\text{day}]$</td>
<td>23</td>
<td>46</td>
<td>91</td>
<td>180</td>
<td>360</td>
<td>720</td>
</tr>
</tbody>
</table>

(5)

This window is in agreement with the results of the minimax identification of aftershocks for Italy. Let $T$ be the time period which contains 75% of
the aftershock sequence of a main shock with magnitude M. Then (5) is the upper bound of the points \((M, T_{75})\) (see Fig. 3b).

### 3.2. Summary of aftershock information.

Most of the information on aftershock identification is contained in the following:

1. A version of the PFGING catalogue containing special marks for fore-, aftershocks and main shocks. Magnitude cells are used to mark the catalogue: "mb" contains the operating magnitude "mp" contains a mark for foreshocks and main shocks:

   
<table>
<thead>
<tr>
<th>Main Shock</th>
</tr>
</thead>
<tbody>
<tr>
<td>mp= { 9.0 foreshock</td>
</tr>
<tr>
<td>0 aftershock</td>
</tr>
</tbody>
</table>

   "ml" is used to point the main shock for each aftershock event:

   non-zero value of "ml" for aftershock defines the relative difference between the aftershock and its main shock ordinal numbers.

   "ms" is not zero only for main shocks and defines the total number of its aftershocks.

2. Appendix 8.2 lists the statistics of minimax aftershocks. Parameters of 95% level aftershock zones are presented: log-areas [km]; the size and the azimuth of the greatest semiaxis; semiaxis ratio, total numbers of aftershocks and foreshocks for the given main shock.

3. Fig 4(a,b) shows respectively the space-distribution of damaging earthquakes \((M \geq 4)\) for main events and for aftershocks of the whole catalogue.

4. Table 1 contains statistics of main and clustered events in the catalogue PFGING, 1900-1994.

5. Fig.5. Maps of aftershock zones and seismogenic zones by GNDT [1992].
Table 1
Statistics of main and clustered events in the catalog PFGING, 1900-93

a) Structure of the catalog

<table>
<thead>
<tr>
<th>M</th>
<th>main shocks (%)</th>
<th>10-days foreshocks, %</th>
<th>aftershocks (%)</th>
<th>number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥3</td>
<td>51</td>
<td>7.7</td>
<td>41.3</td>
<td>14858</td>
</tr>
<tr>
<td>≥4</td>
<td>64.4</td>
<td>5</td>
<td>30.5</td>
<td>2306</td>
</tr>
</tbody>
</table>

b) Structure of main shocks

3839 main shocks (M≥3.5) = 
- 2.4% with minimax aftershocks
- 28.2% with window aftershocks
- 69.4% single events

2464 aftershocks (M≥3.5) = 
- 60.3% minimax type
- 39.7% window type

d) Structure of window aftershock sequence for main shocks of M≥3.5

<table>
<thead>
<tr>
<th>number of aftershocks</th>
<th>with 1-3</th>
<th>0.85</th>
</tr>
</thead>
<tbody>
<tr>
<td>within the window</td>
<td>4-6</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>6-9</td>
<td>0.03</td>
</tr>
</tbody>
</table>

3.3. Conclusions

All the data mentioned above allow us to conclude the following:

i) Space distributions of main shocks and aftershocks with M>4 are quite similar (fig 4 a-b). In both cases the frequency-magnitude relations are linear and have similar variations which are caused by the catalog and grouping of data (compare (a) with (b) and (c) in Fig.7). Also the time series of main shocks and aftershocks have similar trends (fig.6).

ii) Aftershocks with M≥3.5 represent 37% of the total number of earthquakes with M≥3.5 (Table 1). The number of main shocks (M>3.5) processed by minimax procedure is not high (2.4% of the total number of
main shocks with M≥3.5) while their aftershocks with M≥3.5 compose 60% of the total number of aftershocks.

iii) In some cases aftershocks are located in a few seismogenic zones, reflecting seismic interaction between themselves (see for example North part of Calabrian arc in fig. 5). This circumstance is used below for the purposes of "b-value" estimation.

3.4 Discussion

Aftershocks are an independent component of Seismic Hazard though probably they have never been considered from this point of view. Space-time characteristics of strong aftershocks being of the most interest for prediction purpose, were considered by Vorobyeva & Panza [1992].

In the present work aftershock sequences are incorporated into seismic parameter examination. Aftershock zones point out to genetic relations of seismotectonic elements which allows to get more stable estimates of regional magnitude-frequency law parameters.

The use of optimal statistical procedure of aftershock identification of main shock is a new aspect in Seismic Hazard estimations. The procedure is based on the modeling of time-space distribution of aftershock sequence and leads to unbiased estimation of the number of events in the aftershock sequence.

4. Estimation of long term parameters of seismicity (methodology)

4.1. General principles of (a, b, M_u) estimation

Seismicity parameters (a, b, M_u) are considered to be dependent on the point in the main shock model. By statistical reasoning they can not be estimated spatially in detail.

It is known a priori, that the parameter a(g) is the one most varying in space. b-value, being the parameter of long-term magnitude distribution, is a characteristic of a large territory which can contain several areas with different activity level but seismically interrelated among themselves. Finally, the maximum magnitude M_u has weak space-variance, may be with the exception of some limited zones. In fact, according to Keilis-Borok (see for example, [1993]) strong earthquakes occur along high-range lineaments and their intersections.
To attain more stable estimations, parameters (a,b) are estimated using the seismotectonic zoning defined by GNDT [1992]. The zones are uniform by tectonic features, i.e. each area contains one geological structure with one type of tectonic motions prevailing.

The size of each seismogenic zone is small enough to assume the parameter "a" constant (a-zones). In analogy, to define similar zones for b-value ("b-zones" determination) it is natural to assemble "a-zones" in such a way that

- to avoid the separation of seismically interrelated a-zones. It means that an aftershock sequence should be entirely contained in a "b-zone".

- the total number of events N used for the b-value estimation should allow the resolution 0.1 for b, i.e. N=100 or greater.

- "b-zones" are composed, where possible, by assembling a-zones, that can be considered uniform on the basis of their tectonic features.

The last property is natural if it is not in contradiction with the two previous ones.

Seismicity process is often based on the contrast of different types of tectonic motion: areas of triple junction, rift valley and transform faults in the middle oceanic ridges etc. Perhaps, that is why it is difficult to classify zones with different types of tectonic motion by parameter "b". According to Kopnichev [1980] strike-slip zones have smaller b-value than, for example, thrust and deep-slip zones.

Statistical tests of the comparison of b-values in different regions may also be against the assembling of b-zones. The solution of this problem together with methods of statistical estimations of parameters (a,b) under condition of arbitrary grouping of data is briefly explained in 4.2.

The problem of maximum magnitude $M_u$ estimation is rather complex and is considered in this report only in connection with the problem of parameters (a,b) estimation. A set of decisions based on sample of M-max calculated for each century and results of recognition of strong earthquake-prone areas [Caputo et al. 1980, Gvishiany et al. 1989] were preferred to formal statistical methods of $M_u$ estimation.
Apparently, the problem of maximum magnitude has no satisfactory solution in the framework of SHA. Depending on the seismic risk problem, the role of \( M_u \) may vary significantly, therefore the requirements to the accuracy of \( M_u \) can be different. Say, local estimation of \( M_u \) is of exceptional importance in the problem of limit peak acceleration estimate, while it is of less importance in the problem of estimation (1). Let us adduce some arguments by Molchan (see KMK, [9]). Under definite conditions (see Appendix 1) the distribution (1) is as follows:

\[
F_g(A) = \exp(-\Lambda_g(A))
\]

where \( \Lambda_g(A) \) is the average number of events of intensity \( I>A \) at a point \( g \) (I may be expressed by acceleration, velocity or macroseismic intensity).

But

\[
\Lambda_g(A) \propto \int Q_g(M) 10^{-bM} dM
\]

where \( Q_g(M) \) is the area, outlined by isoseismic line \( \{ I=A \} \), and \( a,b \) are the parameters of magnitude-frequency law in the vicinity of the point \( g \).

Besides

\[
Q_g(M) \propto 10^{-b_0 M}
\]

(see KMK, [4,7]). Thus,

\[
\Lambda_g(A) \propto \int_{M_c}^{M_u} 10^{(b_0-b)M} dM
\]

(6)

The significance of the accuracy in \( M_u \) is not so high in the case \( b_Q < b \), it is important when \( b_Q > b \). That is why \( M_u \) estimation in the problem (1) is closely related with the analysis of frequency-magnitude law and of the ground motion field given in isoseismic lines.

Note that statistical estimations of the b-value are sensitive to the a priori assumption about \( M_u \) in regions with low "b-values".

4.2. Statistical approach to the estimation and comparison of seismicity parameters

PFGING catalog data is grouped by magnitude to estimate seismicity parameters in the given region. As a rule, grouping is non-uniform by \( M \) and depends on time (see below).

Neither Aki [1965] nor Utsu [1971] formulas for "b-values" estimation and comparison are valid for such a situation. Those formulas are correct if and only if:

(i) the catalogue is complete for the whole range of magnitude \( M > M_c \) and for the whole period of time,

(ii) \( M_u = \infty \),
(iii) the magnitude grouping step $\Delta \geq 0$ is constant.

The technique developed by Molchan (see KMK, [3]) allows to estimate and compare parameters "b" or (a,b) for arbitrary number of regions or space-time volumes $V$ under conditions of arbitrary grouping in magnitude. Let us remind the main idea of the technique as it is used below.

Parameters (a,b) estimation.

Let $L_j$ be the log-likelihood of observed magnitudes in region $G_i$ under the conditions of the considered model (see section 2, (2)) and arbitrarily grouped data.

If regions $G_i$, $i=1,...,d$ are described by seismicity parameters $(a_i)$ with common $b$-value, then $(a_i,b)$ are estimated by point of maximum of likelihood:

$$L^* = \sum L_i = \max (a_1, ..., a_d, b)$$

The variable $L^*_\Sigma$ is approximately Gaussian, therefore, we construct an approximate distribution of $L^*_\Sigma$ using first 6 moments of $L_i$. This allows to get confidence intervals for $\{a_i\}$ and "b" by standard technique.

Under the conditions (i-iii) the log-likelihood estimation of "b" is given by the well-known formula:

$$\Delta^{-1} \log(1+N)/(\Sigma n_i(i-1)), \quad \Delta > 0 \quad \text{(Kulldorf)} \quad (8a)$$

$$\hat{b} = \frac{N}{\Sigma(M_i-M_c)}, \quad \Delta=0 \quad \text{(Aki)} \quad (8b)$$

where $n_i$ is the number of events in the $i$-th magnitude interval, $N=\Sigma n_i$. The distribution of the estimation (8b) is expressed by chi-square variable $\chi^2$ as follows

$$\hat{b} \overset{\text{dist}}{=} b 2N / \chi_{2N}^2.$$ 

Under conditions (i-iii) estimations (8) have the bias

$$\Delta b = E (\hat{b} - b) = b/N$$

and standard deviation

$$\sigma_b = b/(N)^{1/2}$$

(10)

To eliminate the bias in (8), which is substantial for small $N \approx 25 - 50$, it is better to use the reduced estimation:

$$\hat{b}^* = (1-1/N) \hat{b}$$

therewith (10) remains valid.
(a,b) parameters comparison.

To check the equality of the parameters b or pairs (a,b) for several non-intersecting volumes $T_i \times G_i \times \mu_i = V_i$ ($\mu_i$ is a logarithmic measure of the energy, magnitude in our case) one should test one of the two hypotheses

$$H_1 : b_1 = \ldots = b_d, \ a_i \text{ are arbitrary}$$

or

$$H_2 : b_1 = \ldots = b_d, \ a_1 = \ldots = a_d$$

against the hypothesis

$$H : (a,b) \text{ are not related to } H_1 \text{ or } H_2.$$  

To compare $H_i$ with $H$ Pearson's test is used:

$$\pi_i = -2 \left[ \max_{H_i} \mathbf{L} - \max_{H} \mathbf{L} \right]$$  \hspace{1cm} (11)

where the maximum is taken with respect to (a,b) taking into account conditions of the corresponding hypothesis $H_i$ and $H$.

According to asymptotical theory of hypothesis testing [Wilks, 1962], the hypothesis $H_i$ should be rejected for the hypothesis $H$, if

$$\pi_i > u(f,\alpha)$$  \hspace{1cm} (12)

where $u(f,\alpha)$ is the $\alpha$-quantile of the $\chi_f^2$-distribution

$$f_1 = d-1, \quad f_2 = 2(d-1).$$

Therewith the probability to reject the true hypothesis $H$ is approximately equal to $1 - \alpha$.

Under conditions (i-iii), and $\Delta=0$ the hypothesis $H_i$ testing for two regions may be based on the precise distribution of the value:

$$\hat{b}_1 / \hat{b}_2 \overset{\text{distr}}{=} b_1 / b_2 \cdot N_1 / N_2 \cdot \chi_{i_n} / \chi_{\hat{i}_n}$$

(see 8), i.e. under condition $b_1=b_2$ the distribution of $\hat{b}_1 / \hat{b}_2$ is determined by Fisher distribution [Utsu, 1971].

5. Initial data

In this work we use data from the National catalog of Italy PFG-ING for the period from 1900.01.24 to 1994.01.25 (computer file PFGING9.DAT size=840620, date 94.03.19.11:16a). The main problems of the data analysis are the following:

- choice of the operating magnitude;
- analysis of magnitude accuracy and catalogue completeness on the basis of the choice of the operating magnitude;
- choice of the diagrams of magnitude grouping and completeness as function of region and time.
5.1. Comparison of the catalog with the previous version (computer file PFGING32.DAT size=1017720).

In the process of our work the initial catalog (PFGING32.DAT) was renewed. It was prolonged by data for the period from 1991.05 to 1993.03 and was revised for the common period 1900-1991 (PFGING.DAT). One should keep in mind those changes when comparing the results of seismicity analysis as well as the present state of the catalogue is inferred.

All the changes in the new version of the catalog (PFGING.DAT) for the period 1900-1991 are summed in table 2. Most of the changes can be summarized as follows:

- 147 events with $M \in [3.5, 4)$ changed the depth because in the new version of the catalogue (PFGING32.DAT), for the period from 6.4.1976 to 24.8.1989 we have introduced new values for the depth of 144 events, as given by the ISC Bulletin, and from 24.8.1989 to 3.6.1990 we have introduced new values for the depth of 3 events as given by the NEIC Bulletin;
- 205 events ($M \geq 0$) were removed from the catalog, including 19 events with $M > 3.5$. Half of the removed events belongs to the beginning of the century, 14 of those events have $M > 3.5$. For revised and removed earthquakes see Fig 8a,b. These 205 events were considered duplicates since in the new version of the catalogue (file PFGING.DAT) the seconds are not given in the origin time.

It seems that all events for 3-days period 1985.09.13-15 were removed from the catalog (file PFGING.DAT) by mistake, and thus were inserted again in file PFGING.DAT using the file PFGING32.DAT.

Both versions of the catalog contain events outside the region (fig. 8c). 2/3 of them have either latitude or longitude common with the Italy region. This suggests that some technical mistakes in earthquake coordinates were probably made. The list of events under consideration contains the strong mistaken event 1985.09.12, $mb=7.73$.

However, if the magnitude range $M \geq 3.5$ is considered, then the last changes in the catalog
- should not affect the estimation of seismicity parameters, but
- locally can influence the events distribution with depth.
<table>
<thead>
<tr>
<th>Type of change</th>
<th>Number of changes in the magnitude ranges</th>
<th>Total number of changes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 (0,3) [3,3.5) [3.5,4) ≥4</td>
<td></td>
</tr>
<tr>
<td>Magnitude</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Depth</td>
<td>147 *</td>
<td>147</td>
</tr>
<tr>
<td>Removal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1900-1916</td>
<td>27 46 13 14 3</td>
<td></td>
</tr>
<tr>
<td>1918-1975</td>
<td>56 27 5 1 1</td>
<td></td>
</tr>
<tr>
<td>1985.IX.13-15</td>
<td>0 8 ** 4 ** 0 0</td>
<td></td>
</tr>
<tr>
<td>1900-1985</td>
<td>83 81 22 15 4</td>
<td>205</td>
</tr>
<tr>
<td>Addition</td>
<td>0 2</td>
<td>1 **</td>
</tr>
</tbody>
</table>

\( M_b=7.73 \)

*) including 141 events which were remained of the same type: normal

**) rough errors
5.2. Time periods of catalog homogeneity

The accuracy, completeness and type of registered magnitude vary in time. Thus the catalog should be subdivided into homogeneous parts with respect to the pointed characteristics. The following a priori information was used for this purpose:

The initial catalog consists of two parts
I - PFGING catalog, 1900-1979

The first part is based on three catalogs:
- European catalog by Karnik [1969] 1900-1956
- World catalog by Rothe 1956-1965
- World catalog NEIC 1966-1979

The peculiarities of the European catalog should be correlated with the state of the European seismological network. Thus Fig.9 shows the dynamics of the number of stations: the total number ($N_{st}$) and those which provide full data ($N_{ok}$).

The registered type of magnitude was changed three times during the period 1980-1993: $M_I$ and $M_L$ were replaced by magnitude $M_d$ in 1983; since 1987 magnitudes $M_I$ and $M_d$ started to be registered. Thus the period 1900-93 can be divided into the following relatively homogeneous parts:
Table 3
Data grouping in time (decision and comments)

<table>
<thead>
<tr>
<th>N</th>
<th>Time period</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>European catalog by Karnik with completeness of $M \geq 4.1$</td>
</tr>
<tr>
<td>1</td>
<td>1900-1907</td>
<td>$N_{st}$ $N_{ok}$ (number of stations)</td>
</tr>
<tr>
<td>2</td>
<td>1908-1921</td>
<td>&lt;10 0</td>
</tr>
<tr>
<td>3</td>
<td>1922-1937</td>
<td>10-20 &gt;10</td>
</tr>
<tr>
<td>4</td>
<td>1938-1943</td>
<td>&gt;30 20</td>
</tr>
<tr>
<td>5</td>
<td>1944-1946</td>
<td>25-40 15-30</td>
</tr>
<tr>
<td>6</td>
<td>1947-1955</td>
<td>Second World War; Large variation of $N_{st}$ &amp; $N_{ok}$ in time and space</td>
</tr>
<tr>
<td>7</td>
<td>1956-1965</td>
<td>$N_{st}$ has the lowest level in Italy</td>
</tr>
<tr>
<td>8</td>
<td>1966-1979</td>
<td>$N_{st}$ &amp; $N_{ok}$ increase fast in time and nonuniformly in space</td>
</tr>
<tr>
<td>9</td>
<td>1980-1983.VI</td>
<td>World catalog (M$\geq$6) by Rothe</td>
</tr>
<tr>
<td>10</td>
<td>1983.VII-1987.VI</td>
<td>World catalog NEIC for Europe: M$\geq$4 is complete</td>
</tr>
<tr>
<td>11</td>
<td>1987.VII-1993</td>
<td>ING catalog</td>
</tr>
<tr>
<td></td>
<td>1980-1993</td>
<td>$M_L$ &amp; $M_i$ dominate</td>
</tr>
</tbody>
</table>
5.3. Operating magnitude

There are 4 types of magnitude in the catalog: macroseismic $M_i$ and instrumental $M_L$, $M_p$, and $M_d$, and there is no common magnitude for all events (see the earthquake distribution by magnitude type in fig. 10). That is why it is necessary to choose a single operating magnitude.

In the present work the operating magnitude is defined by the following rule:
The magnitude type is chosen according to its rating. The rating is determined by priority list

$$M_L \{ M_d, M_p \} M_i$$  (13)

Here $M_p$ and $M_d$ are not compared since they are related to different time periods.

Let us comment the priority choice:
- Local magnitude $M_L$ is the basic instrumental magnitude in the Italian catalog since 1956, excluding the period 1983-1987. Instrumental magnitude $M_L$ was used to define the magnitude $M_i$ of the macroseismic data which are present in the PFG catalog. That is why we wanted to relate all magnitudes to $M_L$.
- Duration magnitude $M_d$ dominates in the catalog only for 3 years; it is in non-linear regression with $M_L$ (fig. 11 e): $M_d \equiv M_L$ for $M_L \in (3; 3.5)$, and on the average $M_d$ is smaller than $M_L$ for $M \geq 4$. The range of variation of $M_d$, given $M_L$, is about 1.
- $M_p$ is non-uniform being composed of various magnitudes from various catalogs (World and European). Therefore there is nothing to characterize $M_p$ but it should coincide with $M_s$ when $M_p > 6$.
- Macroseismic magnitude $M_i$ is the least accurate (see below) and is in poor agreement with $M_L$ when $M_L > 4$ (fig. 11a,b,c).

Figure 12 roughly classifies the nonuniformity of priority magnitude. It presents the percentage of each type of magnitude given the range of $M$ and the period of time. It can be seen that the operating magnitude is more or less uniform only within the following magnitude-time intervals:

- $M \geq 5.4$  \hspace{1cm} $T \geq 1956$
- $M = 2.9 - 5.3$  \hspace{1cm} $T = 1980 - 1983$

In all other cases $M$ consists of a mixture of magnitudes of different accuracy.
5.4. Magnitude grouping.

Magnitude grouping is needed because:
1. Data of the type $M_j$ are initially grouped, while recalculating empirical relationships give the illusion about high accuracy of $M$.
2. Instrumental magnitudes are nonuniformly rounded especially in the beginning of the century.
3. Magnitude of the type $M^j$ is much scattered with respect to basic magnitude $M_L$. Grouping should partially attenuate this effect.

Let us consider sequentially these comments:
1) Macroseismic magnitude is defined by the intensity in the epicenter, $I_0$, according to empirical relationships:

$$ M = \begin{cases} 
0.531 I + 0.95 & \text{Lat} > 44 \text{ N Depth} H \\
0.511 I + 1.00 & \text{Lat} < 44 \text{ N unknown} \\
0.51 I + 0.35 + \log H & \text{used rare because of depth uncertainty}
\end{cases} \quad (14) $$

The value $I_0$ takes integer and half-integer values (fig.13). Therefore $I_0$ data should be grouped with step = 1, so we have as a consequence

$$ \Delta M_j = 0.5 \quad (15). $$

2) It was noted that instrumental magnitude is differently rounded: the preference (in manual data processing) is given to values divisible by 1/4, and more often to integer and half-integer values. To show the effect of rounding, let us sum (following to (KMK[7])), all the events with integer value of difference in magnitude. The decimal point of magnitude value defines the number of group $i=0,1,...9$. Under the condition of the Gutenberg frequency-magnitude relation and in absence of rounding effects the plot $N(i)$ should be of exponential type. Fig.14 presents $N(i)$ for magnitude $M_L$ in different periods of time.

As follows from fig.14 the rounding effect takes place for the periods 1900-1955, 1966-1979, 1980-1985. The effect leads to jumps of the plot $N(i)$ in half-integer points and in divisible by 1/4 points $i= 2 & 3, 7 & 8$. There is no such an effect during the periods of computer data processing: $M_L$ (1981-1993).

To get over the errors of magnitude rounding it is natural to group with step = 0.25. Using step $\Delta = 0.1$ we obtain the following grouping:

$$ (3.2, 3.3), (3.4, 3.5, 3.6), (3.7, 3.8) \text{ etc.} \quad (16). $$
It is natural to use this grouping for $M_L$ and large values of $M_p$ ($M_p \geq 6$) as they coincide with $M_d$.

3) Starting from the features of $M_d$ and $M_p$ described above we will use grouping

$$\Delta M_p = \Delta M_d = 0.5, \quad M_p < 6$$

Now we can formulate the rule of the operating magnitude grouping within the fixed time interval $\Delta T$:

The events are grouped with step $\Delta M = 0.5$. If all the observations within the volume $\Delta T \times \Delta M$ are either $M_l$ or $M_p$ ($M_p \geq 6$) then the interval $\Delta M$ is subdivided supplementary into two intervals according to (16).

The result of grouping according to this rule is given in fig. 15.

5.5. Completeness of data

The analysis of the catalog completeness for some space-time volume is conventional and based on Gutenberg frequency-magnitude relation. The difficulties are reduced to the choice of the volume and to decisions in questionable situations when there is an illegible bend on the left side of the frequency-magnitude plot. Here we used a priori information on the completeness of the European and world catalogs during corresponding periods of time (see Table 3).

Sufficiently detailed subdivision of time interval is already defined. Thus to provide reliable identification of the bend the space subdivision should be rather rough.

To analyze the completeness, the region under consideration was subdivided into 5 parts (fig. 16)

East Alps, West Alps, Central Italy, Northern branch of Calabrian Arc and Calabria&Sicily.

In addition we subdivided:

- sea areas were macroseismic data are incomplete: 225 - West Alps, [274,275,280] - Sicily, 267 - N.Calaoritan Arc (Numbering of the regions corresponds to the corrected seismogenic areas given in Appendix 3)
- the areas near the boundary in East Alps (N:201-203) are also possible areas of data incompleteness.

The decisions on the catalog completeness within the mentioned volumes $\Delta T \times \Delta G$ are given in fig. 17; the decisions are illustrated by the example of Calabrian Arc (fig. 18) (for other regions see 8.4).
Central Italy territory is one of the most interesting for the analysis. In 1956-1965 the completeness is decreased by 0.5 (unit of M) for this region with respect to the previous period 1947-1955. Fig.19 shows that M=3.6 is registered reliably before 1955 but during the next period 1956-1965 the completeness of M=3.6 is questionable for this region; the incompleteness is noticeable for the mountain part (Appenines ridge), and it is evident for subregion Umbria&Marche (N 244).

6. Regional analysis of parameters of seismicity

6.1. Maximum magnitude, M_u

The problem of the seismicity parameters (a,b) estimations is usually considered irrespective to the estimation of the maximum magnitude M_u. Thereby it is implicitly supposed that M_u =∞ (see for example estimations by Utsu-Aki). This assumption is not essential for large values of b(M_{max} - M_c). Otherwise the variation of b-value estimations caused by the a priori fixed values of M_u can be significantly larger than the statistical variations caused by the volume of observations.

The earthquake catalog for instrumental and historical periods (PFGING, 1993) contain the main part of information on M_u. In addition the results of pattern recognition of prone-areas for Italy give some information (Caputo et al., 1980). The pointed recognition is based on data about morphostructural zonation and relief. Recently Buguer gravity anomalies have been effectively used for these purposes.

The historical catalog has been critically reviewed by Stucchi [1993]: some events have been fallen in the category of questionable, for some events the intensity was changed (mostly diminished), reestimation of magnitudes is in preparation.

The mentioned recognition of prone-area places (M ≥ 6) was based on instrumental data. So the initial material was not so large to conclude the stability of the results. Most probably the map of morphostructural zonation should be revised.

Thus the present state-of-art allows us only to discuss the basic principles of the zonation M_u (fig.20) for estimations of the parameters (a,b).

The principles followed in the mapping of M_u are the following:
- the elements of the seismotectonic zonation by GNDT (1992) serve as a basis for $M_u$ zonation, as far as $M_u$ is used only for parameters (a,b) estimation;
- $M_u = \text{observed } M_{\text{max}} + \delta$ where $\delta > 0$ is rounding to the nearest half-integer. The rounding is related to the analysis of magnitude grouping, section 5.4. All observed $M_{\text{max}}$ are excluded from the consideration if they are marked by the label of nonreliability by Stucchi.
- $M_u \geq M_{\text{recogn}}$

If a region contains any node recognized as seismically dangerous for $M_{\text{recogn}}$ (Caputo et al., 1980, Gvishiany et al., 1989) then $M_u$ is corrected taking into account the value of $M_{\text{recogn}}$.
- historical earthquakes localized near the boundary of seismogenic zones are related to both zones
- if the historical catalog contains only $I_0$ but not $M$ than $M = \max_i f_i (I_0)$ where $f_i$ are taken from formulas (14) of recalculation of the magnitude $M$ from $I_0$.

6.2. "a" and "b" zones

The first step to the estimation of the seismicity parameters (a,b) is to determine zones where they can be constant. Seismogenic zones by GNDT(1992) (Fig.21 a) were chosen as "a" zones. Some corrections to the zoning are discussed in Appendix 3.

"b-zones" are formed by neighboring seismogenic zones taking into account the geometry of aftershock sequences (Fig.5), tectonic features reflected in seismogenic zones by GNDT and the total number $N(M_{\text{cr}})$ of earthquake with $M \geq M_{\text{cr}}$.

$N(M_{\text{cr}})$, (fig.21b). To define the statistics $N(M_{\text{cr}})$ we use the catalog for 1900-1993 (file PFGING.DAT) with $M_{\text{cr}} = 3.5$. The choice of $M_{\text{cr}}$ is conditioned by the following circumstances:
- In the framework of SHA the "b-value" should be estimated for magnitude $M > 3.8$, which is connected with damaging and destructive earthquakes. Enlarging the magnitude range at weak events leads to diminishing of b-value dispersion, but it may induce a bias in "b" due to the variety of magnitudes, see (13). Numerous earthquakes after 1983 have either $M_d$ or $M_L$ in the ING catalog. These two kinds of magnitude are similar for magnitude $M \geq 3.5$, while when $M<3.3$ $M_d > M_L$ on the
average. Thus the decision on operating magnitude essentially influences the number of weak events.
- the mixed procedure of aftershock identification deals differently with strong and weak (M<4) main shocks. As a rule window method is applied for weak main shocks, and the window size is more connected with epicenter accuracy than with phenomena of aftershocks. It may lead to local variations in occurrence rate of weak main shocks.
- 10-days foreshocks were assigned to main shocks. Thus the choice of high threshold $M_{cr}$ reduces the influence of foreshocks on the estimations of the parameters (a,b).

Aftershock zones (fig.22 a,b). The map of aftershock zones (Fig.5) was completed by three aftershock zones defined by historical data. Those main shocks from historical catalog have noticeable aftershock zones (it happens that aftershock zones degenerate as far as aftershocks locations are often assigned to the main shock epicenter). To estimate the rate of occurrence of main shocks we used data for the instrumental period.

Areas containing seismogenic zones connected by aftershocks are shown in fig. 22a,b. The boundaries of those areas are fuzzy for Central Italy. Due to the high rate of occurrence of the seismicity flow in this region, different clusters may intersect. Thus initial assumptions for aftershock identification algorithm can be violated. (Let us remind that the algorithm is based on the supposition that only one cluster mixed with background seismicity is localized within a priori volume TxG). Thus some aftershock zone can be unstable for Central Italy. This important question should be specially analyzed.

There are no many aftershock zones in North of Italy; as to South Italy they well divide the territory in several blocks: North part of Calabrian Arc; The Center part: Calabria &Messina; North part of Sicily and Etna.

Decisions on b-zones (Fig.23). Because of the mentioned peculiarities of the aftershock zones, Central Italy is the region were is most difficult to identify b-zones. So seismotectonic features dominate in the decisions on b-zones as well as for North Italy, where the aftershock zones are not numerous.
As a result, North Italy is subdivided into West and East Alps, Both part being compressional areas.

b-zones of Central Italy:
- The internal part of North Apennine Arc (235, 248-250). This zone is not classified on the GNDT map (see Fig. 21a). The zone does not contain deep events, but it is not uniform. That is why Roma Comagmatic Region (N 250) has been isolated.
- Central Apennines (N 242-247), extentional areas
- Ancona zone (237-239), compressional areas
- Northern Apennines (N: 226-234, 236), the thrust belt-foredeep- foreland system [Boriani et al. (ed), 1989]

b-zones of South Italy:

- Northern branch of Calabrian Arc, the system of extension and transition zones (253-268),
- Calabria & Messina, extentional area (269-273); -Southern branch of Calabrian Arc, transition area (274-277)
- Sicilian Fracture zone (281-286);
- Etna system, volcanic area
- Gargano Fraction zone (255-257).

Seismogenic zones which have a small number of events and localized outside Italy or at the conjunction of two possible b-zones make difficult the separation of b-zones. Let us name such cases:

- zone 211 separates West and East Alps. It is classed to East Alps as it belongs to the Insubric fault (206-211 zones);
- transition area (zones 223-225) is the boundary between West Alps and Northern Apennines. In spite of small data volume, they are separated in b-zoning. Therewith Maritime Alps and West of Po Basin which are not classified by GNDT have been assigned to the b-zone of Western Alps;
- the regions 202 (Slovenia), 218, 219 (France), and volcanic zone Vesuvius were not taken into account for "b-value" estimation because of scant data. Parameters (a,b) for Vesuvius should be estimated after the revision of the historical catalog.

6.3. (a,b) parameters

Statistical methods of estimation and comparison of parameters (a,b) are given in section 4. The results of the estimation of the parameter "a" are summarized in table 4, while fig.23 presents the estimations of the parameter "b". The estimations of parameter "a" are normalized by unit of km sq. x year and are related to a fixed value of magnitude M*=4.5 (see 11)).
The statistical analysis of "b-zones" uniformity (with respect to parameter "b") preceded the estimation of parameter b. As result some zones have been split: West Alps, Southern branch of Calabrian Arc; while some of them have been joint together: Central Apennines and Ancona zone. Let us consider the analysis of "b-value" in some details.

- West Alps. The external part (Briansone zone) is characterized by the strongest neotectonic motions within the region. The comparison of b-values for external and internal parts shows the difference in b-value estimations: 0.7 and 1.0 respectively. Pearson test $\pi_1$ (see (11)) confirms the difference. The observed value $\pi_1^{obs}$ of $\pi_1$-test corresponds to the low significance level of the hypothesis on the equality of b-values:

$$\varepsilon = \text{Prob} (\pi_1 \geq \pi_1^{obs}) = 0.002.$$  

By this reason the zone was split (see dashed line in Fig. 23).

- Central Appennines and Ancone zones. Both zones are large with high level of seismicity, pure extentional and compressional areas respectively. According to [Boriani et al (eds) 1989] they are characterized together as thrust belt-foredip-foreland system. The estimations of b-value: 0.95 and 0.94 are in good accordance, so both zones are considered further with common value $b=0.94$ and 95% confidence interval (0.90-1.00).

- Northern Apennines. Macrotectonic characteristics of this zone is similar to that for the sum of b-zones mentioned in the previous item. Therefore, narrow (~10 km) compresional (C), extensional (E) and transitional (T) areas are joint to compose b-zone in this case. The formal comparison of "b-values" in those areas shows significant non-uniformity of "b-value".

<table>
<thead>
<tr>
<th>type of area</th>
<th>C</th>
<th>E</th>
<th>T</th>
<th>the observed significant level $\varepsilon=3%$.</th>
</tr>
</thead>
<tbody>
<tr>
<td>b-value</td>
<td>.67</td>
<td>.91</td>
<td>1.1</td>
<td></td>
</tr>
</tbody>
</table>

It does not seem reasonable to split this b-zone. The fact is that frequency-magnitude law (2) is a statistical macro-characteristic of seismicity regime. It reflects the distribution of seismic events with energy (which can be recalculated into liner size). By diminishing the seismic area we can expect that the distribution of seismic events with the size takes the Gutenberg-Richter shape only for small sizes which are much less than the area size. Therefore for strong events in the small area we should use distributions different from frequency-magnitude law (2). The example of Etna region speaks in favour of our decision.

- Etna: volcanic zone of linear size ~ 50 km. Aftershock sequences are concentrated here indicating the interaction of seismicity processes in the internal and external parts of the zone. This is confirmed by the example of dynamics of fore- and after-shocks for the event 1911.09.10, M=4.7 (see...
fig 24 c). Therefore the subdivision of the area looks artificial and leads to various estimations of b-value: 1.00 (internal part) and 1.18 (external part). The confidence zones for of 95% level for (a,b) parameters for both parts of Etna are given in fig 24b. The confidence zone of (a,b) for the whole b-zone is recalculated in confidence zone of the frequency-magnitude law (fig.24a), i.e. for the line a-b(M-M̄). Fig. 24(a,b) illustrates complementary capabilities of the methodology mentioned above.

- West Calabrian Arc, transition area (by GNDT). Aftershock zones connect all parts of the zone with the exception of area (278), which separate Calabrian arc from Sicilian Fracture zone. The frontier zone (278) has significantly smaller b-value b=0.81 than for the rest part of the territory (b=1.2). From the other hand "b" for area 278 is similar to that for the fracture zone. By this reason area (278) is separated from original b-zone.

b-value variations with \( M_u \). As far as the catalog of historical events is in preparation, our decisions on maximum magnitude \( M_u \) can be revised. To investigate the dependence of the b-value of \( M_u \), the b-values were reestimated for the new value of maximum magnitude: \( M_u + 1 \). The reestimated values are about the same: \( \Delta b \approx 0.01 \) with the exception of three cases:

<table>
<thead>
<tr>
<th>Location</th>
<th>b-value</th>
<th>Reestimated b-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>West Alps, internal zone</td>
<td>1.00</td>
<td>1.04</td>
</tr>
<tr>
<td>Calabrian Arc, Southern branch</td>
<td>1.20</td>
<td>1.25</td>
</tr>
<tr>
<td>Sicily, Fracture zone</td>
<td>0.81</td>
<td>0.84</td>
</tr>
</tbody>
</table>

The effect is connected with individual seismogenic zones, where magnitude-frequency law is not linear, and with the narrow range (\( M_c, M_{max}^{obs} \)).
Table 4

(a,b)-parameters for seismogenetic zones of Italy

[. . .] - 95% confidence interval for the b-value
reg - index of a seismogenic zone (fig. 25b)
N - number of events with $M \geq 3.5$
Area [1000 sq km] - number of events with $M^* = 4.5$ per 1000 km$^2$ per 1 year

$A L P S$

<table>
<thead>
<tr>
<th>reg</th>
<th>N</th>
<th>Area</th>
<th>a</th>
<th>reg</th>
<th>N</th>
<th>Area</th>
<th>a</th>
</tr>
</thead>
<tbody>
<tr>
<td>201</td>
<td>41</td>
<td>4.844</td>
<td>-1.630</td>
<td>207</td>
<td>18</td>
<td>2.383</td>
<td>-1.698</td>
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<tr>
<td>203</td>
<td>4</td>
<td>1.278</td>
<td>-2.065</td>
<td>208</td>
<td>4</td>
<td>1.854</td>
<td>-2.242</td>
</tr>
<tr>
<td>204</td>
<td>18</td>
<td>2.074</td>
<td>-1.637</td>
<td>209</td>
<td>19</td>
<td>1.029</td>
<td>-1.310</td>
</tr>
<tr>
<td>205</td>
<td>90</td>
<td>3.097</td>
<td>-1.113</td>
<td>210</td>
<td>40</td>
<td>4.839</td>
<td>-1.659</td>
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<tr>
<td>206</td>
<td>61</td>
<td>3.731</td>
<td>-1.363</td>
<td>211</td>
<td>13</td>
<td>6.156</td>
<td>-2.206</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>West Alps, Briansone zone</th>
<th>b = 0.70 [.59 - .81]</th>
</tr>
</thead>
<tbody>
<tr>
<td>reg</td>
<td>N</td>
</tr>
<tr>
<td>212</td>
<td>25</td>
</tr>
<tr>
<td>213</td>
<td>24</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>West Alps, internal zone</th>
<th>b = 1.00 [.80 - 1.22]</th>
</tr>
</thead>
<tbody>
<tr>
<td>reg</td>
<td>N</td>
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<td>N</td>
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<td>227</td>
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Table 4 (continue)

Central Appenines

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<td>4.044</td>
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</tr>
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<td>43</td>
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Tuscan area

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Roma comagmatic zone

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**CALABRIAN ARC**

Northern branch

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Calabria and Messina

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b = .94 [ .90-1.00]  

b = .90 [ .60-1.20]  

b = .78 [ .68-.90]  

b = .91 [ .79-1.10]  

b = .79 [ .68-.90]
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**Etna**

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(b=1.06 [1.00-1.12]

(internal part)

(External part)

**Southern branch**

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(b=1.20 [.94-1.48]

**Table 4 (continue)**

**Fracture Zones**

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(b=.81 [.70-.92]

**Gargano**

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**Sicily**

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<td>1.978</td>
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**Individual seismogenic zones**

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</table>
7. Conclusion and problems

The present work is made in the framework of the project "Statistical analysis of seismicity and hazard estimation for Italy (mixed approach)". The supposed output of the project is to produce maps of probability of not exceeding some PGA (Peak ground acceleration) threshold in a given period of time. Two problems are solved in the context of this:

- statistical estimations of local parameters \((a, b)\) over the territory of Italy have been determined through the sophisticated treatment of seismicity of Italy;
- the theoretical method of using those estimations for the calculation of the distribution \(F_g(A)\) of PGA maximum in the given time period.

It will take the following to solve the final problem of the project:

- to estimate the distribution of main shocks with depth dependently on the region;
- to analyze the new version of the historical catalog in order to refine the parameters of seismicity. This especially concerns the region of Vesuvius having a deficiency in instrumental data. The methodology should be the same as mentioned above;
- to transform theoretical formulas of calculation of the distribution \(F_g(A)\) into a thrifty algorithm;
- to analyze the role of estimations of maximum magnitude for calculations \(F_g(A)\). As it was mentioned in section 4.1, it requires to investigate the ensemble of PGA fields presented in isolines for the given area;
- to summarize present-day empirical data on isoseismal lines (isolines of macroseismic intensity). In the framework of this project it is necessary in order to compare synthetic and empirical PGA data. From the other hand, it is useful for statistical modeling of strong motions (see KMK [4,6,7]). The preliminary work started with isoseismal areas catalog by Postpishl [1985] and Shenkareva [1973]. It is shown that for the earthquakes of Italy on the whole the isoseismal lines of the level I outline the area

\[
Q_I (M) = C_I 10^{b_Q M + \sigma_z} \quad I=5,6,7
\]

where \(M\) is the earthquake magnitude, \(b_Q = 0.98\), \(\sigma = 0.3\) and \(\xi\) is the standard error of the dispersion. The value \(b_Q\) serves as an indicator of the role of maximum magnitude in the problem of \(F_g(I)\) estimation (here \(A\) is substituted by intensity) (see section 4.1). Parameter \(b_Q\) should be refined and compared with the analog parameter for PGA.
The present work can be also considered as an investigation in the framework of Seismic Hazard Analysis. From this point of view the work contains some new methodical elements:

- aftershock identification is made by means of a new statistical procedure based on the principal of optimization of the trade-off between the two kinds of errors in the aftershock identification process. The received catalog of main shocks is of interest by its own right;
- aftershock zones are widely used for "b-value" estimation indicating the interrelation between the individual seismogenic zones.

It is of theoretical interest to compare the aftershock zone and the isoseismal area for the same main shock. This work is connected with analysis of aftershock zones stability.

Acknowledgments

The authors would like to thank Professor Abdus Salam, the International Atomic Energy Agency and UNESCO for hospitality at the International Centre for Theoretical Physics, Trieste.
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Kopnichev V., Shpilker G. (1980). Space-time source characteristics of strong earthquakes with different type slip. Izvestia AN SSSR, Physics of the Earth N 9, 3-11 (In Russian)


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8. Appendix

8.1. Probabilistic seismic hazard

To calculate the probability of not exceeding some threshold of Peak Ground Acceleration (PGA) in a given period of time let us suppose that

(i) seismic events \( x = (\text{time, epicenter, magnitude}) \) form the Poissonian flow with measure \( \lambda(dx) \), i.e. for any volume \( V \) of \( x \)

\[
\text{Prob (number of events from } V = n) = \frac{\lambda_V^n}{n!} e^{-\lambda_V}
\]

where

\[
\lambda_V = \int_V \lambda (dx)
\]

(ii) additional parameters of seismic source \( \varepsilon_x = (\text{depth, focal mechanism parameters etc.}) \)

are statistically independent for different events \( x \) (In particular, \( \varepsilon_x \) can be a deterministic function of \( x \))

(iii) seismic effect \( A_{g0} (x,\varepsilon) \) (i.e. peak acceleration, velocity, displacement or macroseismic intensity) in a given point \( g_0 \) is a deterministic function (which takes value 1 if (\( x,\varepsilon \)) take a determined value, and takes value 0 otherwise), or a function of (\( x,\varepsilon \)) with independent values.

Then

\[
\text{Prob (} A_g (x,\varepsilon) < A \text{ for all } x = (t,g,M) \in T \times G \times M = \exp(-A_{g0} (\bar{A}))
\]

where

\[
A_{g0}(A) = \int_x \int_\varepsilon \text{Prob (} A_{g0} (x,\varepsilon) > A \text{) dF(} \varepsilon \mid x \text{) } \lambda(dx), \quad X=G \times M \quad (A1)
\]

\( F(\varepsilon \mid x) \) is the conditional distribution function of \( \varepsilon \) given \( x \) In other words, \(-A_{g0} (\bar{A}) \) is the accumulated frequency-PGA law in the point \( g_0 \) if \( A \) is measured by PGA

Proof. Under conditions (i-iii) events

\( \omega = (x,\varepsilon,A) \)

form the Poissonian flow in the volume \( X \times E \times A \) with measure
\[ \Pi(d\omega) = \lambda(dx) \, dF(\epsilon \mid x) \, dF(A \mid x, \epsilon) \]

where \( F(A \mid x, \epsilon) \) is the conditional distribution of the effect \( A \) of a given given seismic source \((x, \epsilon)\). Therefore, the number \( v_A^n \) of events \((A2)\) with \( \{ A > A \} \) has a Poissonian distribution with parameter \( \pi = \int_{A > A} \Pi(d\omega) = \Lambda g_0(A) \)

where \( \Lambda g_0(A) \) is given by \((A1)\).

But

\[ \text{Prob}(A < A \text{ for all sources } (x, \epsilon) \in T \times G \times M \times E) = \text{Prob}(v_A = 0) = \exp(-\pi) \]

that proves the statement.

Particular case:

Let us suppose

(a) \( \lambda(dx) = 10 \, a(g) + b(g) \, M \, dg \, dM \, dt \quad M \in [M_c, M_u(g)] \)

where \( a(g) = a_i \), \( b(g) = b_i \) in zone \( G_i \)

(b) \( A g_0(x, \epsilon), \ x = (t, g, M) \) is independent on \( t \) deterministic function

(c) \( A g_0(g, M, \epsilon) \) increases with \( M \) then

\[ \Lambda g(A) \equiv T \sum_i \sum_{\epsilon} [G_i] \frac{M_u(i)}{M_i(a, \epsilon)} 10^{a_i + b_i M} \, dM \, P_i(\epsilon) \quad (A3) \]

where \( \{ P_i(\epsilon) \} \) is the distribution of the parameter \( \epsilon \) for the zone \( G_i \)

\[ |G_i| \]

is the area of \( G_i \)

\[ M_u(i) = M_u \]

for \( G_i \)

\[ M_i(A, \epsilon) \]

is the root of the equation

\[ A g_0(g_i, M, \epsilon) = A \quad (A4) \]
for fixed $\varepsilon$ and $g_i \in G_i$ ($g_i$ can be the center of cell $G_i$).

Proof. According to (c) the equation (4) has an unique solution $M_i (\bar{A}, \varepsilon)$.
Under condition (b)

$$\begin{align*}
1 & \quad M > M_g (\bar{A}, \varepsilon) \\
\prob (A_{g_0} (t, g, M) > \bar{A}) &= \\
0 & \quad M > M_g (\bar{A}, \varepsilon)
\end{align*}$$

Substitution of (5) and (a) in (A1) leads to the approximate formula (A3).
8.2. Minimax aftershock data (table):

Date (year, month, day), coordinates (latitude, longitude), operating magnitude (M), parameters of aftershocks 95% zone: \( \log(\text{area}[\text{km}^2]) \), largest semiaxis \( R_1 \) [km], semiaxis ratio \( R_1/R_2 \), azimuth for the largest semiaxis (A), number of aftershocks (Na), number of foreshocks (Nf).

<table>
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<th>lat</th>
<th>lon</th>
<th>h</th>
<th>M</th>
<th>log(S95)</th>
<th>R1</th>
<th>R1/R2</th>
<th>A</th>
<th>Na</th>
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8.3. Corrections to the zonation by GNDT

Seismotectonic zonation by GNDT is used in the report for the description of seismicity in Italy (see section 6). It is supposed that earthquakes are distributed uniformly within a fixed seismogenetic area and independently of the other seismogenic areas.

These hypotheses impose the following a priori requirements to the zonation:
1) an area should be homogeneous from the neotectonic point of view;
2) the active faults must not be the boundaries of regions;
3) if possible, boundaries of regions should not divide clouds of epicenters;
4) the density of epicenters should be approximately uniform inside the region.

We consider here the seismotectonic regionalization of Italy (ZONAZIONE SISMOGENETICA DEL TERRITORIO NAZIONALE, Pisa 9-11 September 1991, computer file) currently accepted by GNDT (Fig. 25a).


These corrections were made in collaboration with Prof. P. Scandone.

The regionalization is significantly changed in two regions (Northern Apennines and Sicilian fracture zone). The description of other changes is given with respect to the reasons caused the changes. The resulting regionalization scheme is presented by fig. 25b. (the numbers of regions given in the text contain 200 in addition).

Northern Apennines.

Regions 21-27 by GNDT are changed in accordance to detail investigations by P. Scandone (K. Meleti et al., 1993), who placed at our disposal the regionalization scheme characterizing the type of neotectonic:
1) dip-slip, SW-NE is the orientation of the axis T;
2) thrust, SW-NE is the orientation of the axis P;
3) strike-slip, the displacements are oriented in the directions of sub-vertical ruptures perpendicular to the lineaments.

The generalization of this scheme led to the identification of the following regions (the dominate types of motion are given in brakets):
- 226 and 229 - compress zones (2,3);
- 227,228,230-232 - fault zones (3), with slightly expressed neotectonic motion. The regions 230-232 are identified in order to check the homogeneity of the activity level;
- 234, 235 - fault tectonic is slightly expressed (1,3), the dominant direction of the faults is NW-SE;
-236 - submeridional area completing the North fault zone. It is nonuniform by types of mechanism, a bit more active on the South.

We include in the regionalization the additional region 235 along the extensional front of the Tyrrhenian sea (northern part of Tuscan coast).

Sicilian fracture zone.

Ragusa zone (reg. 53, 53a/94 GNDT) is divided into two parts according to the scheme by R.Catalano et al.(1989): Hyblean tectonic unit (Reg#281) and Gela-Catania trough (Reg. 282).

Malta eskarpment being the system of N-S normal faults, is a first rang lineament (M.Caputo et al., 1980); it is associated with large variations in depth. The northern segment of this structure (to the North from Taomina line) is included into the reg. 271 (Messina strait). Aftershocks of the 1908 Messina earthquake were concentrated along this narrow NNE-SSW zone (Mulargia et al., 1988) but were not observed on Hyblean tectonic unit. Reg. 280 includes the central part of this structure (Scarpata di Malta e Siracusa), the South boundary is determined by the boundary of the region under consideration.

The southern part of reg.54 GNDT (reg.285) which belong to the hypothetical Hyblean tectonic unit (Bigi et al., [1993]; Savelli, [1988]; Sartori [1989], contains the great normal fault trending NE-SW observed in Mare di Sicilia and characterized by strike-slip motion, it is expanded by the system of N-S faults to Banco Nerita. The northern part (Reg. 284) is represented by deformed Foreland basin deposits: the folding zone to North from Hyblean unit.
There are two complement areas with low seismic activity, which belong to the allochthonous Appenninic units:
- Reg. 283 - to the South from Mt.Kumata-Alcantara line (Catalano et al., 1989). The southern border, drawn by epicenters locations, outlines the outcrop of flysch series and deformed abyssal deposits of Trapanese-Saccense Platform.
- Reg. 286 - the SW part of Sicily, which includes the west extension of folding zone of reg.284; historical data contain earthquakes near Marsala.

Subdivision of GNDT regions which are non-uniform by neotectonic features.

- Reg. 45 GNDT is divided into continental and sea parts (reg.267). The continental part (reg.266) is represented by Lower Crati Trough (i.e. the earthquakes are connected with the extension). The strongest events are located in reg. 267 (latitude ~ 39-39.2 N). Perhaps the seismicity here is caused by the large fault in the ESE direction (Bigi et al., [1993]): this supposition may be confirmed by the break of the border of Apenninic allochthonous at the far extension of this zone to the East (Longitude 17.5-18 E).
- Reg. 19 is subdivided into continental and sea parts (reg. 224,225). The seismicity in reg. 225 is related to Ligurian sphenochasm within the area with Moho depth > 20km, i.e. are related to Provencal-Ligurian basin.
- On the Northern branch of the Calabrian arc (latitude 40 N 5') Sartori [1989] traces a W-E fault along the southern border the of Q -deposits of the Sinni basin and the North outcrops of Frido Unit (Bigi et al., [1993]). The fault can be traced to the West by outcrops of Cilento Unit. Left slips are supposed along the fault. The boundary between the regions 41 and 42 (GNDT) is displaced to the North in order to include this slightly revealed transversal zone into one region (reg. 262).

Changes and subdivisions in the regions non-uniform by activity:

- Reg. 12 GNDT is subdivided into Northern (reg.213) and Southern (reg.214) parts in accordance with lineaments locations [Weber C. et al., 1985].
- The eastern part of reg.11 GNDT (reg.212) with low level of seismic activity is assigned to reg. 211;
- Reg. 29 GNDT is a complicate and non-uniform zone. It is supposed that seismicity process differs at the Eastern and Western parts [Calamita & Deina, 1988]. The increasing of activity is connected with tectonic line M.Sibillini thrust - Ancona-Anzio line [Locardi,1988], the activity
decreases in the SW part. Aftershock sequences (1979 and 1915) speaks in favour of integrity of the region, as they connect Apennines with the graben zone. To determine the activity level we separated the part of the reg. 44 with less activity level from the end (by [Wezel, 1985] representation) of Umbro-Marchean and Marchean ridges: apparently, reg.242 is the part of foredeep zone, and reg. 243 is related to the NW continuation of the main thrust front.

Reg 30 GNDT, being the entire compression zone is divided into three parts according to activity level (reg 237, 238, 239).

- Gargano fracture zone. Reg. 37 GNDT is divided into two parts: two large E-W faults (reg.256) are separated from the system of smaller NW-SE faults (reg. 255). Besides, aseismic parts of Adriatic see and local seismoactive section of Isole Tremini horst are excluded from the consideration. Reg. 38 GNDT is localized at normal WSW-ENE faults (reg.257), the sea area of low seismicity is excluded from this region.

- Reg. 50 GNDT includes the boundary between volcanic zone of young Tyrrenian basin on the North and Calabrian tectonic unit on the South. The region is divided into two parts (reg. 275, 276) by the south boundary of outcrops of volcanic rocks of Eolian Island Arc. To complete the picture the sea region (274) is added between reg. 275 and Aeolian islands (it contains aftershocks of an earthquake localized in reg. 275).

Vesuvio zone (reg. 40 GNDT, reg.258). The new version of boundary outlines the field of subduction-related volcanic rocks according to Bigi et al., [1993]. NW-SE normal fault limits the region from the East. Low active sea areas are excluded

The changes in the boundaries intersecting the clouds of epicenters

- The southern boundary of Reg.11 GNDT which aligns along the lineament of the second order and intersects two epicenters (magnitude of about 5) was replaced to the South (reg.212);

- Tuscan geothermal zone. The eastern corner of the 28 GNDT is located inside of the group of epicenters related with local uplift (Ophiolite-bearing complex, Jurassic) inside oceanic-type post-collision basin. There is no such type of seismicity in other parts of this region. NE boundary of the region also divides the cloud of epicenters. For reg.249 we exclude marine part and draw NE boundary according to [SM].
- Roman comagmatic region. The section between reg. 28a and 31 (Rome territory) have the level of seismic activity similar to the nearest parts of neighboring volcanic regions. We outlined the region (reg.250) by outcrops of volcanic rocks according to (Bigi et al., [1993], Savelli [1988]). The region is obviously non-homogeneous by the density of epicenters: groups of earthquakes are related to Monte Amiata and Monti Volsini on the north and near to Velletri on the south. In the area between these volcanic groups the level of seismic activity with M>3 increases towards the extensional front of the Tyrrhenian Zone. By this reason to estimate the seismicity level we subdivide the region into two more or less homogeneous parts (250a, 250b).

- Reg.35 GNDT (reg. 251) (Ortona-Roccamonfina line) separates the northern and southern arcs [Locardi, 1988] being an integral part of the Abbruzzi-Latium platform zone as revealed by the seismicity: the seismicity level is continuous but the depth of hypocenters increases as the line is approached from the west, while the seismicity level drops on the east side of the line.

On the east the boundaries are corrected by the epicenters map. At the SE part the region is enlarged a bit to include a group of earthquakes connected with the zone of Roccamofina. According to instrumental data (1984) aftershocks are well localized within the proposed boundary of the region.

The northern boundary of the reg. 39 GNDT is aligned with the second order lineament (middle Pliocene-Pleistocene thrust front). Strong events connected with this line belong also to region 36 GNDT, some part of them are outside the regionalization. The southern boundary of reg.39 GNDT captures part of events connected with reg. 41 GNDT. We assigned reg. 259 with reconsidered boundaries of the region 39 GNDT.

Reg. 43 represents large transverse zone (Sangineto line) having the W-E orientation. Some authors [Sartori, Brigo, Chisetti, etc] draws Sangineto line in the NEE-SWW direction along surface normal fault. This line was also defined as a lineament [Caputo]. The region GNDT is slightly enlarged at the NE to include active zone near Sybaris-Copia (reg.268).

The boundary of the reg. 46 GNDT (Catanzaro trough) is changed to the SE.

An adding of regions where earthquakes with magnitude >3 occurred.
- gap between Brianson line and Piemont zone (reg.215, West Alps)
- Liguro-Piemont basin (reg.221, West Alps)
- system of grabens in Tuscan nappe [Locardi, 1988; Wezel, 1985] between Umbro-Sabina arc [Locardi, 1988] and Tuscan geothermal zone (reg.248);
- NW part of the Tuscan graben system to the NW from Tuscan geothermal zone (reg.235);
- transition zone between Umbro-Sabina arc (reg. 29 GNDT) and front of external chain zone (reg. 30 GNDT), separated into two parts by the activity level (reg. 240 and 241);
- for completeness reg. 265 with low seismicity level is added between regions 44-45 GNDT.
- reg. 254 to the east from reg. 253 (36 GNDT); there are magnitude 3.9 in XX cen. and historical events with M 6.1;
- reg. 260 (41 GNDT) includes the intersection of two lineaments (W-E and NW-SE directions) and volcano Vulture. Many authors draw here the Vulture tectonic line with N-S direction [Locardi]. The fault with WNW-ESE direction is also localized here. This complicate tectonic knot occupies the northern part of the region with high density of epicenters. Eastern part of this group of epicenters is outside the region. We assign here reg.261 with magnitude 4.6 in XX cen. and historical events with M 5.6 (1273, 40.67, 15.83);
- reg. 270 is to east from reg. 269 (47 GNDT) with magnitude 5 in XX cen. and historical events with M 6;
- For completeness seismactive zone has been added between reg. 48 and 49 GNDT (reg. 272).
8.4. Analysis of data completeness (set of figures (a-g)).

This appendix includes time-magnitude relations for 6 subregions of Italy: East Alps, West Alps, Central Italy: Apennines ridge and its complement to Central Italy, Northern branch of Calabrian Arc, and Calabria & Sicily (see fig. 16). The relations are based on the PFGING catalog data for 1900-1993 years in order to take a decision on the catalog completeness for the 11 time intervals listed in table 13 (section 5.2).

Figures (a-f) also contain the decision on data completeness and are related to 11 time intervals and 6 subregions with the exception of Northern branch of Calabrian Arc (the last one is used in the text to illustrate our decision, see fig. 18).

Fig (g) presents time-magnitude relations for each subregion taking into account only representative data. Non-linear behavior of some frequency-magnitude relations in fig. (g) is caused by the following factors: probably inexact decisions on completeness of data, the operating magnitude quality and time variations of weak seismicity.
Appendix 4, a.

Analysis of data completeness for Western Alps

H is number of events, arrow mark the decision on the data completeness.
Appendix 4, b. Analysis of data completeness for Eastern Alps

Notation: \( N \) is the number of events, arrow marks the decision on the data completeness.
Appendix 4, c.
Analysis of data completeness for Central Italy

N is number of events, arrow marks the decision on the data completeness.
Appendix 4, e. Analysis of data completeness for part of Central Italy: complement of Apennines ridge

Notation: $N$ is the number of events, arrow marks the decision on the data completeness
Appendix 4, f. Analysis of data completeness for Calabria & Sicily
Notation: N is the number of events, arrow marks the decision on the data completeness
Appendix 4.g.
Frequency-magnitude relations for the time-magnitude intervals of data completeness
---
center and magnitude interval of data grouping
Figure captions.

Fig.1. Irpinia earthquake 1980, M=6.5  
  a) distance-time distribution of seismicity after the main shock  
  Notations: asterisk - minimax aftershocks, small stars - background events, 
  the small square marks the distance between the main shock and the center 
  of aftershock scattering, dashed line - the decision for aftershocks and 
  background seismicity separation according to minimax procedure.  
  b) space projection of minimax aftershocks and 95% aftershocks zone. 
  Square marks the main shock location.  
  c) number of aftershocks versus time (integrated from the end).  
  d) number of minimax aftershocks versus magnitude (integrated from the 
  end)

Fig.2. Friuli earthquake, 1976, M=6.1.  
  a-d) are the same as in Fig.1. Solid lines in Fig.2c mark the time of strong 
  aftershocks.

Fig. 3. Space (a) and time (b) characteristics of aftershocks.  
  Notations: asterisks - minimax aftershocks data, solid line - window characteristics 
  (see (4) in the text)

Fig.4. Space-distribution of damaged earthquakes (M≥4), 1900-1994. a) 
  main shocks and foreshocks, b) aftershocks

Fig.5. Minimax aftershocks with their 95% zones and seismogenic zones 
  by GNDT.

Fig. 6. Time series of seismic activity in the catalog PFGING, 1900-93 (a) 
  all events, (b) without aftershocks, (c) aftershocks

Fig.7. Frequency-magnitude law for (a) all events, (b) all events without 
  aftershocks, (c) aftershocks. Cross symbol - N=0 for M≤M_u

Fig. 8. Comparison of two last versions of PFGING catalogs in the time 
  interval 1960-1990: (a) revised, (b) removed and (c) false earthquakes

Fig.9. Dynamics of European seismic network according to V.Karnik 
  Period 1901-1955  Notations: solid circle - total number of stations, open 
  circle - stations which provide full data
Fig. 10. Structure of magnitudes in the PFGING catalog depending on time.

Fig. 11. Macroseismic (a,b,c) and duration (e) magnitudes versus $M_L$ (PFGING - catalog)

Fig. 12. Magnitude-type mixture of operating magnitude depending on time

Fig. 13. Empirical frequency-intensity law for PFGING catalog (Postpischl, 1985b)

Fig. 14. Distribution of decimal points for magnitude $M_L$ depending on time (PFGING catalog).

Fig. 15. Time-magnitude grouping of data (decision)

Fig. 16. Partition of the region for the analysis of data completeness.

Fig. 17. Time-magnitude intervals of data completeness depending on area (decision). Notations: Solid (dashed) lines bound the intervals of completeness, dashed line corresponds to the reduced area

Fig. 18. Analysis of data completeness for North Calabrian Arc. Notations $N$ is the number of events, the arrow marks the decision on the data completeness, the dashed line marks the lower magnitude used in the calculations, cross symbol - $N=0$ for $M\leq M_U$.

Fig. 19. Strong reduction of data completeness in Umbria&Marche region (N 244) in 1956-1965. This effect is screened by data of Central Italy (see the top figures). The legend is the same as on Fig. 18.

Fig. 20. Map of $M_U$: decision $a_n$ maximum magnitude for the problem of $b$-value estimation.

Fig. 21. Information for $b$-zones constructing.

(a) Corrected seismogenic zones by GNDT (1992) $C =$ compressional areas; $E =$ extensional areas; $F =$ areas of fracture infomland zones; $T =$ transition areas; $TP =$ areas of transpression; $V =$ volcanic areas.
(b) The total number of earthquakes of $M \geq 3.5$ in time-magnitude intervals of data completeness.

**Fig. 22.** Aftershock information on b-zones constructions. Notations: solid lines - aftershock zones of events after 1900 (a) and before 1900 yr (b); fat solid lines - boundaries of seismogenic zones connected by aftershock areas.

**Fig. 23.** b-zones. Notations: initial ( --- ), additional (- - - ) and omitted ( + + + ) boundaries of b-zones.

**Fig. 24.** Etna region: (a) frequency-magnitude law (solid line) and its 95% confidence area (dashed line); (b) 95% - confidence areas of (a,b) parameters for the internal and external parts of the region; (c) Foreshocks ( □ ) and aftershocks ( ◊ ) dynamics for the event 1911.09.10, $M=4.7$. (The example of the interaction between two parts of the region).

**Fig. 25.** Seismogenic zones by GNDT (a) original, 1992; (b) corrected. Notations: 25 -zone index. The index for the corrected area is changed to "index" +200 in the text.
Fig. 1. Irpinia earthquake 1980, M=6.5

a) distance-time distribution of seismicity after the main shock Notations: asterisk - minimax aftershocks, small stars - background events, small square marks the distance between the main shock and the center of aftershock scattering, dashed line - the decision for aftershocks and background seismicity separation according to minimax procedure.
b) space projection of minimax aftershocks and 95% aftershocks zone. Square marks the main shock location, c) number of aftershocks versus time (integrated from the end), d) number of minimax aftershocks versus magnitude (integrated from the end)
Fig. 2. Friuli earthquake, 1976, M=6.1.

a-d) are the same as in Fig. 1. Solid lines in Fig. 2c mark the time of strong aftershocks.
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Notations: asterisks - minimax aftershocks data, solid line - window characteristics (see (4) in the text)
Fig. 4. Space-distribution of damaged earthquakes (M≥4), 1900-1994.
Fig. 5.

Minimax aftershocks with their 95% zones and seismogenic zones by GNDT.
Fig. 6. Time series of seismic activity in the catalog PFGING.
Fig. 7. Frequency-magnitude laws for (a) all events, (b) all events without aftershocks, (c) aftershocks.

- Full catalog 1900-93
  - $b = 0.78$
  - Events: 14571
  - $M_{AG} = 2.70 - 7.65$

- Without Aft
  - $b = 0.72$
  - Events: 9461
  - $M_{AG} = 2.70 - 7.65$

- AFT only
  - $b = 0.30$
  - Events: 6089
  - $M_{AG} = 2.70 - 7.65$
Fig. 8. Comparison of two last versions of PPGING catalogs in the time interval 1900-1990: (a) revised, (b) removed and (c) false earthquakes.
Dynamics of European seismic network according to V.Karnik [1969]
1901-1955
(solid circle - total number of stations; open circle - stations which provide full data)

Fig. 9.
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<td></td>
<td>6272</td>
</tr>
<tr>
<td>1987.VI</td>
<td>Md</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1987.VII</td>
<td>ML</td>
<td></td>
<td>12770</td>
</tr>
<tr>
<td></td>
<td>Md</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 10. Structure of magnitudes in the PFGING catalog depending on time
Fig. 11. Macroseismic (a, b, c) and duration (e) magnitudes versus $M_L$ (PFGING - catalog)
Notations: ■ - ML, ■■ - Md, ■■■ - Mp, ■■■■ - Mi

1900-1907
1908-1921
1922-1938
1939-1943
1944-1946
1947-1955
1956-1965
1966-1979
1980-1983¹
1983-1987²
1987-1993³

M = 2.9-3.3

1900-1907
1908-1922
1922-1938
1939-1943
1944-1946
1947-1955
1956-1965
1966-1979
1980-1983¹
1983-1987²
1987-1993³

M = 3.4-5.3

1900-1907
1908-1921
1922-1938
1939-1943
1944-1946
1947-1955
1956-1965
1966-1979
1980-1983¹
1983-1987²
1987-1993³

M = 5.4 - 7

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Fig. 12. Magnitude-type mixture of operating magnitude depending on time
Fig. 13. Empirical frequency-intensity law for PFGING catalog (Postpischl, 1985b)
Fig. 14. Distribution of decimal points for magnitude M depending on time (PFGING catalog).
Fig. 15 Time-magnitude grouping of data (decision)
Fig. 16. Partition of the region for the analysis of data completeness.
Fig. 17. Time-magnitude intervals of data completeness depending on area (decision). Notations: Solid (dashed) lines bound the intervals of completeness, dashed line corresponds to the reduced area.
Fig. 18. Analysis of data completeness for northern branch of Calabrian arc.

Notation: N is the number of events, arrow marks the decision on the data completeness.

center and magnitude
interval of data grouping.
Fig. 19. Strong reduction of data completeness in Umbria & March region (N 244) in 1956-1965. This effect is screened by data of Central Italy (see the top figures)

center and magnitude interval of data grouping
Fig. 20. Map of $M_\text{max}$: decision on maximum magnitude for the problem of $b$-value estimation.
Fig. 21 Information for b-zones constructing.
(a) Corrected seismogenic zones by GNDT (1992)
C = compressional areas; E = extensional areas; F = areas of fracture
inoreland zones; T = transition areas; TP= areas of transpersion;
V = volcanic areas.
(b) The total number of earthquakes of M ≥ 3.5 in time-magnitude
intervals of data completeness.
Fig. 22. Aftershock information on b-zones constructions.
Notations: solid lines - aftershock zones of events after 1900 (a) and before 1900 yr (b); fat solid lines - boundaries of seismogenic zones connected by aftershock areas.
Fig. 23. $b$-zones

Notations: initial (—), additional (— — —) and omitted (+——+) boundaries of $b$-zones.
(a) frequency-magnitude law (solid line) and its 95% confidence area (dashed line);
(b) 95%-confidence areas of (a,b) parameters for the internal and external parts of Etna region.
(c) Foreshocks (•) and aftershocks (O) dynamics for the event 1911.09.10, M=4.7.
(The example of the interaction between two parts of the region).

Fig. 24. Etna region
Fig. 25. Seismogenic zones by GNDT

(a) original, 1992; (b) corrected

Notations: 25 - zone index. The index for the corrected area is changed to "index" +200 in the text.