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Seismic hazard maps of Italy

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Abstract
The Italian «Gruppo Nazionale per la Difesa dai Terremoti» has conducted a project in recent years for assessing seismic hazard in the national territory to be used as a basis for the revision of the current seismic zonation. In this project the data on the major earthquakes were reassessed and a new earthquake data file prepared. Definition of a seismotectonic model for the whole territory, based on a structural-kinematic analysis of Italy and the surrounding regions, led to the definition of 80 seismogenic zones, for which the geological and seismic characteristics were determined. Horizontal PGA and macroseismic intensity were used as seismicity parameters in the application of the Cornell probabilistic approach. The main aspects of the seismic hazard assessment are here described and the results obtained are presented and discussed. The maps prepared show the various aspects of seismic hazard which need to be considered for a global view of the problem. In particular, those with a 475-year return period, in agreement with the specifications of the new seismic Eurocode EC8, can be considered basic products for a revision of the present national seismic zonation.

Key words *probabilistic seismic hazard – seismogenic zonation – PGA attenuation – intensity attenuation – Italy*

1. Introduction

In a recent summary, Muir-Wood (1993) identified five distinct generations of hazard maps:

1) *Historical determinism* maps the maximum shaking experienced in the past; it lacks any statistical meaning but gives a minimum value of reference hazard.

2) *Historical probabilism* treats the seismicity data using statistical models (*e.g.*, by simple counting or by more robust statistics).

3) *Seismotectonic probabilism* incorporates geological and seismological constraints in building the seismic source model; the most common application of this approach is the Cornell (1968) method, which is based on three specific assumptions: the event magnitude is exponentially distributed, the recurrence times form a Poisson process, and the seismicity is uniformly distributed over the Seismogenic Zone (SZ).

4) *Non-Poissonian probabilism* acknowledges the periodicity of major earthquake recurrence and takes into account the time elapsed since the previous events (usually only the last one).

5) *Earthquake prediction* is the ultimate stage of hazard assessment, and tries to evaluate probabilities of timing, location, and size of the impending event.

National seismic codes and zonations are based on seismic hazard estimates computed with the most suitable approach for the seismotectonic knowledge available (see McGuire, 1993). The first three of the above types of hazard map are very popular, while non-Poissonian probabilism, and its recent hybrid variation (Wu *et al.*, 1995), are mainly research topics. UNDR's GSHAP project (Giardini and Basham, 1993) has proposed the Cornell

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(1968) approach as the reference method for all countries where seismotectonic knowledge supports this approach.

Italy is one of the most seismically active countries in the European-Mediterranean region and, although it is a developed nation, earthquakes frequently cause extensive damage and victims (Belice 1968: 231 deaths; Friuli 1976: 978 deaths; Irpinia 1980: 2914 deaths). Geological and seismological studies have been undertaken here since the beginning of the present century and the state of knowledge can be considered good. Nevertheless, the national seismic zonation currently adopted is based on studies done in the Seventies using the historical probabilistic approach.

The aim of this paper is to present the results of the long project of hazard assessment of the Italian territory for updating the seismic zonation. This project follows the seismotectonic probabilistic approach and, consequently, moves Italy one step forward in the Muir-Wood (1993) classification. The paper focuses on those aspects strictly connected to seismic hazard assessment, and describes problems, solutions adopted and the final maps; earthquake catalogue preparation and the seismotectonic zoning are here only summarized, as they are the results of specific projects described elsewhere (Camassi and Stucchi, 1996; Scandone 1997; Meletti *et al.*, 1997). The basic assumptions of the Cornell (1968) approach are here ignored as well, because extensive documentation, also within the specific Italian context, is readily available (Algermissen and Perkins, 1976; Mayer-Rosa and Schenk, 1989; Peruzza and Slejko, 1993).

2. The Italian seismic code

Since Italy has repeatedly experienced destructive earthquakes, the various governments ruling parts of the territory have tackled the problem of preserving people and property from earthquakes (see also, Consiglio Superiore dei Lavori Pubblici Servizio Sismico, 1986). The first legislative measures were taken by the Bourbon government in Calabria after the 1783 earthquakes, which caused about 30000 deaths (Boschi *et al.*, 1995). Subsequently, the choice of sites for rebuilding, as well as construction standards, were considered by the laws and regulations issued by the Papal states after the 1859 earthquake in Norcia. After the unification of Italy, all previous regulations lapsed and the Italian state was unprepared to handle the situation after the 1883 earthquake which ruined all villages on Ischia island. The quake which destroyed Reggio Calabria and Messina on December 28, 1908, causing about 80000 deaths (Boschi *et al.*, 1995), was probably the strongest event in the Italian peninsula over the last ten centuries. Soon thereafter, the national seismic code was promulgated: it consisted of a list of the municipalities in Sicily and Calabria where technical rules for building, defined by Royal Decree, were applied. The seismic zonation was updated after each successive destructive earthquake simply by adding municipalities to the official list: it was, therefore, based only on the fact that a municipality had experienced damage from earthquakes since 1908, without any scientific analysis of Italian seismicity, and had the principal purpose of public aid (for more details see Petrini, 1991). In 1974, new legislative measures were promulgated (law 64/1974) defining the general criteria to follow in anti-seismic construction and delegating to mininsterial decrees the specific definition of the technical rules (issued in 1975) and seismic zonation: for this reason the law possesses an inherently dynamic character. The seismic zonation, intended as a list of regulated municipalities, is, therefore, established by decree and can be easily updated after a damaging earthquake (according to the old philosophy) or, better, when increased knowledge of Italian seismicity requires a revision of the zonation. Although the classified municipalities were inserted into two seismic categories according to the damage sustained, this distinction was rather fictitious.

After the 1976 Friuli earthquake, the regional public administration asked the scientific community to provide technical support for reconstruction of the villages destroyed: this can be considered the first urban intervention based on seismic hazard studies (Faccioli, 1979; Giorgetti *et al.*, 1980). Many different studies were devoted to Italian seismicity after the 1976 Friuli earthquake, with a cooperation among geologists, geophysicists, and engineers in the framework of the «Progetto Finalizzato Geodinamica» (PFG) of the «Consiglio Nazionale delle Ricerche» (CNR). The PFG project had the merit of fixing the state-of-the-art in geology and seismology at that time and of producing results of national importance. The most relevant products were the catalogue and the atlas of Italian earthquakes (Postpischl, 1985a,b) and the shakeability maps of Italy (Gruppo di Lavoro Scuotibilità, 1979; Petrini *et al.*, 1981). The latter was produced using the existing catalogue (Carrozzo *et al.*, 1973), a general attenuation relation (Iaccarino, 1973), and the theory of the extreme values (Gumbel, 1958) applied to macroseismic intensity as shaking parameter: as previously stated, it can be considered an example of historical probabilism. These maps were the basis of a CNR proposal for seismic zonation (see Petrini, 1980; Consiglio Superiore dei Lavori Pubblici Servizio Sismico, 1986; Petrini *et al.*, 1987), which was completely accepted by the Italian government following the 1980 Irpinia earthquake which caused about 3000 deaths (Boschi *et al.*, 1995), and it was translated into a series of decrees by the Ministry of Public Works between 1980 and 1984. The new seismic zonation considers a revision of the second category, where many municipalities which were not considered seismic before were inserted. In practice, the already classified municipalities were left in their old class (1st and 2nd category); the municipalities whose computed hazard was comparable to the already classified sites were inserted into the second category; in addition, a third category was defined for some municipalities of Southern Italy, where even minor shaking would be expected to produce severe damage.

3. The GNDT project for the revision of the present zonation

More than fifteen years have passed since the CNR's proposal for a seismic zonation, and research activity of the CNR's «Gruppo Nazionale per la Difesa dai Terremoti» (GNDT) in recent years has been oriented to two main goals: 1) a proposal for a new seismic zonation of the national territory, and 2) the definition of the methodologies to be used for seismic risk estimation and the testing of strategies for its reduction.

With reference to the first main goal, a global project of seismic hazard assessment in the Italian territory was defined for updating the national seismic zonation. This project consisted of three main tasks: compilation of an earthquake catalogue and a seismological database, preparation of the SZ map, and the hazard assessment by probabilistic methodologies. The final results were obtained and consigned officially in summer 1996 to the Civil Protection Department, which financed the project. The results will be considered by the Ministry of Public Works for use in legislation.

Although in the original project (see Slejko, 1992) different approaches to hazard evaluation (*e.g.*, Monachesi *et al.*, 1994) were envisaged, the final hazard assessment was done following the most robust approach available (Cornell, 1968) and represents a due and intelligent stage towards the national risk assessment. It is a due stage because it aligns Italy with the majority of the countries scientifically developed in engineering seismology: more sophisticated approaches have mostly only been applied in the United States (see McGuire, 1993). It is an intelligent stage because the project has been developed in a homogeneous way by facing and solving all the aspects of the chosen methodology. This project, which combines the use of a consolidated method with the realization of conventional products (*i.e.* a map of Peak Ground Acceleration (PGA) with 475-year return period, according to the seismic Eurocode EC8, Eurocode8-Part5, 1994), can thus be considered a good example of third generation hazard assessment.

We first present a summary of the evolution of the project itself. Then, while the details of the earthquake catalogue preparation and seismotectonic modelling will just be mentioned, a full description of the hazard computation will be given. During all the phases of the project, the code SEISRISK III (Bender and Perkins, 1987) with areal source setting was used.

3.1. *Preliminary phases*

The first results of the project were obtained in 1991 (Peruzza *et al.*, 1993; Slejko *et al.*, 1993; Slejko, 1996) using those products available in the early stages: the existing earthquake catalogue (compiled during the PFG project by Postpischl, 1985b) and a preliminary seismogenic zonation (ZS1) of Italy obtained by enlarging the seismotectonic model of the Apennines (Scandone *et al.*, 1992). After a simple aftershock removal (Slejko *et al.*, 1993), the completeness analysis of the catalogue for identifying the seismicity rates was based on historical evidence, and the Karnik (1969) relation was used for converting intensity into magnitude. The hazard results were computed in terms of both PGA and macroseismic intensity independently. The Sabetta and Pugliese (1987) relation was used for attenuating PGA, and the Grandori *et al.* (1987) relation was used for attenuating intensity with mean parameters preliminarily derived. Almost concurrently, the first results from the data produced by the GNDT (the earthquake catalogue NT2, Stucchi *et al.*, 1993, and the revision ZS2 of the previous seismogenic zonation) were obtained (Peruzza *et al.*, 1993; Slejko, 1995, 1996). A new relation (Rebez, 1994) calibrated on the NT2 catalogue data was defined for translating intensity into magnitude values. Completeness analysis and PGA attenuation relation were the same as in the previous stage. The third preliminary hazard assessment was done with a further updating of the earthquake catalogue (NT3) and the seismogenic zonation (ZS3), and with a revision of the intensity/magnitude relation. An analysis of the stationarity of the seismic process (Albarello *et al.*, 1995) was done to check the choices suggested by the historical analysis. Concerning the PGA results, the new attenuation relation for European earthquakes (Ambraseys, 1995) was used. On the other hand, for macroseismic intensity the parameters of the Grandori *et al.* (1987) intensity attenuation relation were computed from the intensity map of the typical earthquake for each SZ. It is worth noting how the hazard results have driven the joint work of catalogue updating and SZ revision up to the ultimate products used in the present, fourth, final stage.

3.2. *Earthquake catalogue and database*

Great effort in the GNDT project was given to the preparation of a new earthquake catalogue (NT4.1; Camassi and Stucchi, 1996) expressly designed for hazard purposes. The catalogue is completely new and has specific characteristics, such as for example the fact that it contains main events only. This differentiates it from the previous main parametric catalogue of Italy (Postpischl, 1985b) which was used as guide for the new one. This new catalogue is highly integrated with the new GNDT seismological database DOM4.1 (Monachesi and Stucchi, 1997), treating destructive events and consisting of about 37 000 macroseismic observations for about 10 000 different Italian localities. In the compilation of DOM4.1, each destructive event was studied from the historical point of view, and with particular effort given to analysing contemporary sources. This phase of the study led to a thorough revision of macroseismic intensity assessment, especially compared to intensity estimates reported in the previous Italian catalogue, with a general tendency to decrease the values of epicentral intensity as a consequence of an accurate historical interpretation of the ancient descriptions and a rigorous, homogeneous, application of the macroseismic intensity scale. During this operation, many false events (about one hundred) reported in the PFG catalogue (Postpischl, 1985b) were identified: they were mainly caused by errors in source reading or interpretation, and in event duplication during transfer of information from one catalogue to another. Since it is impossible to retrieve information on low magnitude seismicity from historical sources, it was taken, after an accurate revision, from existing parametric catalogues, but these records mainly come from the recent instrumental period. Existing parametric catalogues were used for the events located on the borders, which could also affect the hazard estimates in the Italian territory.

The GNDT catalogue (see description in Camassi and Stucchi, 1996) contains at present 2421 records of earthquakes in the time window 1000-1980, with epicentral intensity I_0 larger than, or equal to, V-VI Mercalli-Cancani-Sieberg (MCS, see, *e.g.*, Console and Gasparini, 1977), or magnitude larger than, or equal to, 4.0 (fig. 1). The catalogue considers all earthquakes whose epicentres are included in a polygon comprising the SZ's of interest for hazard assessment in Italy. The catalogue is freely available for scientific purposes at the

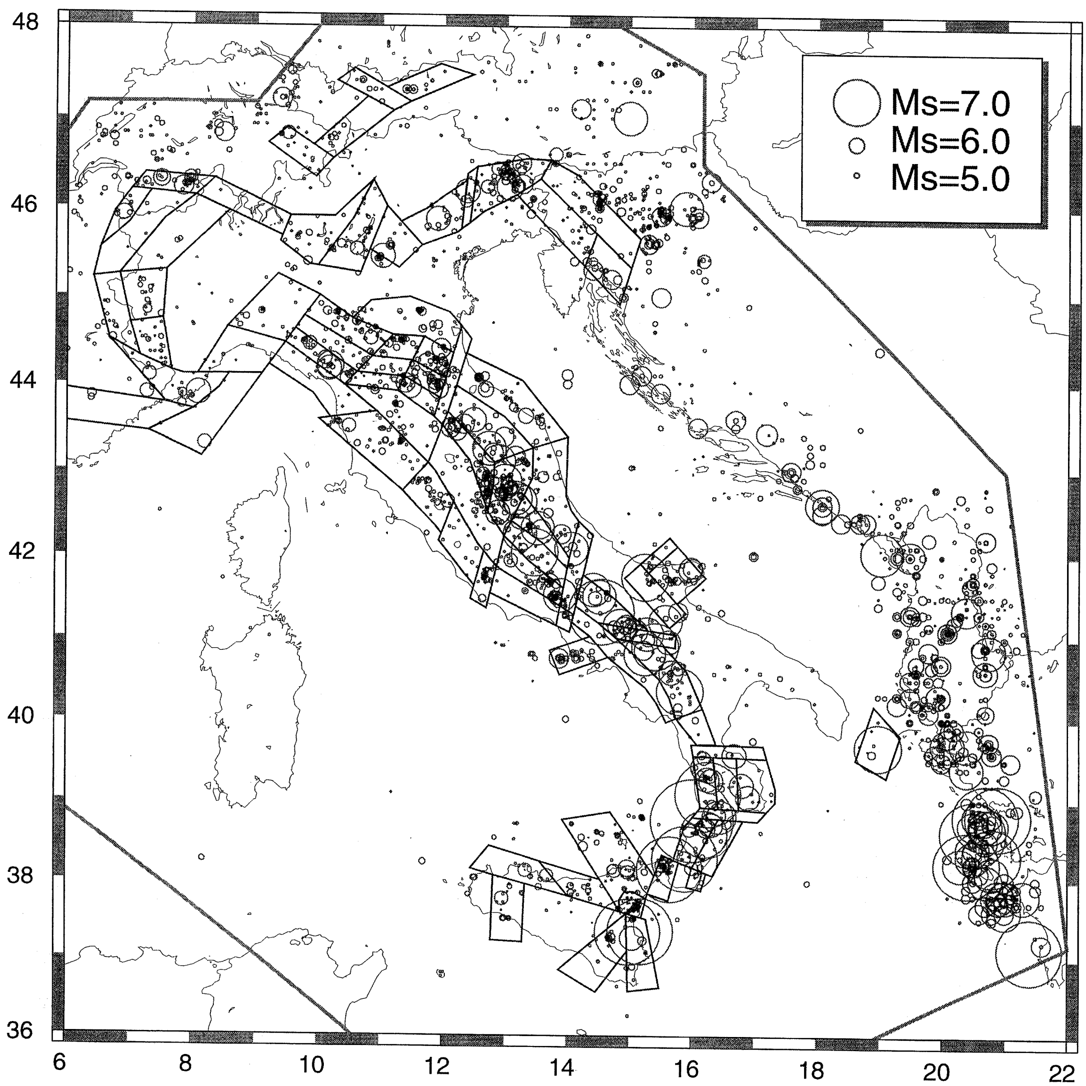


Fig. 1. Epicentre distribution of earthquakes in the GNDT catalogue (Camassi and Stucchi, 1996). The external polygon encloses the area covered by the catalogue, the inner ones represent the SZ's.

official GNDT web site http://emidius.itim.mi.cnr.it/NT.html. The site also contains a description of the catalogue, format, compiling modalities, characteristics, bibliography and suggestions for users.

It is important to note that the epicentral parameters (coordinates and intensity I_0) of destructive events ($I_0 \geq$ VII-VIII MCS) are not directly linked to the maximum effects only, but are computed in such a way as to best reproduce all the site intensities observed during the earthquake. Thus, by properly attenuating the epicentral intensity, a macroseismic field as similar as possible to that actually observed can be obtained. For all these destructive events the hypocentral parameters were assigned in a homogeneous way: in cases where both macroseismic and instrumental hypocentral data were available, the macroseismic data were given higher priority. As the seismogenic zonation of Italy is strictly connected to the GNDT catalogue, every record of the catalogue is assigned to an SZ. The attribution of an earthquake to a specific SZ is generally geographic (the earthquake is inside the SZ) but sometimes (about 90 records) seismotectonic interpretation suggests assigning the event to another SZ.

One of the main targets of the GNDT catalogue was to be the data base for hazard estimates; the authors, therefore, decided to compile the value of a reference magnitude for each event in the catalogue. The type of magnitude used is the surficial wave magnitude M_s. The principal reasons for this choice of M_s are its availability since the beginning of this century, and the specific use of this type of magnitude in the principal attenuation relations for the European area available in the literature. The M_s magnitude values contained in the catalogue came from the literature, or were derived by *ad hoc* relations (in Camassi and Stucchi, 1996) from other types of magnitude. For all the events of the historical period characterized by the availability of macroseismic intensity only, the magnitude estimation was derived from a tabular I_0/M_s conversion (Camassi and Stucchi, 1996) prepared using the macroseismic intensities of the catalogue itself and the related M_s values. The tabular aspect of the conversion (to each value of intensity there corresponds a «suggested» value of magnitude) was chosen to safeguard the specific nature of I_0 without forcing it with an analytical relation.

3.3. *Seismotectonic modelling and seismogenic zoning*

The innovative aspect of the present seismogenic zoning is that it is based on strong constraints defined by kinematic evolutive modelling (Scandone *et al.*, 1992; Cinque *et al.*, 1993; Patacca *et al.*, 1993) instead of just following the neotectonic structural features and epicentral distribution; this is a procedure that is rarely used in the seismotectonic literature. Kinematic modelling consists in the definition of a logical link between the areas under stress and the volume balance (the consumed has to be compensated by the created), in respect to some established boundary conditions. These are essentially two: the opening of the Southern Tyrrhenian Sea, and the indentation of the Adriatic microplate in the Western Alps. In the Western Alps the continental collision is explained with a geometry that puts the European plate under the Adriatic plate, while the opposite situation is expected in the Apennines; this is confirmed by the thrust belt migration (westwards in the Western Alps and eastwards in the Apennines) and by the origin of the cover nappes.

The seismogenic zoning does not address the individual faults responsible for the long-lasting earthquake catalogue of Italy: this is mainly due to the geologic complexity of the country, but also to the behaviour of the structures, in terms of uncertainties in their location and low activity rate, as suggested from paleoseismological studies (*e.g.*, Michetti, 1994; Pantosti and Valensise, 1995). The SZ's in the present model represent, therefore, the surficial projection of one or more seismogenic structures having similar kinematic behaviour and rupture mechanisms; they jointly define some kinds of mega-structures Alps- and Apennine-oriented, with transverse transfer zones. The model was modified during the project as new results became available; in its last version (ZS4, see the GNDT web site) it consists of 80 SZ's (see fig. 2). According to their behaviour, the SZ's are interpreted differently (*e.g.*, as compressive, extensive, volcanic). Until now, only the volcanic sources have been subjected to particular treatment as regards the propagation properties for PGA, while most of them have a characteristic attenuation relationship for the macroseismic intensity (grey areas in fig. 2), as will be explained later. Uncertainties in the location of the source are taken into ac-

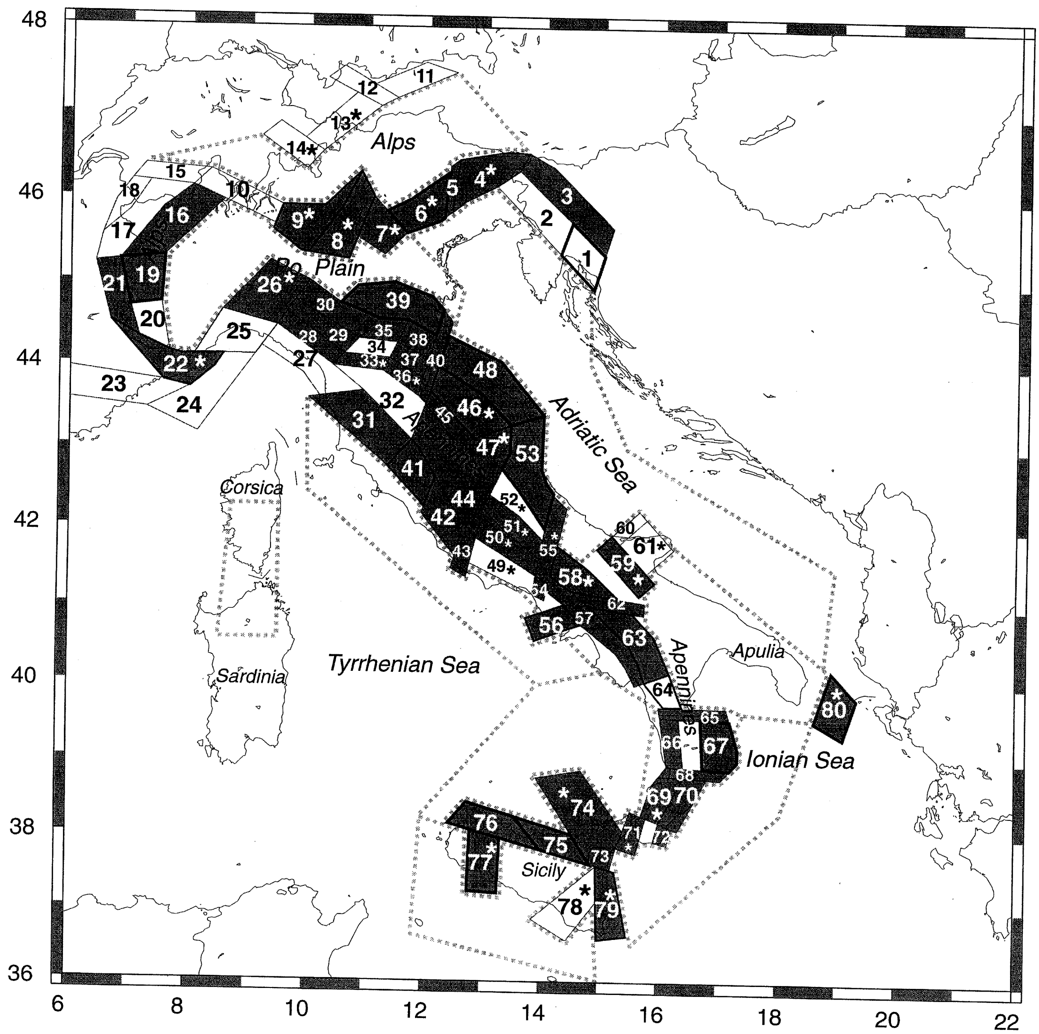


Fig. 2. Seismotectonic model of Italy (Scandone, 1997); numbers indicate the SZ code. Asterisks indicate the SZ's for which the maximum magnitude has been introduced; grey areas mark the sources having a peculiar macroseismic intensity attenuation relationship. The thickness of the line represents the uncertainty in source location introduced in the hazard computation: thin line for 1 km; medium line for 2 to 9 km (*e.g.*, SZ 8); thick line for 10 km or more (*e.g.*, SZ 6). Background SZ's are delineated by grey dotted lines.

count; as most of the SZ's are adjacent, the mislocation of the boundaries is applied inwards, leaving therefore a source of similar shape but smaller in size, which will be called the nucleus hereafter. In fig. 2 the SZ's with border uncertainties are marked with a thick border. Finally, the SZ's are assumed to be homogeneous in their interiors, as the probabilistic treatment requires.

Figure 1 shows that for Italy almost all the earthquakes fall into an SZ. The scattered seismicity remaining outside the actual 80 SZ's was collected into 9 background zones for hazard computation (see fig. 2). These zones were designed to surround Italy and most of them collect the seismicity in the sea. The first background zone is a strip between the SZ's in Northern Italy (from SZ 4 to SZ 15) and the SZ's in Switzerland and Austria (from SZ 11 to SZ 14). The second background zone is the area of the Po plain. A further zone belongs to the Adriatic Sea, two other zones to the Apulia area and the Ionian Sea, another one to the sea south of Sicily, and two more to the Tyrrhenian Sea. The last background zone is a small area from Southern Corsica to Northern Sardinia. It is not large enough to be considered a true background zone: it is not designed upon seismotectonic constraints but only on the basis of the seismicity distribution, which is too poor for defining an actual SZ.

4. PGA hazard assessment

Seismic hazard maps in PGA have been produced worldwide since the late Seventies, when the Cornell (1968) approach was translated into computer codes (*e.g.*, Algermissen *et al.*, 1976; McGuire, 1976), and offer a traditional representation of earthquake hazard. This kind of information is commonly used in urban planning, definition of new building specifications and, sometimes, for retrofitting old constructions. PGA is frequently used as a physical quantity in building projects, when a more complete hazard parameter is not available. This more complete hazard parameter can be identified in the spectral acceleration (or velocity), which gives the expected shaking at different frequencies. From the theoretical point of view, there is no further difficulty in producing spectral maps, but from the practical point of view, data suitable for constructing spectral attenuation relations are rarely available.

4.1. *Seismicity rates*

The characteristic seismicity of every SZ is given as the number of earthquakes in each magnitude class counted on the basis of the completeness interval. The shaking at the site is computed from the discrete summation of the individual contributions given by each magnitude class seismicity rate, without introducing the condition of exponential distribution for magnitude as requested in the original Cornell (1968) approach. The possibility of using intervallic seismic rates (number of events in 100 years for each magnitude class), so avoiding interpolation of the data with the Gutenberg-Richter (GR) relation, leads to two main advantages: firstly if different return periods are considered the hazard assessment really changes as a function of varying seismic release over time, while if a GR approach is adopted different return periods produce only a homogeneous raising (or lowering) of values; secondly it is thus possible to adequately describe those SZ's which suggest a «characteristic earthquake» behaviour. The latter observation comes from the limited spatial extent of some Italian SZ's which approaches that of the real source size. The disadvantage consists in the direct influence of possible catalogue errors and lacunae in the hazard computation: fig. 3, for example, shows fluctuations in the seismicity rates where the richest are fed predominantly by macroseismic data.

In previous hazard estimates computed during the GNDT project (see *e.g.*, Peruzza *et al.*, 1993; Slejko, 1996) the time periods used to compute the seismicity rates were defined on an historical basis; *i.e.*, they were the periods when data collection quality for natural phenomena were thought to be homogeneous. In this final phase, a test on the stationarity of the

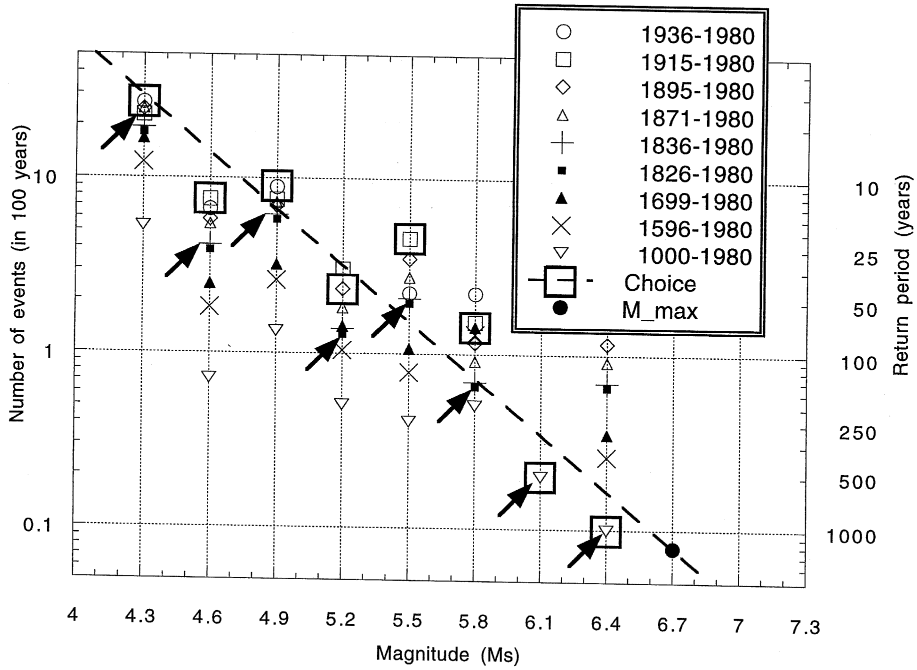


Fig. 3. Seismicity rates and maximum magnitude for SZ 4; different time periods are plotted (see legend); arrows indicate the rates suggested from the completeness analysis, large open squares the selected ones. The line is the Gutenberg-Richter interpolation, on which the maximum magnitude (M_{max}) is evaluated.

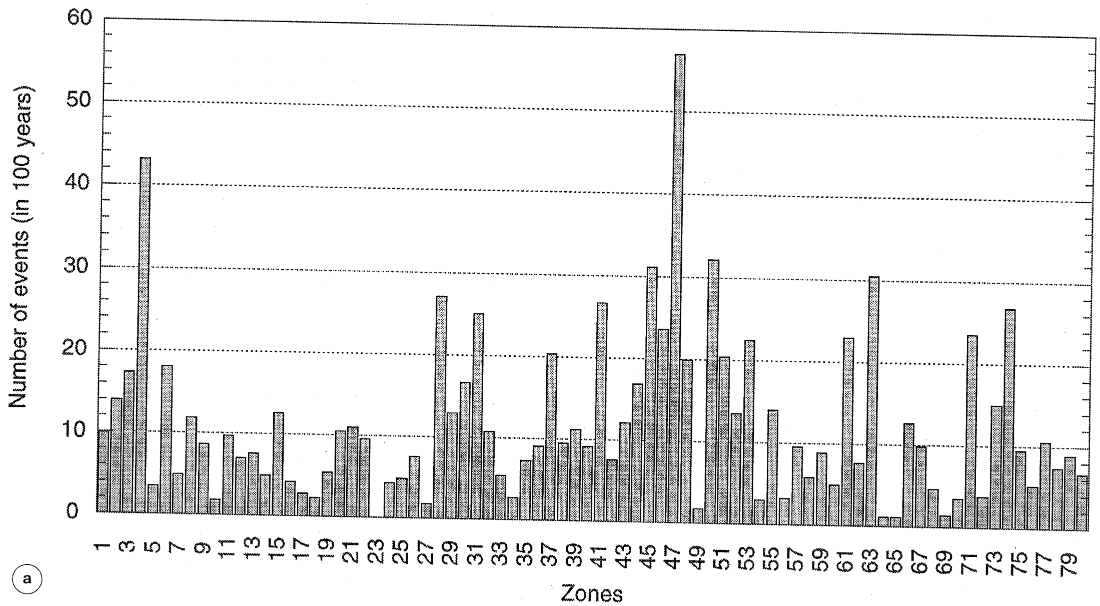
earthquake catalogue was introduced to verify that the periods of data collection identified by the historical analysis were homogeneous (Albarello *et al.*, 1995). It is clear that stationarity and completeness are not synonymous, and the test shows variations in seismicity regardless of fluctuations in the seismic cycle. Nevertheless, the test provides indications to support historically based choices. The analysis of stationarity is based on the Cox and Stuart test (Rock, 1988), where a mobile window investigates the variation, at some confidence level, of the earthquake number in time for each magnitude class (sampled at 0.3 degrees). The GNDT catalogue was divided into four sub-catalogues (Northern, Central, Southern Italy, and Sicily), and for each of these sub-catalogues the periods of stationarity/completeness were identified. They are used to compute the seismicity rates by counting the earthquake number in each magnitude class during those time periods, and then normalising the number to 100 years.

The procedure for adequately determining the seismicity rate was thus established on an objective basis. In fact, the completeness period of each magnitude class identifies the seismicity rate and, consequently, the related return period (T = 100 years / seismicity rate). The highest seismicity rate related to a time period not shorter than the return period computed with respect to the completeness interval is chosen. This procedure warrants a cautious choice based on the analysis of the whole catalogue. An example of this procedure is given in fig. 3 (data refer to SZ 4), where the rates computed for nine different time periods are marked with different symbols, the rates suggested by the stationarity test are marked by arrows, and the final choices are marked by large open squares. On the right side of the plot (secondary *Y* axis), return periods are reported: this is another way to read the seismicity rates of the left side (standard *Y* axis). For the magnitude classes from 4.6 to 5.5 in fig. 3, the suggested number of events has been changed in favour of a rate related to a shorter (but richer in earthquakes) period in agreement with the return period indicated by the stationarity test. For example the suggested period for the class 5.2 was 1836-1980 and the seismicity rate for this period is 1.38 which corresponds to a return period of about 73 years. According to this return period it is possible to choose the shorter period 1895-1980 (longer than 73 years) but not, for example, the period 1915-1980 (65 years) which is too short. The situation for magnitude class 5.5 is different because the suggested period is 1826-1980 and the number of events is 1.94, with a corresponding 52 year return period. This return period allows the selection of the value for the shorter 1915-1980 period. The other kind of change is due to the possibility of obtaining a higher, and more cautious, rate from a period longer than that showing completeness (*e.g.*, magnitude class 5.8): this period, although incomplete, is richer in events than the complete period. The indicated period for the 5.8 class is 1826-1980, 0.65 events (return period 154 years), so it is impossible to select a shorter period as above, but we can select the longer period 1699-1980 which reports a higher number of events.

These adjustments, always conservative, are related to the particular seismic behaviour of the SZ's, while the suggested completeness period was computed grouping several zones and cannot adapt to every case. Several tests performed have shown that the contribution of these changes in the seismic rates leads to a small variation in the final hazard assessment. The described procedure was followed strictly for all SZ's. For SZ 64, where paleoseismological investigations revealed the traces of a strong earthquake in the late Middle Ages, a magnitude 6.6 earthquake in the year 1200 was introduced into the NT4.1 catalogue (Camassi and Stucchi, 1996) for hazard purposes. This event is not mentioned in historical sources and, therefore, is missing in all previous earthquake catalogues.

Another important point for seismicity definition is the maximum magnitude value considered in input. The geological complexity of Italy and the present relatively incomplete knowledge of seismotectonic processes prevent a clear assignment of seismicity to specific tectonic structures. Moreover, it is impossible to assign one or more faults to all 80 SZ's. For these reasons it was decided to introduce a maximum magnitude for some SZ's on the basis of the catalogue seismicity only. The time span covered by the Italian catalogue (ten centuries) supports the idea that most/all the maximum magnitudes occurred during this time period. On the contrary, paleoseismological investigations revealed strong earthquakes also in presently defined low seismicity areas (Pantosti *et al.*, 1993). Thus, it was decided to follow an objective procedure. The chosen rates (large open squares in fig. 3) were fitted by the least-squares regression to the GR relationship (dashed line in fig. 3); the extrapolated rate for a magnitude greater by one step unit (0.3 in our case) was considered as maximum magnitude if it involved a mean return period between 1000 and 3000 years (closed circle in fig. 3 at magnitude 6.7). This time span is larger than the time window of the catalogue and, therefore, it involves events possibly missing in the catalogue. On the other hand, it is not too long to account for events with a very low rate. These criteria for assigning the maximum magnitude are satisfied only by 28 SZ's (35%). The zones for which the maximum magnitude was computed are indicated by an asterisk in fig. 2. The maximum magnitude rate generally has a limited influence on hazard estimates because of its low value (return period longer than 1000 years). This is not true for a few SZ's, where seismicity is peculiar or the catalogue contents for low magnitudes are poor, and the GR relationship displays a very low *b*-value and, consequently, the earthquake rate of the maximum magnitude is close to one event in 1000 years.

Figure 4a,b shows the contributions of low and high seismicity to the hazard assessment



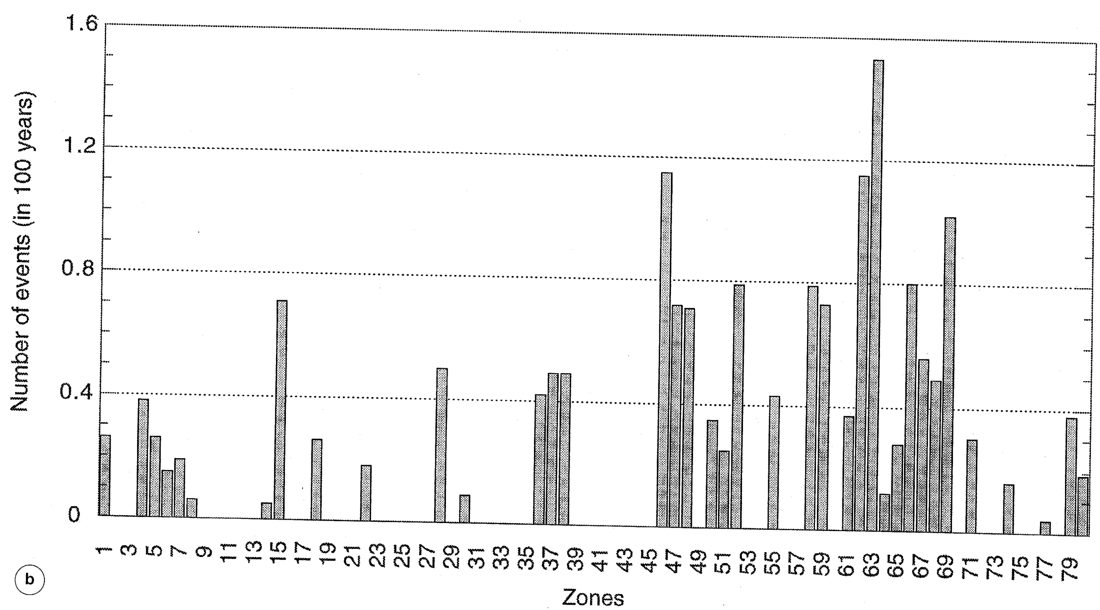


Fig. 4a,b. Seismicity rates expressed in magnitude for the SZ's: a) low seismicity, in the $4.2 \leq M_s \leq 5.0$ range; b) high seismicity, for $M_s \geq 6.0$. Rates for SZ 23 were discarded in the final elaboration as not contributing significantly to hazard in Italy.

for each SZ. The first part (fig. 4a) shows the cumulative rate (number of events normalized to 100 years) in the magnitude range $4.2 \leq M_s \leq 5.0$. The number was obtained by simple summation of the individual rates. It can be seen that SZ 4 and SZ 47 display the maximum cumulative rates, with more than 40 events in 100 years. Figure 4b gives information on the high-end magnitude contribution, showing the cumulative rate for $M_s \geq 6.0$. The highest value is reached by SZ 63, followed by SZ 46, SZ 62, and SZ 69. A comparison of the two graphs clearly shows the different behaviours of the SZ seismicity: some releasing mainly low events (SZ 4), some high (SZ 69), and some both (SZ 63).

4.2. *PGA attenuation relations*

The attenuation relation to use in seismic hazard assessment can be chosen from among those of general or of regional validity. In our case PGA attenuation relations of European validity do exist (*e.g.*, Ambraseys, 1995) as well as Italian attenuation relations (Sabetta and Pugliese, 1987; Tento *et al.*, 1992). Considerations of the applicability range of these relations drive the choice.

Ambraseys (1995) calibrated different relations on 1260 strong-motion records for 619 European earthquakes in the magnitude (M_s) range 2.0-7.3, many of which (24%) occurred in Italy. The Sabetta and Pugliese (1987) relation was calibrated on 95 strong-motion records for 17 earthquakes in the magnitude (M_s for values 5.5 or larger, and M_l for values smaller than 5.5) range 4.6-6.8 which occurred in Italy. The Tento *et al.* (1992) relation can be considered as an update of the Sabetta and Pugliese (1987) relation, and was calibrated on 137 strong-motion data for 40 earthquakes in the M_l magnitude range 4.0-6.6 which occurred in Italy. Their standard deviation (σ), which quantifies the uncertainty in the relation, is (in log units) 0.24 for the Ambraseys (1995), 0.19 for the Sabetta and Pugliese (1987), and 0.29 for the Tento *et al.* (1992) relations. It should be pointed out that σ generally increases as the data set used increases. The behaviour of the first two of these relations is slightly different: the Sabetta and Pugliese (1987) relation gives higher PGA values for strong events ($M = 6.9$), while the Ambraseys (1995) relation gives higher PGA values for medium magnitude events ($M = 4.7$, see fig. 5). Choosing between them is not easy: in the GNDT project, preference was given to the Ambraseys (1995) relation because it is calibrated on a wider strong-motion data set, and because it applies over a wider magnitude range. In particular, the relation obtained for the magnitude range 4.0-7.3 (830 records of 334 earthquakes) was used in the computation. The Sabetta and Pugliese (1987) relation was used only for pointing out the differences dependent on attenuation.

As the Sabetta and Pugliese (1987) relation refers to two different kinds of magnitude according to the size of the earthquake, the M_s magnitude from the catalogue was converted into M_l using the GNDT relation (Camassi and Stucchi, 1996) when necessary. Both attenuation relations were extrapolated to values lower than their threshold values when necessary, and the Sabetta and Pugliese (1987) relation needed to be extrapolated also for high values.

The Ambraseys (1995) relation is defined for distance from the fault, although only for large magnitudes was it possible to compute such distances, which were otherwise substituted by the epicentral distance. The Cornell (1968) approach, in the Bender and Perkins (1987) formulation, computes the hazard at each site of the study region by discrete summation of the individual contributions from the mass centre of the elementary areal cells in which the SZ is subdivided. This distance is rigorously neither the epicentral distance nor that from the causative fault, but in practice can be assumed to be equal to either.

The Ambraseys (1995) relation applies to an average soil while the Sabetta and Pugliese (1987) one contains two parameters accounting for the specific kind of soil (rock, shallow or deep alluvium).

Both relations are azimuth independent and do not consider the intrinsic differences of the SZ tectonic regime (compressional, tensile, transcurrent, volcanic, etc.). The available data

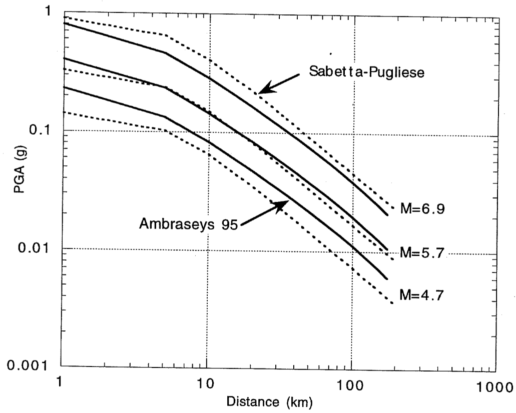


Fig. 5. Horizontal PGA *versus* distance for three magnitude levels: full lines refer to Ambraseys (1995), dotted lines to Sabetta and Pugliese (1987). Rocky soil conditions are always used.

(mainly macroseismic) suggest, on the contrary, higher attenuation at least in the volcanic SZ's. It was thus decided not to consider σ when computing the hazard contribution from the three SZ's 41, 43, and 54. For the two further volcanic SZ's, 56 and 73, a fictious σ equal to half that of the considered relation was taken. The original σ was considered for all the remaining SZ's.

4.3. *Results*

As final results, some of the seismic hazard maps in terms of PGA calculated for the 100- and 475-year return period are presented here. These two periods are conventionally used to represent the hazard standards for ordinary buildings: in particular T = 100 years corresponds to 90% non-exceedance probability in about 10 years, while T = 475 years is the reference used in the Eurocode EC8, and corresponds to 90% non-exceedance probability in 50 years. Computation of the final maps was done over a $0.05° \times 0.05°$ grid, and PGA is given in g (gravity acceleration), the contouring interval being 0.04 g.

The first seismic hazard map (fig. 6; if not explicitly cited, the attenuation relation used is that of Ambraseys, 1995) shows the PGA with 100-year return period without taking into account the attenuation σ, and fig. 7 shows again PGA related to the same return period but with σ. The hazard areas for both the maps are the same, but the maximum values reached in fig. 6 are in the range 0.12-0.16 g, while in fig. 7 the same areas reach one higher class (0.16-0.20 g), and inside these areas there are some zones of 0.20-0.24 g marked in light green. Going from south to north, the first important area is the Messina Straits (near the town of Reggio Calabria), where PGA values larger than 0.12 g (fig. 6) and 0.20 g (fig. 7) are reached. Northwards we find similar important areas near Potenza and between Perugia and L'Aquila. Another maximum lies north-east of Firenze (and south-east of Bologna), always with values larger than 0.20 g (fig. 7); and the same acceleration is reached also in a very narrow area between Genova and Firenze. The last important area is located in the northeasternmost sector of the Alps, north-west of Trieste.

The seismic hazard maps for a 475-year return period without (fig. 8) and with σ (fig. 9) were prepared according to Eurocode EC8. The general increase in PGA values expected for the increased time period is not homogeneous over the area (compare fig. 8 with fig. 6): there are higher values in Southern Italy, as high as 0.28 g near Campobasso, Potenza, and along the Calabrian arc, where a spot north of Reggio Calabria reaches values as high as 0.28-0.32 g. Figure 9 is the final hazard map for the Italian territory. Starting from the north, the highest values (larger than 0.36 g) occur in Northeastern Italy, as well as in the area between Bologna and Firenze, the area between Perugia and L'Aquila, a small area south-west of Campobasso, the zone near Potenza, and the Calabrian Apennines. Several other areas exceed 0.32 g (in red). By introducing σ, a homogeneous increase in the expected ground motion is not obtained (see fig. 8), but other areas are pointed out. We maintain that this effect is related to the high medium magnitude seismicity rates (5.0-6.0) of some of the large SZ's, as in the cases of SZ's 4, 34, and 47. It should be remembered however that the

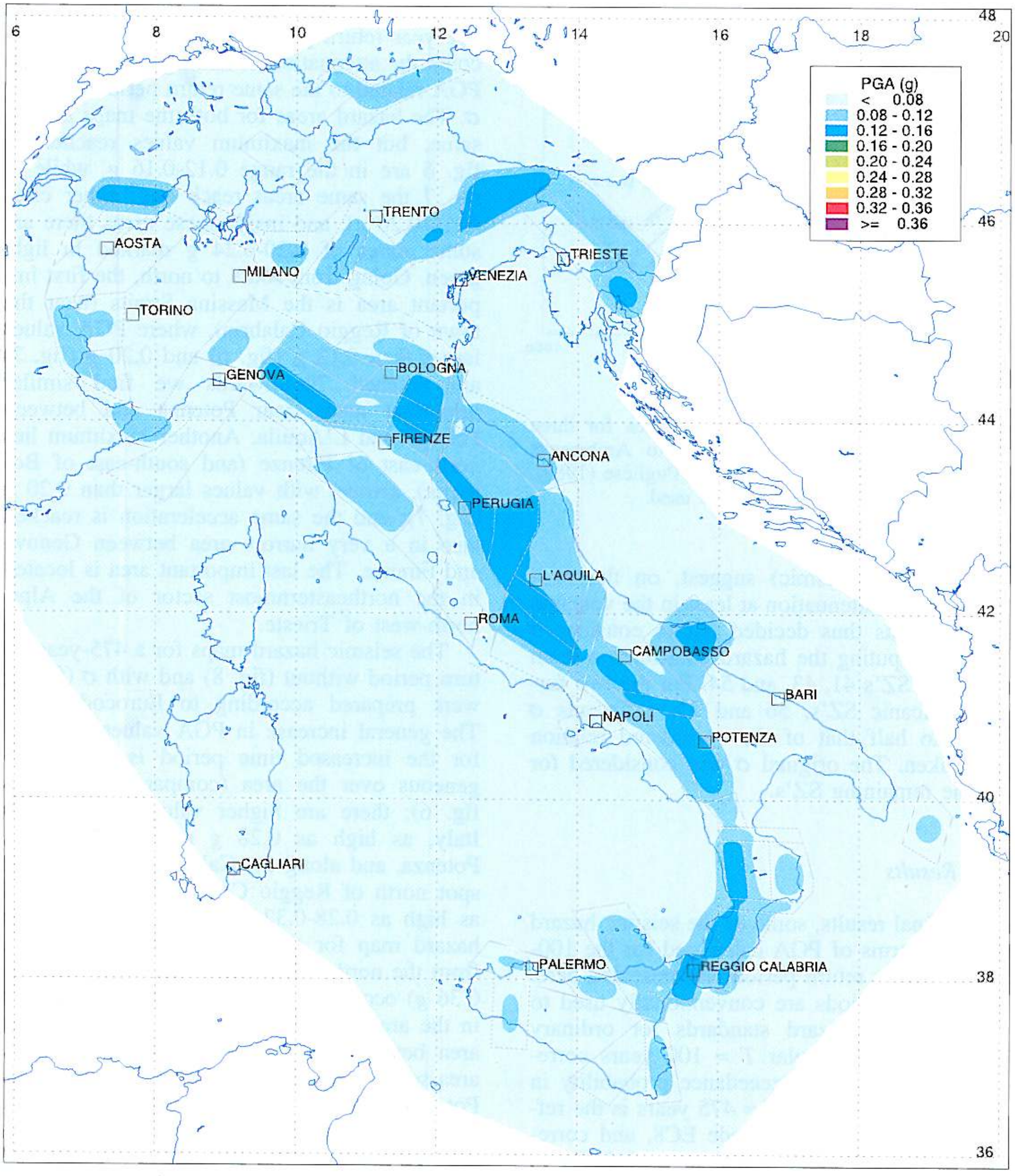


Fig. 6. Horizontal PGA (expressed in g) with 100-year return period; Ambraseys (1995) relationship is considered, without the use of σ in attenuation.

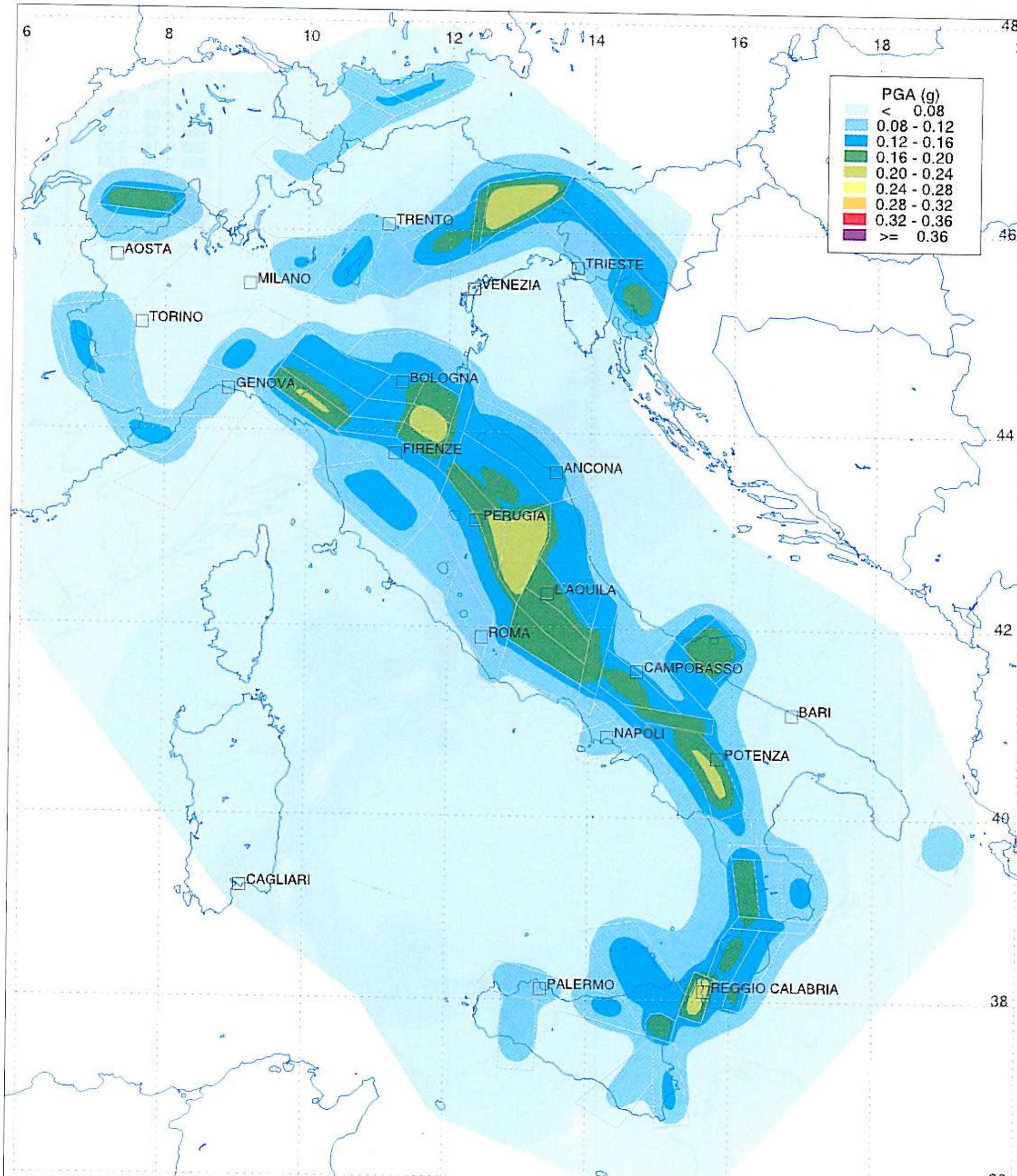


Fig. 7. Horizontal PGA (in g) with 100-year return period; Ambraseys (1995) attenuation relation with σ.

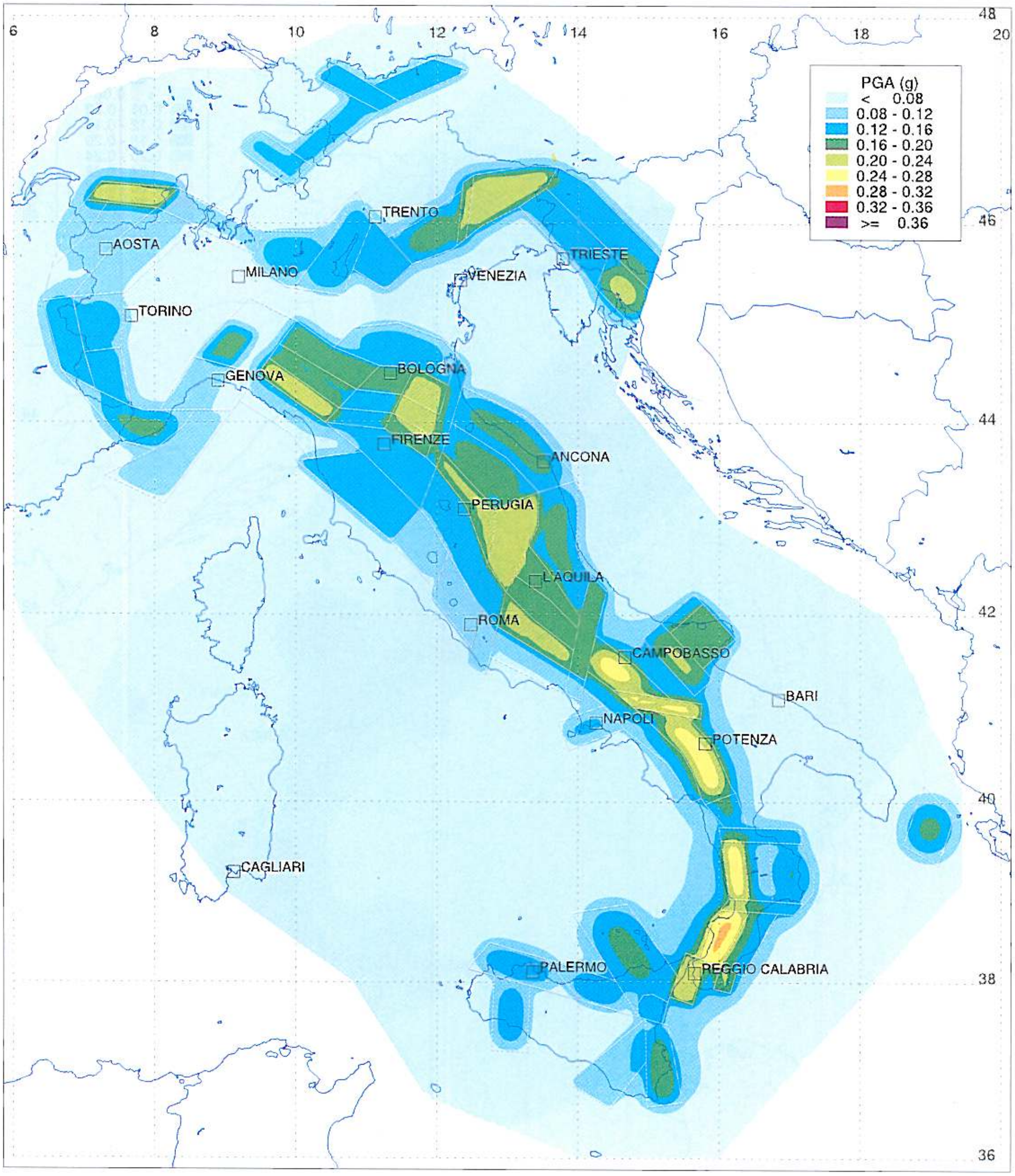


Fig. 8. Horizontal PGA (in *g*) with 475-year return period; Ambraseys (1995) attenuation relation without σ.

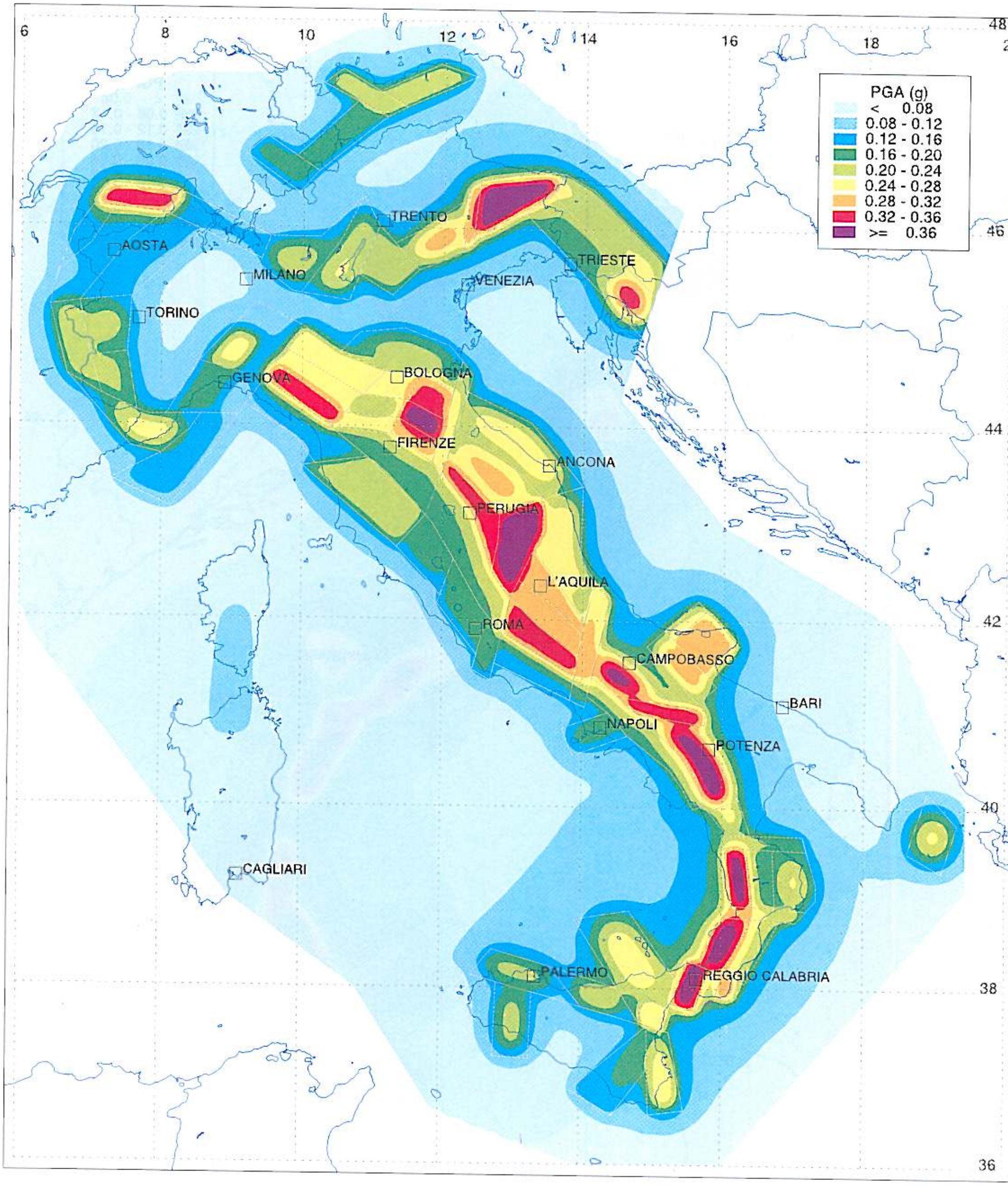


Fig. 9. Horizontal PGA (in g) with 475-year return period; Ambraseys (1995) attenuation relation with σ.

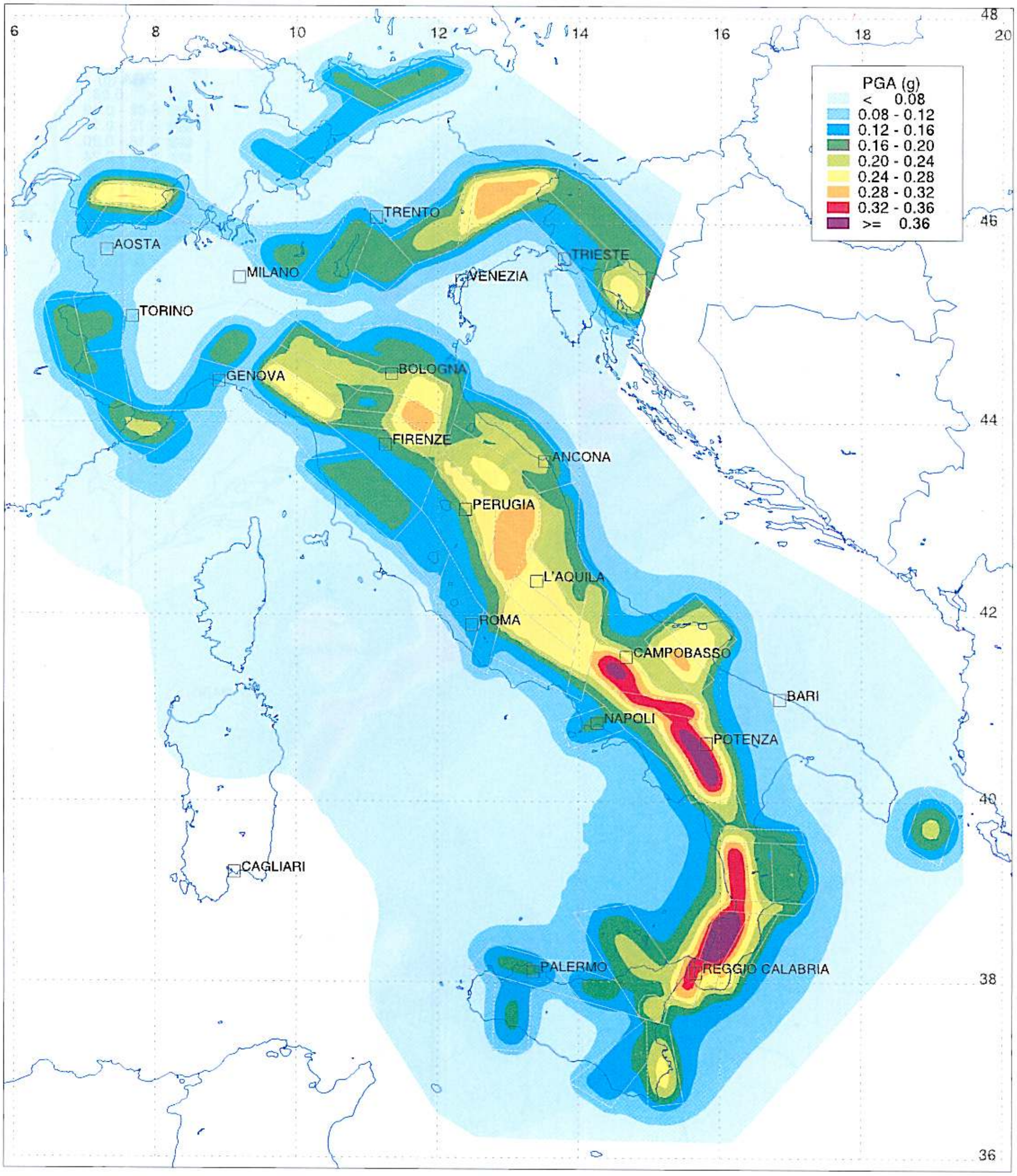


Fig. 10. Horizontal PGA (in g) with 475-year return period; Sabetta and Pugliese (1987) attenuation relation for rock with σ.

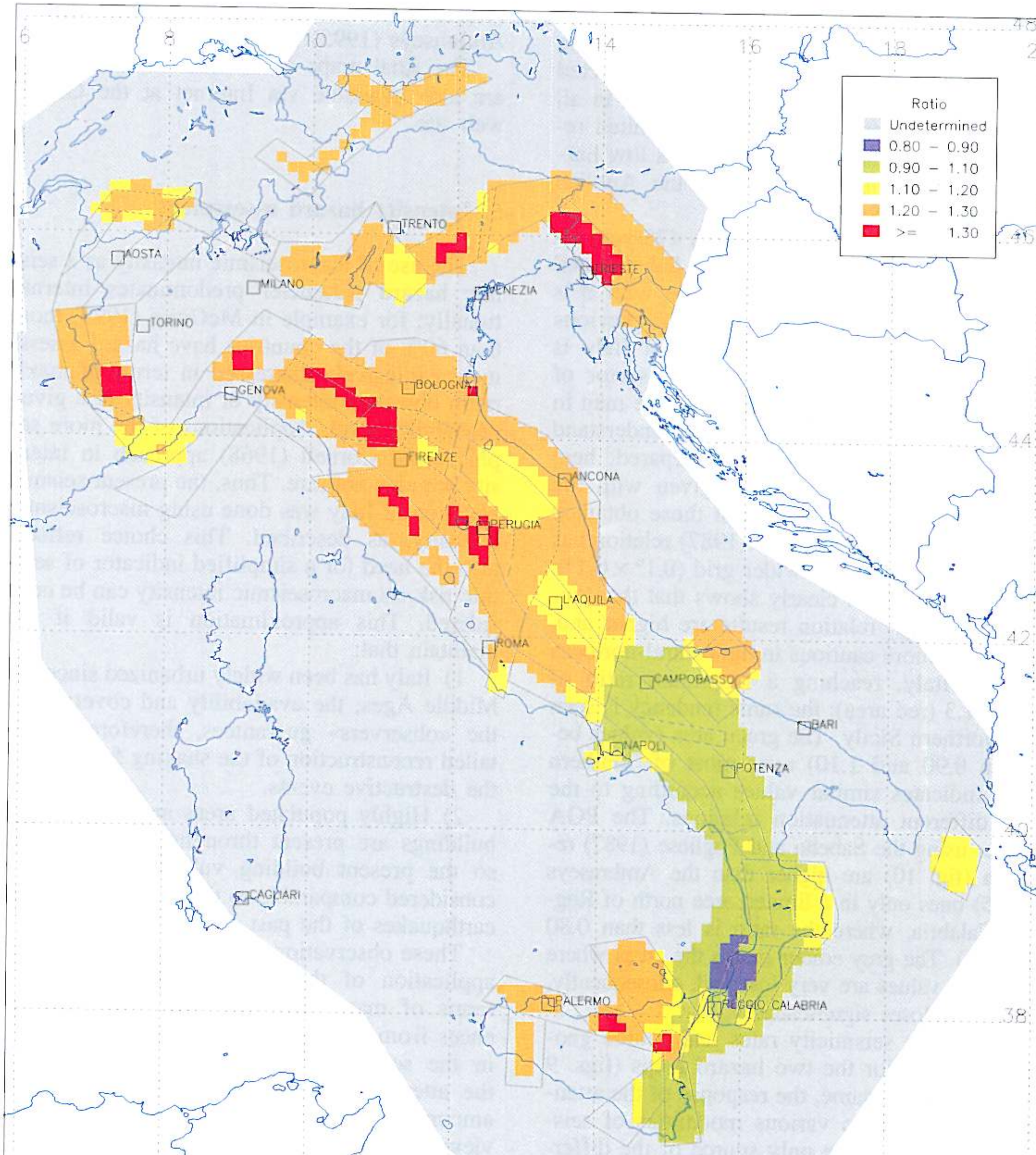


Fig. 11. Influence of attenuation relationship used on the hazard results: the ratio between the PGA's at 475-year return period for the two models is mapped (Ambraseys, 1995, for average soil of fig. 9 and Sabetta and Pugliese, 1987, for rock of fig. 10); grey area indicates very low PGA values, with consequent loss of meaning of their ratio.

differences between colours in the PGA scale is small (0.04 g) and often leads to misleading conclusions. The highest hazard is expected near Potenza, with 0.39 g. It is evident in all the maps presented here that only limited regions of the national territory have a low hazard: for example the Po plain, the Apulian peninsula, and Sardinia.

In fig. 10 the hazard map with 475-year return period, obtained using the Sabetta and Pugliese (1987) attenuation relation with σ is shown. The good agreement with the previous map (fig. 9) in the southern part of Italy is easily seen. In the central-northern sector of Italy, on the contrary, the values of the map in fig. 10 are much lower. To better understand these differences, fig. 11 was prepared; here the ratio between the results given with the Ambraseys (1995) relation and those obtained by the Sabetta and Pugliese (1987) relation has been computed over a wider grid ($0.1° \times 0.1°$). This map (fig. 11) clearly shows that the Ambraseys (1995) relation results are higher and, therefore, more cautious in the central-northern part of Italy, reaching a maximum ratio of about 1.3 (red area); the same tendency is seen for Northern Sicily. The green area (values between 0.90 and 1.10) over most of Southern Italy indicates similar values according to the two different attenuation relations. The PGA values using the Sabetta and Pugliese (1987) relation (fig. 10) are higher than the Ambraseys (1995) ones only in a limited area north of Reggio Calabria, where the ratio is less than 0.80 (fig. 11). The grey colour marks the areas where the PGA values are very low and, consequently, their ratio loses significance.

Since the seismicity rates and source geometries used for the two hazard maps (figs. 9 and 10) are the same, the response of the attenuation relations to various modalities of seismicity release is the only source of the differences in the PGA values. The higher values north of Reggio Calabria are due to the effects of the Sabetta and Pugliese (1987) relation on the high magnitude seismicity there. In Central-Northern Italy, on the contrary, medium magnitude seismicity is emphasized by the Ambraseys (1995) relation. It must be pointed out, furthermore, that the Sabetta and Pugliese (1987) relation refers to rock whereas that of Ambraseys (1995) to an average soil.

The final maps of seismic hazard in Italy are also available via Internet at the GNDT web site.

5. Intensity hazard assessment

The use of macroseismic intensity as a seismic hazard parameter predominates internationally; for example in McGuire (1993) more than 60% of the countries have hazard assessment exclusively expressed in terms of maximum observed intensity or intensity at a given probability level. Applications of the more sophisticated Cornell (1968) approach in intensity are also not rare. Thus, the present seismic zonation of Italy was done using macroseismic intensity, as described. This choice reflects also the need for a simplified indicator of seismic risk, as macroseismic intensity can be considered. This approximation is valid if we maintain that:

1) Italy has been widely urbanized since the Middle Ages; the availability and coverage of the «observers» guarantees, therefore, a detailed reconstruction of the shaking for most of the destructive events.

2) Highly populated areas and low quality buildings are present throughout the country; so the present building vulnerability can be considered comparable to that for the strongest earthquakes of the past.

These observations suggest using a specific application of the probabilistic approach in terms of macroseismic intensity. The differences from the traditional use of PGA consist in the seismicity rates expressed in I_0, and the attenuation relationships. Thus, the huge amount of macroseismic data, collected and reviewed in the framework of the GNDT project, was reinterpreted with a specific hazard-oriented procedure (see the section devoted to the earthquake catalogue, and Corsanego *et al.*, 1997). This implies the adoption of earthquake epicentral parameters derived directly from original macroseismic data sets, in conjunction with the attenuation relationships, to reproduce the damage distribution. Using macroseismic intensity, the seismic hazard results depend critically on the adopted attenuation relationship; the propagation characteristics derived from the Italian macroseismic data sets are sometimes so peculiar that the final choice was a one-source-one attenuation solution. For about 70% of the SZ's, we selected characteristic relationships, derived usually from a so-called representative earthquake, which is the strongest earthquake which had occurred in the SZ. Although tricky, this is a flexible solution that respects the observations better than a mean attenuation relationship for the whole territory.

5.1. *Seismicity rates*

The same procedure used for defining the SZ seismicity rates in terms of magnitude was followed for defining the seismicity rates in intensity. As for magnitude, the NT4.1 catalogue also has an I_0 value for each event; when an actual intensity value was not available, a «virtual» value of I_0 was calculated from magnitude using an *ad hoc* relation (Camassi and Stucchi, 1996). A stationarity analysis (Cox and Stuart test, see Rock, 1988) similar to that adopted for magnitude was applied to intensities by grouping the sub-catalogues into four megazones (Northern, Central, Southern Italy, and Sicily). The suggested «complete» period of time was calculated for each degree of intensity class, using also the intermediate degrees (*e.g.*, VI/VII) as individual classes.

The choice of intensity rates was driven by the same criteria used for magnitude: the values were suggested by the stationarity test and sometimes changed cautiously by choosing a longer and more seismic period than the complete one, or a shorter one but always longer than the return period suggested by the completeness test (see the description for magnitude).

For the intensity hazard assessment, no maximum intensity values were added to the intensity rates as it is not obvious that a possible future larger magnitude will produce severer damage than that which has already occurred.

Figure 12a shows a synthesis of the chosen SZ seismicity rates for medium-low intensity. The number of events in 100 years is the summation of all the rates in the IV/V $\leq I_0 \leq$ VII MCS intensity range. The graph gives a rough idea of the contribution of medium to low intensity data to seismic hazard assessment for each SZ. Figure 12b refers to the high-end intensity contribution (rates for $I_0 \geq$ IX MCS). It is interesting to note the high seismicity of some SZ's in Central Italy (*e.g.*, SZ 47) and the volcanic SZ 73 (Etna) only in the low band, and the high rate of SZ 15 (Switzerland) and some SZ's in Southern Italy (*e.g.*, SZ 69) in the high band. There is, of course, a general agreement between these rates with those for magnitude (fig. 4a,b). Nevertheless, some differences mainly in the high band clearly arise. In some cases, they are due to magnitude estimates not in agreement with the intensity derived from the M_s/I_0 relation (Camassi and Stucchi, 1996); for instance in SZ 73 Etna low magnitude quakes can produce high intensity (Azzaro and Barbano, 1997). In some others, they come from the different completeness periods suggested by the stationarity test. All these aspects produce intensity maps which are not a simple trasformation of the PGA maps, since they derive from a completely separate elaboration.

5.2. *Intensity attenuation relations*

Great effort was devoted by GNDT to the definition of procedures to treat macroseismic data sets to obtain attenuation relationships. There are many reports on the ability of attenuation relationships to reproduce the observed damage (Drei, 1991; Zonno *et al.*, 1992; Rotondi *et al.*, 1994; Peruzza, 1995; Cella *et al.*, 1996); other experiments were devoted to the recognition of homogeneities in the propagation of intensity, and their dependence on epicentral intensity (Peruzza, 1996a).

The main rules (see Peruzza and Mucciarelli, 1997) may be summarized as follows:

1) There must be internal coherence between the way attenuation coefficients are derived, and their utilization.

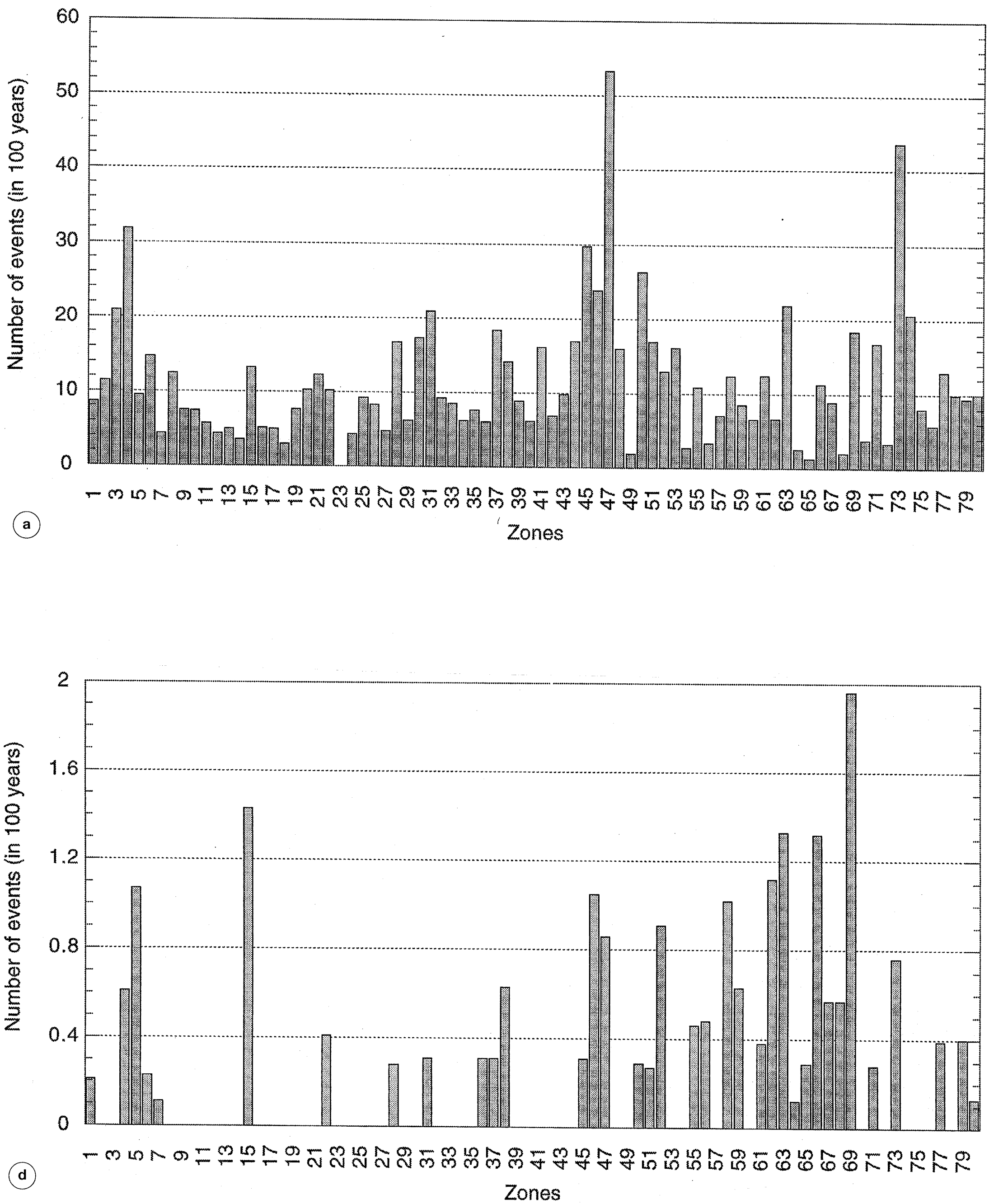


Fig. 12a,b. Seismicity rates expressed in intensity for the SZ's: a) low-medium seismicity, in the IV/V $\leq I_0 \leq$ VII MCS range; b) high seismicity, for $I_0 \geq$ IX MCS. Rates of SZ 23 were discarded in the final elaboration as not contributing significantly to hazard in Italy.

2) Attenuation characterizations based on expert judgements are usually not confirmed by the data.

3) Observations do not support attenuation dependence on epicentral intensity.

4) Azimuthal dependance of propagation is significant only in the near field, while local effects dominate in the far field; isotropic attenuation has therefore to be preferred when regional seismic hazard computations on standard soil conditions are performed.

The final solution adopted by GNDT (see Peruzza, 1996b) for attenuation relationship follows two formulations; that proposed by Grandori *et al.* (1987) reported in eq. (5.1) was adopted for SZ's with representative earthquakes (56 out of 80, see fig. 2);

$$I_0 - I_i = \frac{1}{\ln \psi} \ln \left[1 + \frac{\psi - 1}{\psi_0} \left(\frac{D_i}{D_0} - 1 \right) \right] \tag{5.1}$$

where I_0 is the epicentral intensity, I_i the intensity at the site, D_i the distance of the site from the epicentre, and ψ, ψ_0 and D_0 the unknown coefficients.

The relation proposed by Berardi *et al.* (1994) in eq. (5.2) was used elsewhere;

$$I_0 - I_i = \alpha + \beta \sqrt[3]{D_i} \tag{5.2}$$

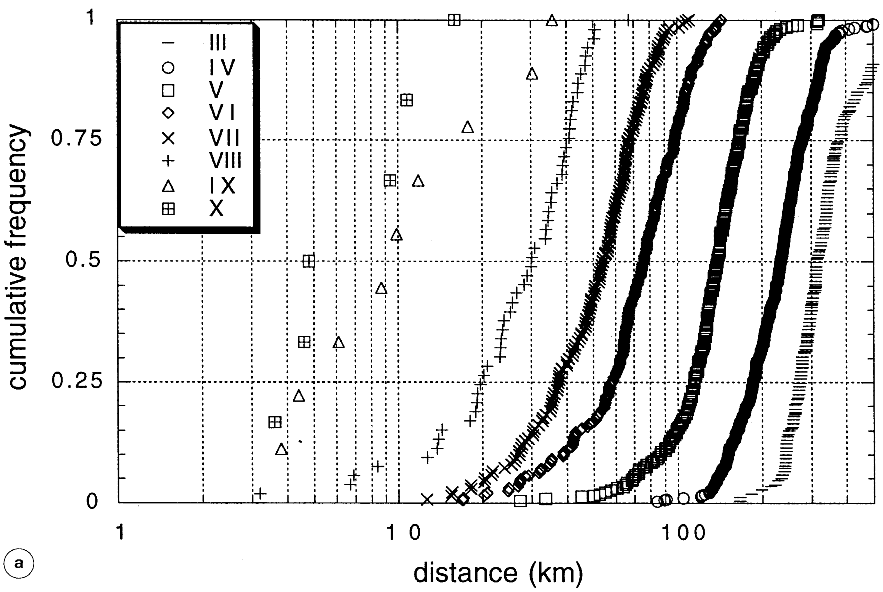
I_0, I_i and D_i have the same meaning as before, while α and β are the unknown parameters.

In the first case the procedure for evaluating the attenuation relation (see Peruzza, 1996a,b; and final results in Peruzza, 1998) starts with the computation of the sample cumulative curve of distances from the epicentre reported in the earthquake catalogue; the experimental data are grouped in macroseismic degrees (fig. 13a) with a weighting to distinguish certain from uncertain observations. Then, the distance D_i corresponding to the distance expected not to be exceeded at 50% probability level is selected for each intensity class. Finally the unknown coefficients of the Grandori *et al.* (1987) formula are obtained by a non-linear, least-squares method on the D_i's (fig. 13b). An example is given using the 1980 Irpinia earthquake in fig. 13a,b. The coefficients obtained (Peruzza, 1996b) for most of the SZ's (41 cases) derive from the strongest event in the SZ; in the other cases, the maximum earthquake is not documented in such a way that the statistical treatment of the data set is reliable, and another event has been chosen. The mean attenuation relation following eq. (5.2) was obtained by minimization of the residuals on all the observations of the representative earthquakes with intensity larger than, or equal to, V MCS.

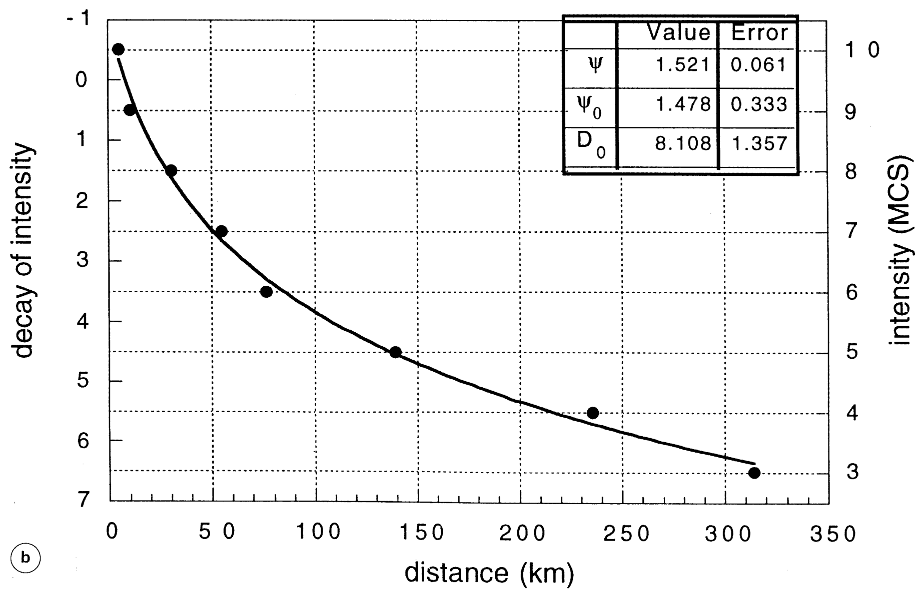
Figure 14a-c illustrates the different behaviours of the attenuation relationships in the very near field (fig. 14a, where the decay of intensity of the different sources is plotted at 10 km distance from the epicentre), near field (50 km in fig. 14b) and far field (150 km in fig. 14c). In particular, the volcanic areas (SZ's 56 and 73, see fig. 14a) exhibit a decay of about 3 degrees in 10 km, while the other four SZ's (31, 38, 54 and 57) show significant strong attenuation properties (more than 1.5 degrees in 10 km). At greater distances (fig. 14b), some more SZ's (16, 41, 42 and 45) have a low impact on the hazard, as the expected decay of intensity with respect to the epicentral intensity is greater than 4 degrees. At 150 km (fig. 14c) all the attenuation relationships predict a decay of at least 3 degrees (SZ's 43 and 80), and usually about 5 degrees but with appreciable variations from one source to another. It is significant that the mean attenuation relation (horizontal double reference line in fig. 14a-c) usually predicts higher decays at very short distances, but lower in the far field.

5.3. *Results*

The computation of seismic hazard maps using many attenuation relationships does not differ from the traditional approach with the exception that each SZ has its own attenuation relation. Maps using one single mean attenuation function for all the SZ's were produced as benchmark products, and compared with those obtained with different attenuation relationships. Intensity half degrees were rounded up: this is in agreement with the criteria used in compiling the maximum observed intensity



a



b

Fig. 13a,b. Example of treatment of an intensity data set to derive the Grandori *et al.* (1987) attenuation relationship; data refer to the 1980 Irpinia earthquake: a) cumulative sample curve for the various intensity classes *versus* epicentral distance; b) curve fitting of the Grandori model on the 50% fractile distance.

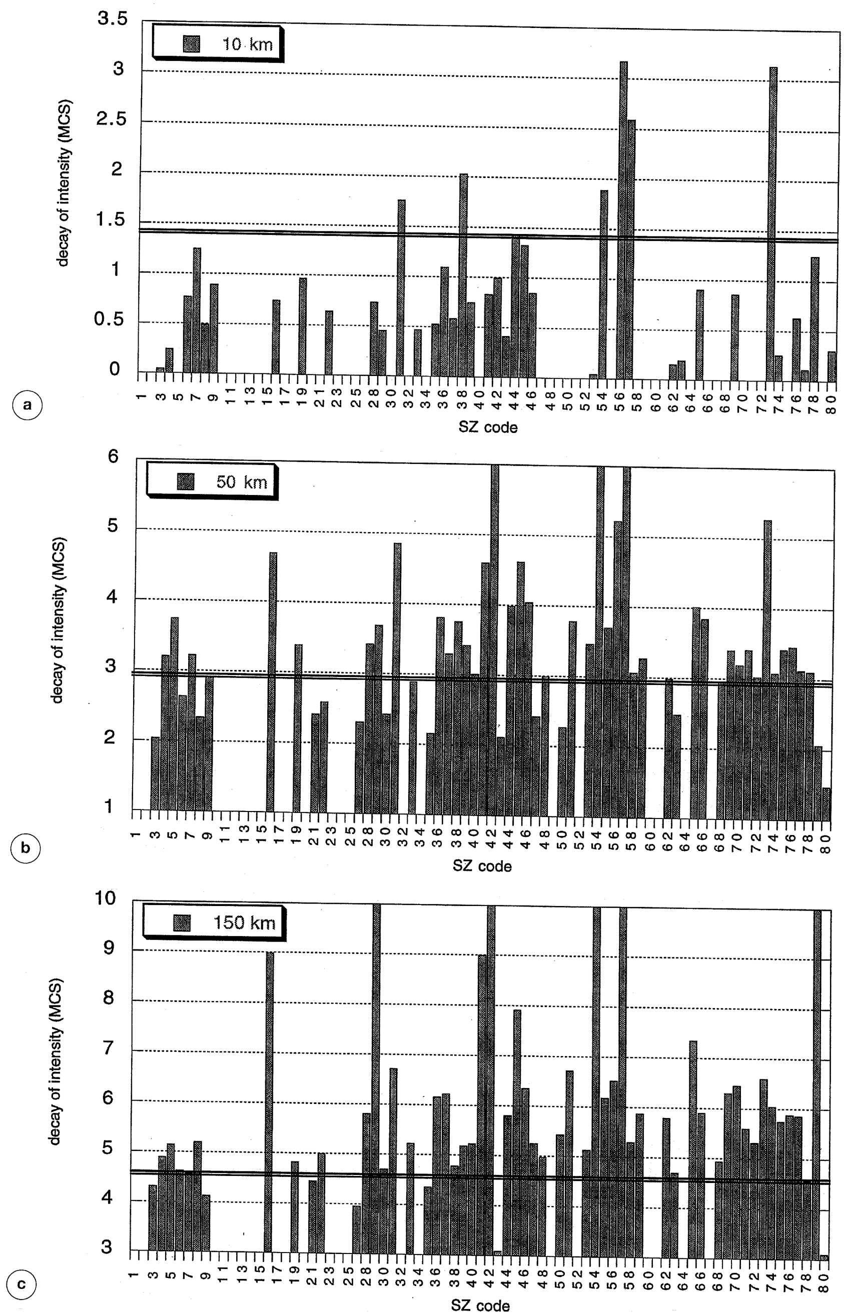


Fig. 14a-c. Synthetic representation of the behaviour of the Grandori *et al.* (1987) attenuation relationships (Peruzza, 1996b) derived for macroseismic intensity in the different SZ's: a) intensity decay at 10 km distance from the epicentre; b) at 50 km; c) at 150 km. The horizontal straight line indicates the decay expected by the mean model of eq. (5.2), applied to all the other SZ's.

map of Italy (Molin *et al.*, 1996). No standard deviation in the attenuation relations was taken into account. Following common practice, in fact, the uncertainty in attenuation is introduced as a cautionary coefficient: the use of many different levels of caution (the standard deviations derived from the different data sets) would have altered or masked the effective seismic content of the sources. The maps are therefore comparable with the PGA products without σ (fig. 8); an increase in the results taken by default as about one macroseismic degree as a substitute for σ in attenuation is fully justified by the dispersion in the observations. Figure 15 shows the results obtained with the homogeneous, mean attenuation relationship; the map is quite flat with the maximum expected intensity located in Southern Italy: the volcanic areas (SZ's 73 and 56) are well marked. Using characteristic attenuation relationships, the map (fig. 16) is nearer to expectations. The most hazardous areas are in the Northeastern Alps (SZ's 4 and 5), Central and Southern Apennines (the long red stripe from SZ 47 to 63), and Calabria; the presence of volcanic areas lowered their importance. In both the maps, the maximum values reached are in SZ 69, with expected intensity for $T = 475$ years being IX-X MCS. Mapping the differences of the two elaborations, about 50% of the national territory lies within the range of $\pm 1/2$ degree. Wide areas in the Northeastern Alps, the Po plain and around SZ 8, the Western Alps on the border with France (SZ's 21 and 22), Central Italy (Sz's 47, 48, 50, 51, 52) and the Southern Apennines (SZ's 57, 62 and 63) show an increase of about one degree with the use of the characteristic attenuation relationships. Decreases by the same amount are confined to small areas, east of Bologna, along the coast west of Perugia, in the volcanic areas (SZ's 56 and 73) and in Central Sicily.

6. Conclusions

The results of the GNDT project for the revision of the seismic map of Italy have been shown and the statistical aspects discussed. The results are in agreement with the EC8 standards for seismic zonation (map in terms of PGA) and could be used for defining the seismic areas where building retrofitting is a priority (map in terms of intensity). The final maps (figs. 9 and 16) represent the consolidated result of a complex project involving all the main topics of seismotectonics and seismic hazard assessment.

They should, moreover, provide a first step in further elaborations (*e.g.*, time dependent approaches, see Working Group on California Earthquake Probabilities, 1990, 1995; Peruzza *et al.*, 1997). As an example, the map in fig. 17 is here presented: it shows a different aspect of seismic hazard and derives directly from the elaborations previously described. The probability of exceeding 0.1 g in 20 years is mapped by municipalities. The representation gives a quantity with direct practical use and, in addition, avoids computation at points where seismic hazard has no sense (for instance in the sea). This map indicates Northeastern and Central Italy as the most dangerous areas for moderate shakings with a probability greater than 70%. The probability level emphasizes the differences with respect to the previous maps and, in particular, the 20-year window is the time elapsed since the last earthquake record in the NT4.1 catalogue. This image of Italian seismic hazard is not surprising as it is in agreement with what is shown in fig. 7, but it seems out of tune with the occurrence of larger quakes in recent centuries (see section 2). The explanation is quite simple if we consider that these regions are characterized by frequent medium magnitude seismicity and 0.1 g represents on average a damaging but not destructive shaking. For higher acceleration values (*e.g.*, 0.3 g) other parts of Italy, where large magnitude quakes are frequent (the Calabrian arc), show higher exceedence probability.

In conclusion, the standard hazard maps are useful for a revision of the seismic zonation, and can offer a vision of the expected shaking in the various regions as well. Italy is thus promoted from the countries using seismic hazard maps of the historical probabilism generation to those using the seismotectonic probabilism generation.

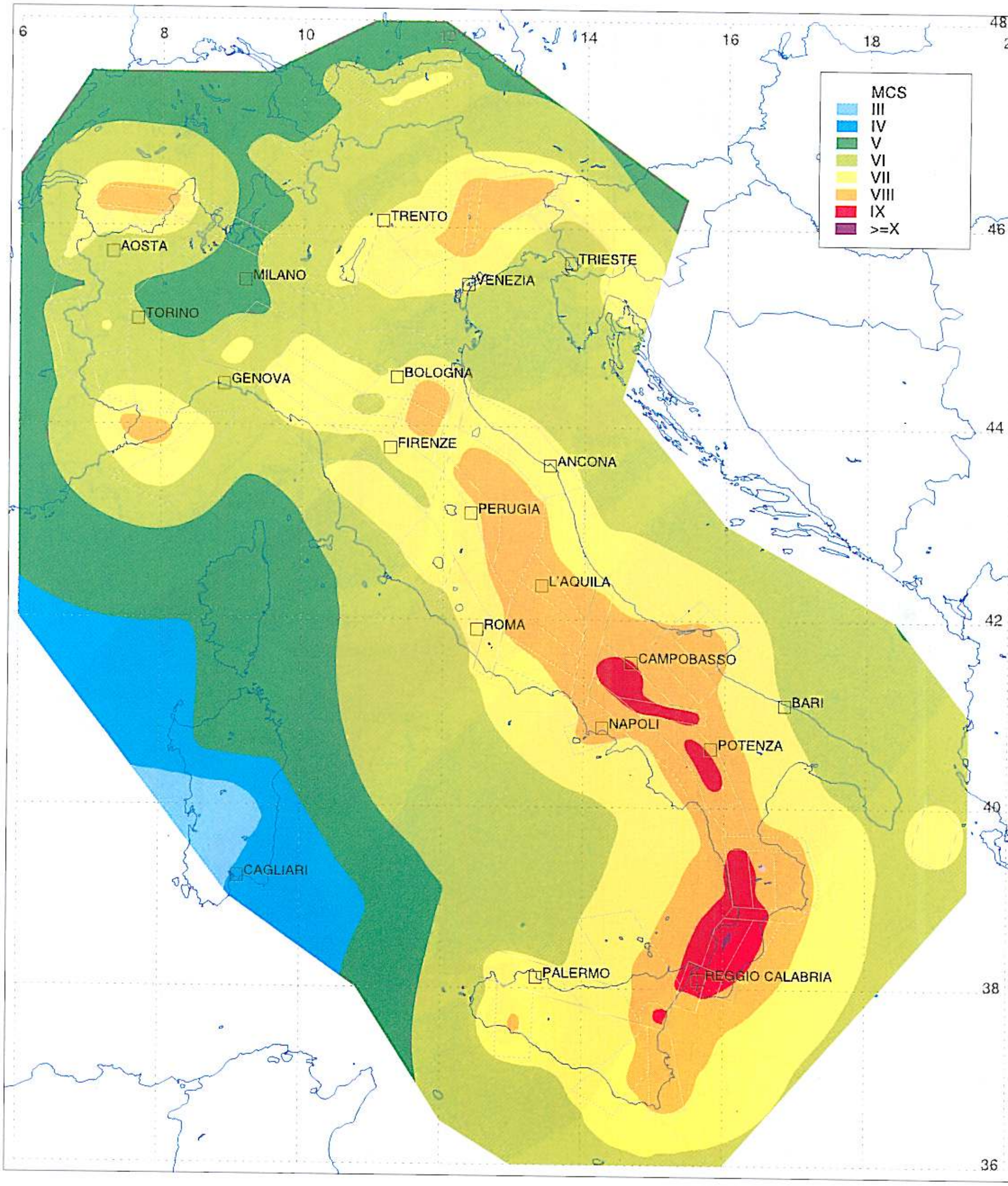


Fig. 15. Macroseismic intensity with 475-year return period using one mean attenuation relationship; no σ in the attenuation has been accounted for. Half degrees are rounded up in the graphical representation.

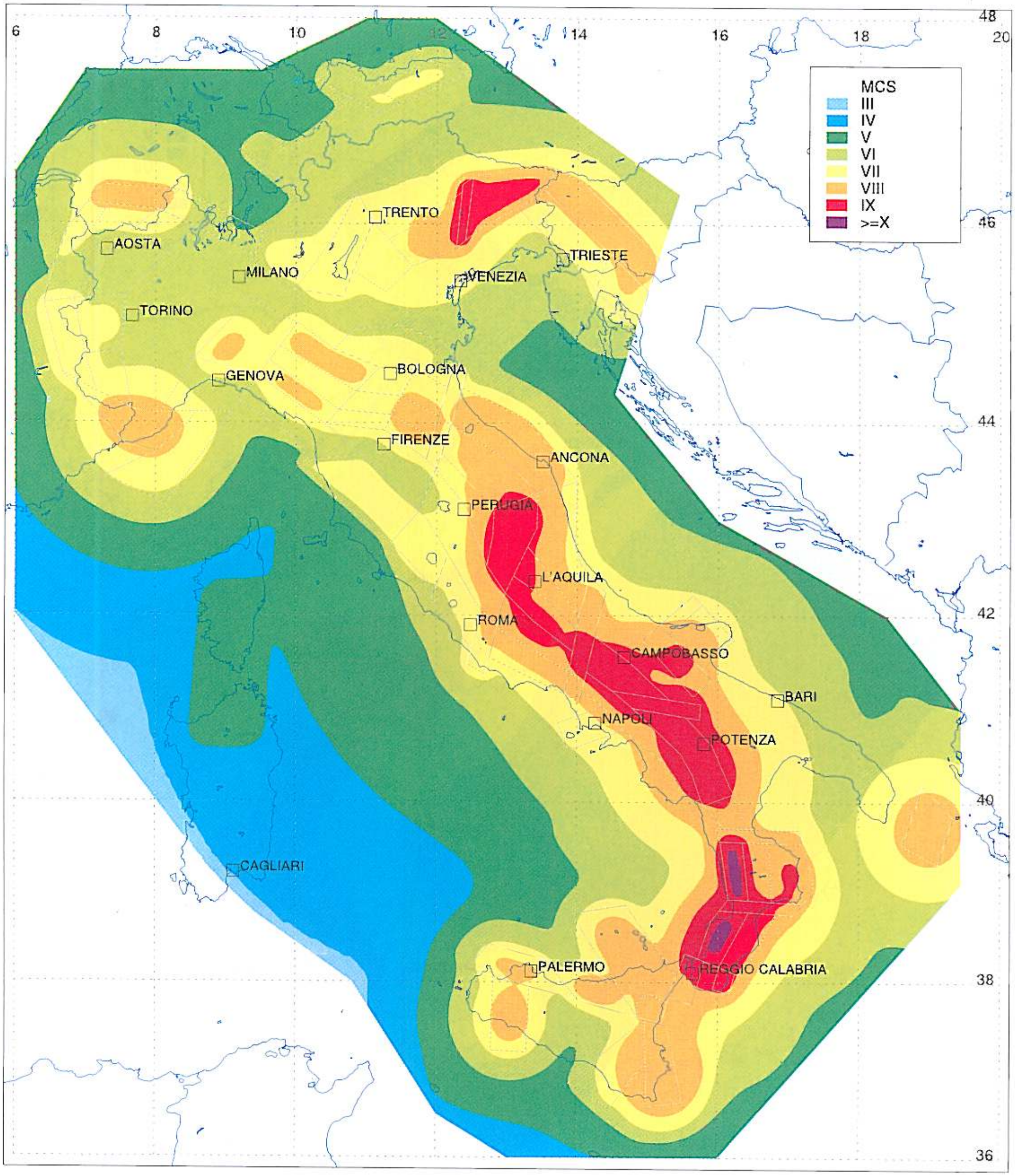


Fig. 16. Macroseismic intensity with 475-year return period using different attenuation relations, no σ in attenuation considered. Half degrees are rounded up in the graphical representation.

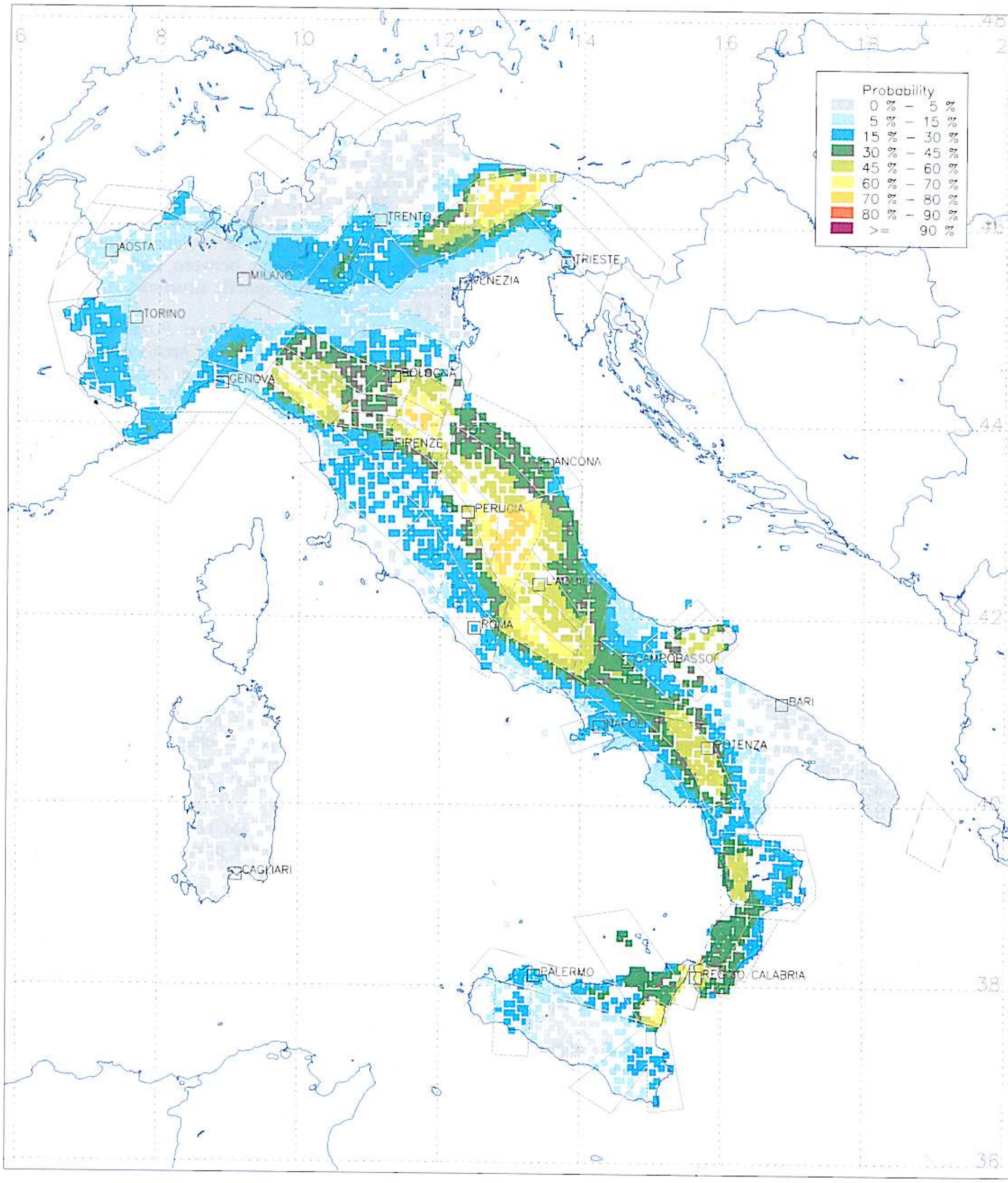


Fig. 17. Probability of exceeding 0.1 g in 20 years: the computation refers to the municipalities, and σ in attenuation of PGA has been accounted for.

Acknowledgements

This research was conducted in the framework of the GNDT activities, and benefits from the contributions of all members of the «Seismic Hazard» working group, among whom special thanks are due to Ezio Faccioli. It is only the final part of a complex project also involving the «Seismicity» working group, coordinated by Massimiliano Stucchi, and the «Seismotectonics» working group, coordinated by Paolo Scandone. A special thought goes to Vincenzo Petrini, director of the GNDT for many years. Many thanks are due to Robin McGuire, who read the manuscript offering useful suggestions, to David Perkins, for interesting discussions, and to Peter Guidotti, who checked the English text.

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