

First studies of probabilistic seismic hazard assessment in the volcanic region of Mt. Etna (southern Italy) by means of macroseismic intensities

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ABSTRACT Results of probabilistic seismic hazard assessment (PSHA), in terms of macroseismic intensity applied to the Mt. Etna region, are presented. PSHA has been performed using a numerical procedure based on the extensive use of local macroseismic information, as an alternative to the usual Cornell-McGuire methods. The large amount of intensity data available for this area - coming from the Italian intensity database DBMI04 for the regional earthquakes, and from the Etna catalogue for the 'local' events - has provided fairly exhaustive seismic site histories (i.e. the data set of macroseismic observations available for a given locality) to estimate the seismic hazard for 402 localities on the volcano. In order to improve the completeness of the site catalogue when historical information is missing, observed intensity data have been integrated with values calculated from epicentral information obtained by using an attenuation law specific for the Etna region. Using a probability distribution considering the completeness of the input database and the uncertainty of intensity data, the hazard in terms of maximum intensity (I_{exp}) characterised by a 10% probability of exceedance in an exposure time of 50 years, has been computed. The highest values ($I_{exp} = IX$ or X) are found in the south-eastern flank of Mt. Etna while the rest of the volcano is exposed to a lower hazard ($I_{exp} = VIII$). Despite the low energy ($M \leq 4.8$) compared with that of the large regional earthquakes affecting the area ($6.6 \leq M \leq 7.4$), the local events strongly influence the pattern of the hazard in the eastern sector of Mt. Etna, representing a significant, and sole, source of hazard when a shorter exposure time (e.g. 30 years) is considered.

1. Introduction

In recent years, probabilistic seismic hazard maps in Italy (Slejko *et al.*, 1998; Albarello *et al.*, 2000; MPS Working Group, 2004) have generally been obtained following a standard method based on Cornell (1968) and McGuire (1993) approaches. This procedure is characterised by the assumption that in each seismogenic zone the seismicity is uniformly distributed following the Gutenberg-Richter relationship, and can be represented as a Poissonian point process. In practice the homogeneous behaviour, in terms of seismic rate and *PGA* attenuation relationship, hides the site effects due to soil conditions or topographic response (e.g. Peruzza *et al.*, 2001; Rebez *et al.*, 2001). An alternative approach to probabilistic seismic hazard assessment (PSHA) for overcoming the aforementioned limitations is the use of site intensity data, especially in a country

such as Italy that has a very rich historical seismological tradition (Monachesi *et al.*, 1994; Mucciarelli *et al.*, 2000; Albarello *et al.*, 2002). In particular, Albarello and Mucciarelli (2002) developed a probabilistic method for seismic hazard assessment based on the use of the seismic history of the site (i.e. the data set of macroseismic observations available for that locality), taking into account the different levels of completeness and uncertainty. To improve the completeness of the site catalogue, virtual site intensities are calculated from epicentral data using attenuation laws and introduced into the data set when historical data are missing. Finally, the seismic hazard, expressed in terms of macroseismic intensity with a fixed probability of exceedance (10%) during a defined exposure time (50 years), is computed.

We applied this method (hereafter ‘site approach’) to the Mt. Etna region, in the framework of the activities developed by the S1 project (2007), funded by the Italian Civil Protection Department and devoted to the management and development of the national seismic hazard map (MPS Working Group, 2004). This area is exposed both to the effects of large crustal earthquakes occurring in eastern Sicily (Azzaro *et al.*, 1999) and to shallow, very frequent events due to local volcano-tectonic structures (Azzaro, 2004).

In this paper, we present the first results of the PSHA calculated using macroseismic data with the software SASHA, developed by D’Amico and Albarello (2007), and issued as freeware in the framework of the S1 project. The ensuing hazard map is expressed in terms of intensity characterised by 10% probability of exceedance in 50 years. Furthermore, different exposure times are investigated to verify if the contribution of local seismogenic sources and/or site effects in determining the seismic hazard of the area may be significant.

2. The data set

The knowledge base used for the PSHA is the seismic history of the site, that is the effect of the historical earthquakes at a given locality expressed in terms of macroseismic intensity. Obviously, the more complete is the knowledge of the earthquakes affecting a locality, the more reliable is the seismic hazard assessment. In the framework of the ‘site approach’ (Albarello and Mucciarelli, 2002), seismic site histories are reconstructed according to these steps: (i) observed intensity data available for a given locality are collected; (ii) ‘virtual’ or attenuated intensities are computed using an attenuation law from epicentral parameters; (iii) the two data sets are merged, using calculated data (i.e. ‘virtual’ intensities) only in absence of the documented ones. Uncertainty pertaining to considered intensity values has been taken into account. For this purpose, each macroseismic observation is expressed by a probability array: each element of the array represents the likelihood (probability) that a given intensity value has been actually reached at the site for a given earthquake. These probabilities have been assessed by subjective judgements in the case of documented intensities or by the attenuation relationship (in its general probabilistic form) for intensity values deduced from epicentral information [further details can be found in Albarello and Mucciarelli (2002) and Albarello and D’Amico, (2004; 2005)].

Characteristics of the input data set are hereinafter reported.

2.1. Observed intensities

The Mt. Etna region is affected by strong regional events ($6.6 \leq M \leq 7.4$), such as the 1169 and

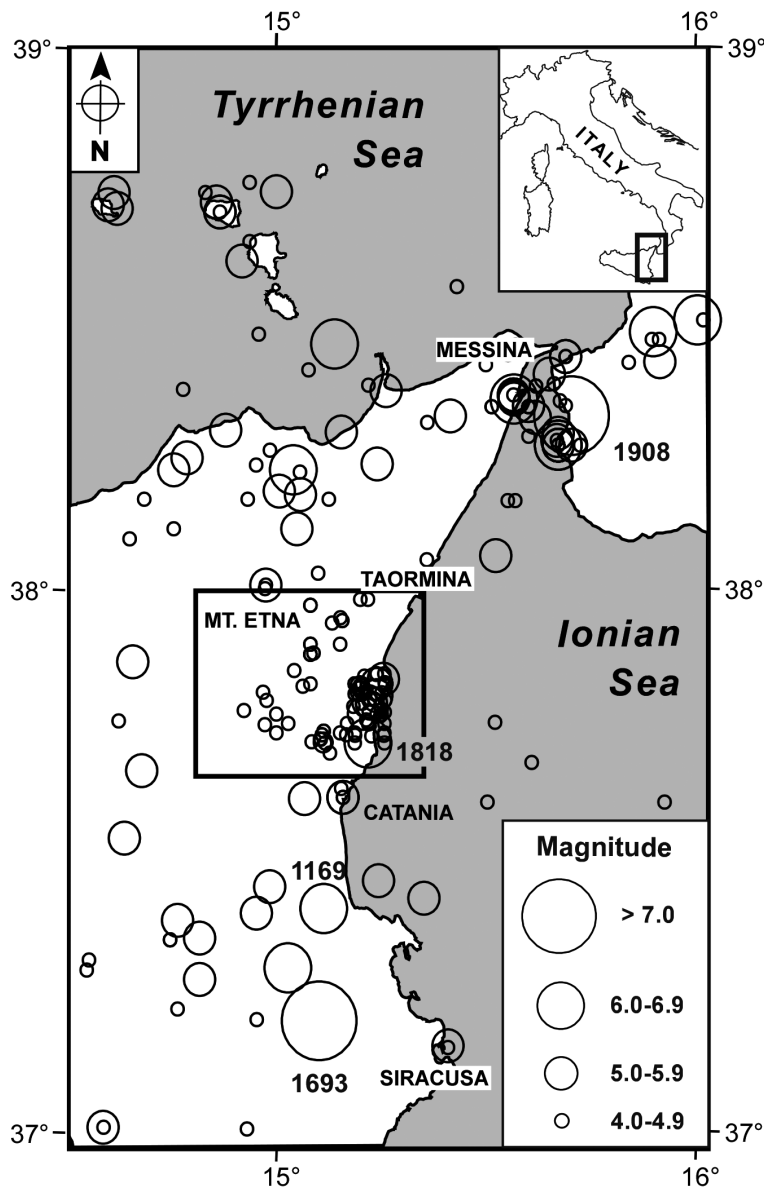


Fig. 1 - Distribution of seismicity in eastern Sicily from 1000 to 2002 according to the parametric catalogue of the Italian earthquakes (CPTI Working Group, 2004). The box shows the location of the studied area; dates indicate the regional events influencing the seismic hazard in the area.

1693 Val di Noto earthquakes, the Etnean 1818 earthquake and the Messina 1908 earthquake (CPTI Working Group, 2004), to mention but the main ones (Fig. 1). These shocks produced major destruction in the studied area, mainly in Catania and surrounding territory and throughout the eastern sector of Mt. Etna. On the other hand, this area is also exposed to local earthquakes that, albeit of low magnitude [$M \leq 4.8$ according to Azzaro and Barbano (1997)], produce severe damage or even destruction, epicentral intensities I_0 reaching up to X EMS-98 (Grünthal, 1998)

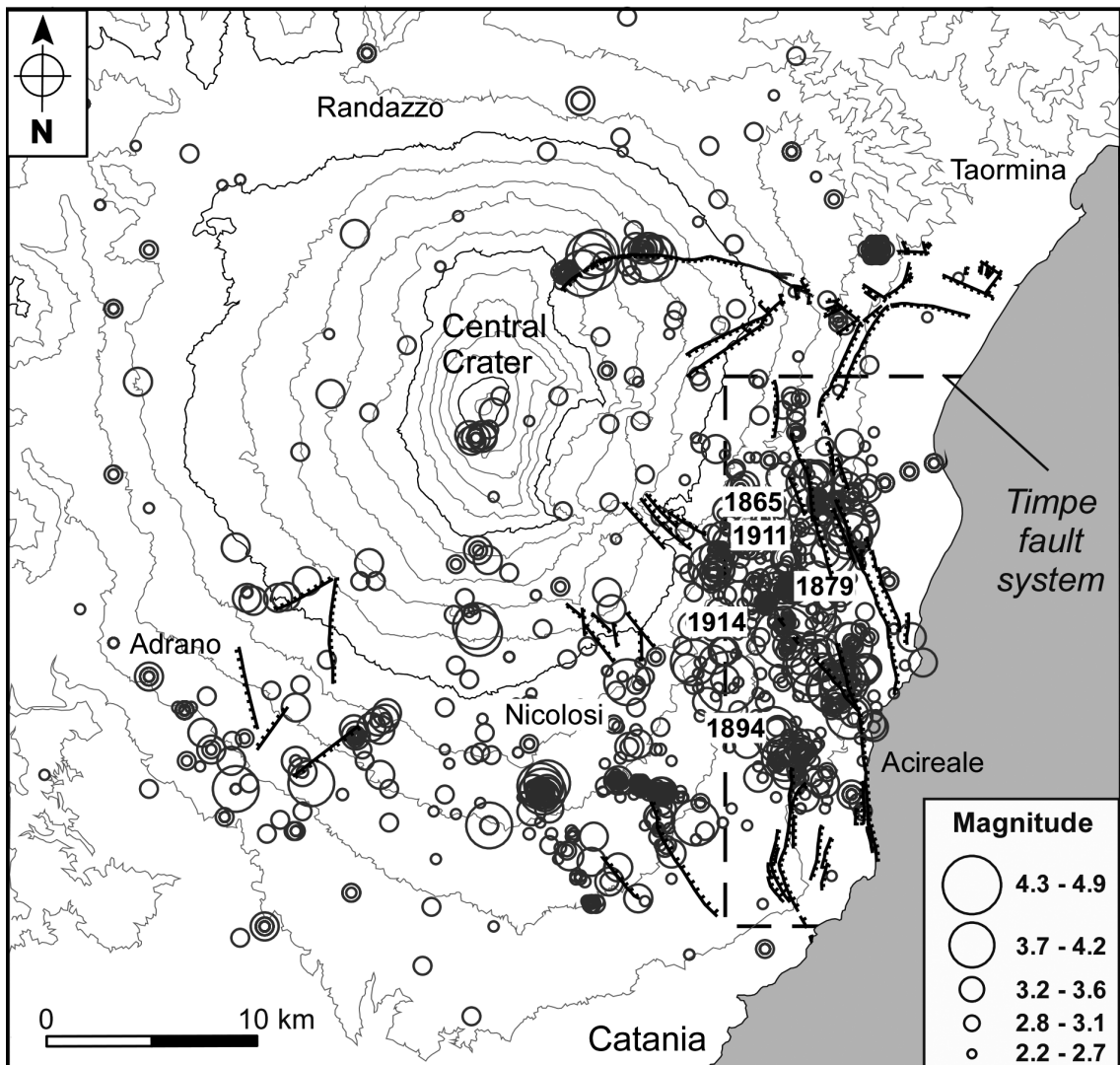


Fig. 2 - Location of the earthquakes in the Etna area from 1832 to 2005 according to the local catalogue [data from Azzaro *et al.* (2000, 2002, 2006b)]. The pattern of the local seismogenic faults is also shown [bars on downthrown side, from Azzaro (2004)]. Dates indicate the strongest local events influencing the seismic hazard in the area.

because of the extreme shallowness ($h \leq 3$ km) of the foci (Azzaro, 2004). These events are very frequent - 190 shocks exceeded the damage threshold over the last 200 years - and are mostly located in the eastern flank of the volcano, which is traversed by a dense network of seismogenic faults (Fig. 2).

Therefore, the intensity data set used for the present analysis is constituted by macroseismic observations related to (i) regional earthquakes with effects in the Etna region and (ii) local events. The data set of the first group is extracted from the intensity database DBMI04 (Stucchi *et al.*, 2007) related to the parametric catalogue of the Italian earthquakes (CPTI Working Group, 2004). The CPTI catalogue covers the time-span from 217 B.C. to 2002 but adopts space-time

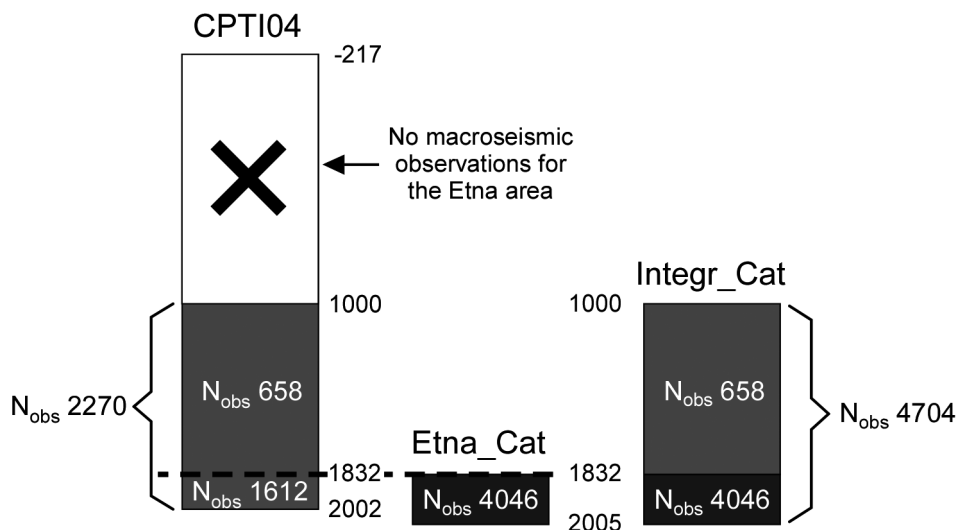


Fig. 3 - Definition of the integrated data set used in the study and comparison of macroseismic observations (N_{obs}) available on the national and local seismic catalogues.

windows to select only the mainshocks (events within ± 30 km and ± 90 days are discarded) with epicentral intensity $I_o \geq V-VI$ MCS, so many Etnean earthquakes are missing. For this reason, we also considered the catalogue compiled specifically for the Etna area (lat. N 37.5° - 37.9° , long. E 14.7° - 15.3°) by Azzaro *et al.* (2000, 2002, 2006b), that adopts a lower energy threshold and also includes fore- and aftershocks; it covers the time-span from 1832 to 2005. By integrating the two sub-data sets (Fig. 3), we obtained a database of 4704 macroseismic observations in all. This catalogue lists 536 events and covers the time interval from 1000 to 2005, as no observations for the Etna region exist before such a date.

2.2. Calculated intensities

To improve the completeness of the site catalogue, the data set of intensities observed at each locality has been integrated with 'virtual' values calculated from the epicentral parameters (epicentre location and epicentral intensity) by considering two attenuation laws: a general attenuation relationship, valid for the Italian territory, for the regional events and a specific law for the local earthquakes with epicentre in the volcanic area. For the Etna region, in fact, the application of a specific law is required since the attenuation of macroseismic intensity with distance is much higher than in tectonic zones, with the decay of intensity ΔI (difference between epicentral I_o and site intensities I_s) reaching 4 degrees at 20 km from the epicentre (Azzaro *et al.*, 2006a). This aspect plays an important role in the reliability of results and the adopted solution provides the best estimation of expected intensity values.

The regional attenuation law is in log-linear form and was recently developed by Pasolini *et al.* (2007) from the analysis of DBMI04 intensity data (Stucchi *et al.*, 2007): in its probabilistic form, the attenuation relationship is a Normal distribution with an average I_s , depending on the epicentral distance, and given by the equation:

$$I_s = I_E - 0,0086 (D - 3.91) - 1.037 [\ln(D) - \ln(3.91)]$$

with

$$D = \sqrt{R^2 + 3.91^2}$$

where R is the epicentral distance in km. I_E is the macroseismic intensity equivalent of the magnitude estimated for all the events in the considered catalogue by a procedure defined in Pasolini *et al.* (2007). The standard deviation σ associated to the considered distribution varies depending on the way the computation of I_E is followed. Three values are supplied: $\sigma = 0.690$ if I_E is directly assessed from the macroseismic field, 0.87 and 0.98 if I_E is derived from instrumental magnitude or epicentral intensity, respectively.

The local attenuation relationship has been specifically derived for the Etna region (Azzaro *et al.*, 2006a) through an empirical model by fitting average intensity decays ΔI versus hypocentral distances by the least-square method. In this case also, in its probabilistic form, the attenuation relationship is a Normal probability distribution whose average depends on the hypocentral distance D :

$$\Delta I = 0.98 \ln(D) + 1.01$$

with a standard deviation σ equal to 0.82.

The program SASHA implements both attenuation relationships so as to compute the probability distribution describing the likelihood of each possible intensity value at each site. In particular, the local attenuation relationship has been used only for the earthquakes whose sources are located below the Etna volcano. In all the other cases, the general attenuation relationship has been considered.

3. Site seismic history

The integration of DBMI04 (Stucchi *et al.*, 2007) with Etna intensity database (Azzaro *et al.*, 2000, 2002, 2006b) has enabled us to reconstruct the seismic histories of 402 Etnean localities. This operation has notably increased the macroseismic information available for each site, for the classes of intensity from II to XI, so that all the values can be used in PSHA. For instance, the number of data with site intensity $I_s \geq V$ MCS (i.e. the more relevant in terms of hazard), were even doubled in some localities with respect to the DBMI04 database alone (Fig. 4).

In order to improve the completeness of the site catalogue and then to achieve more reliable PSHA estimations, the site seismic histories have been enriched by adding calculated data (i.e. 'virtual' intensities) in absence of the documentary ones. This led to the acquisition of very comprehensive and detailed seismic histories. In general, the seismic histories show little information, related only to regional earthquakes, before the 17th century and plenty of observations since 1800 (Fig. 5) mainly regarding Etna events. Moreover, a common feature of the seismic histories is that destructive earthquakes ($I_o \geq IX$ MCS) are not frequent while damaging earthquakes ($VI \leq I_o \leq VIII$ MCS) are rather recurrent.

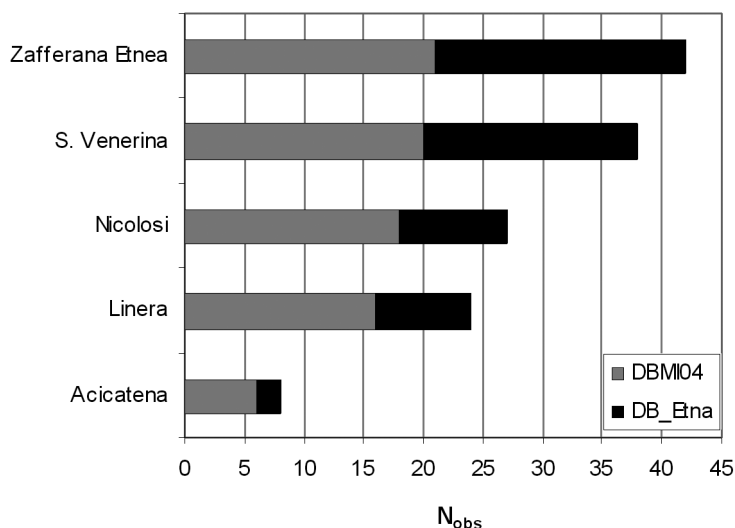


Fig. 4 - Number of macroseismic observations (N_{obs}) available for some localities in the Etna region. These values have been obtained by adding the local intensity database to the national one. Only intensities $\geq V$ MCS are shown.

Three types of situations can be recognised if seismic histories are analysed in more detail: (i) localities with maximum intensities clearly due to regional events (e.g. Acicatena); (ii) localities showing high values determined both by regional and local earthquakes (e.g. Nicolosi); (iii) sites characterised by maximum intensities deriving only from Etna events (e.g. Linera). This behaviour depends on the position of the inhabited zones with respect to the local seismogenic faults that, when located nearby, are capable of overprinting the regional shaking (see next section).

Fig. 6 shows the completeness analysis for different intensity classes of the whole data set (observed and calculated values), carried out according to the statistical approach by Albarello *et al.* (2001). The completeness time for intensity classes VI, VII and VIII ranges from roughly 1650 to 1750, with an uncertainty of ca. 200 years, whereas for intensities IX and X the data set appears to be reasonably complete from 1400 and 1450, with an uncertainty of ca. 400-450 years (Table 1).

4. Seismic hazard

The seismic hazard is evaluated on the basis of the site approach applied to the local seismic

Table 1 - Completeness time T_c for different intensity classes and associated uncertainties T_l and T_u expressed as interquartile ranges.

Intensity	T_l	T_c	T_u
VI	1624	1730	1820
VII	1560	1672	1779
VIII	1542	1649	1753
IX	1253	1471	1655
X	1148	1402	1598

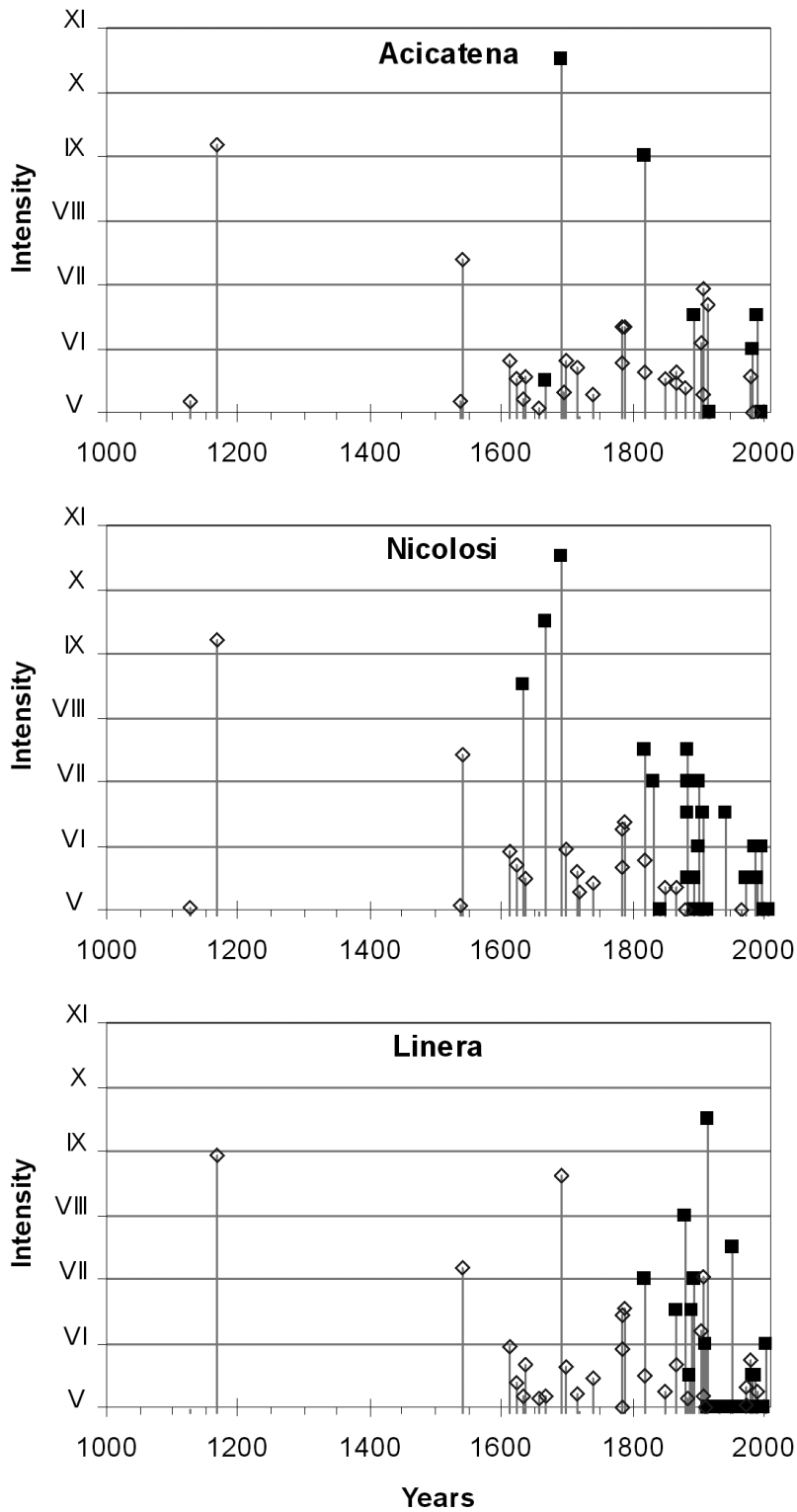


Fig. 5 - Example of site seismic histories reconstructed by the integration of observed (squares) and computed (rhombuses) intensity data.

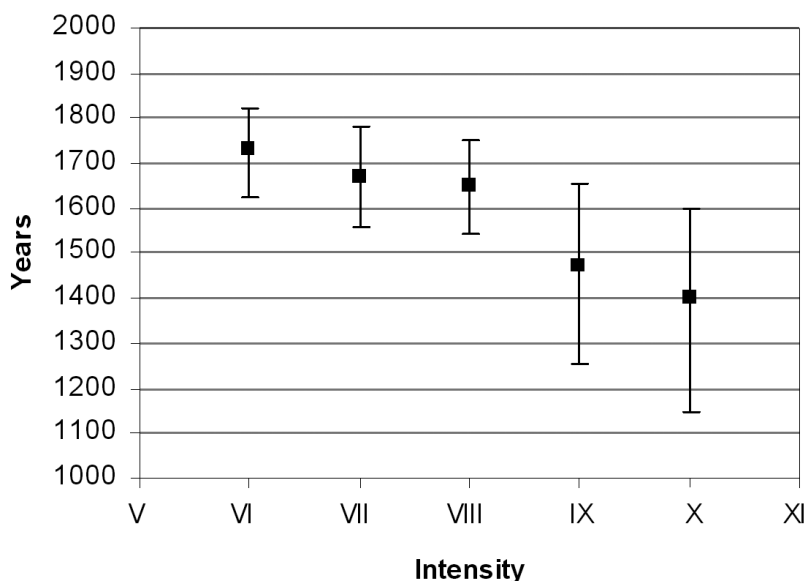


Fig. 6 - Completeness of macroseismic data set for different intensity thresholds for the whole Etna area. Bars indicate uncertainty of estimation.

history, taking into account the different levels of completeness of the intensity data set at each locality (Albarello and Mucciarelli, 2002). From the seismic history, the probability that at least one earthquake will occur in a time-span of 50 years and produce effects at least equal to a given intensity at that site, has been estimated (Table 2). For each locality, the expected intensity (I_{exp}) is then defined as the higher intensity value having an exceedance probability $\geq 10\%$ in 50 years, according to the Italian seismic rules.

Fig. 7a shows the seismic hazard expressed in terms of expected intensities during an exposure time of 50 years (which corresponds to a return period of 475 years in a Poissonian model), for 402 localities in the Etna region. The inhomogeneous distribution of the points on the map reflects the location of inhabited centres around the volcano, most of them lying in the more densely urbanised eastern sector, whereas the north-western sector of Etna comprises only a few towns and the summit areas are almost deserted.

In the map of Fig. 7a, it is possible to recognize two different zones: (i) the south-eastern sector of Etna, exposed to the highest values of hazard ($I_{exp} = IX$ or X) and (ii) the remaining areas of the volcano, characterized by lower expected intensities ($I_{exp} = VIII$). A careful analysis of data reveals that in the first zone the hazard is actually due to the contribution of two different types of seismic sources: the large regional events such as the 1169, 1693 and 1818 earthquakes are predominant in the sector included between Catania-Nicolosi-Acireale while the main Etna shocks (e.g. 1865, 1879, 1894, 1911 and 1914) mostly influence the hazard in the area north of Acireale. This finding proves evident on the map of Fig. 7b, which is obtained using only the intensity data set of the Etna catalogue from 1832 to 2005. Although we use a partial data set in this case, the number of observations of higher intensity does not decrease, since in this area the

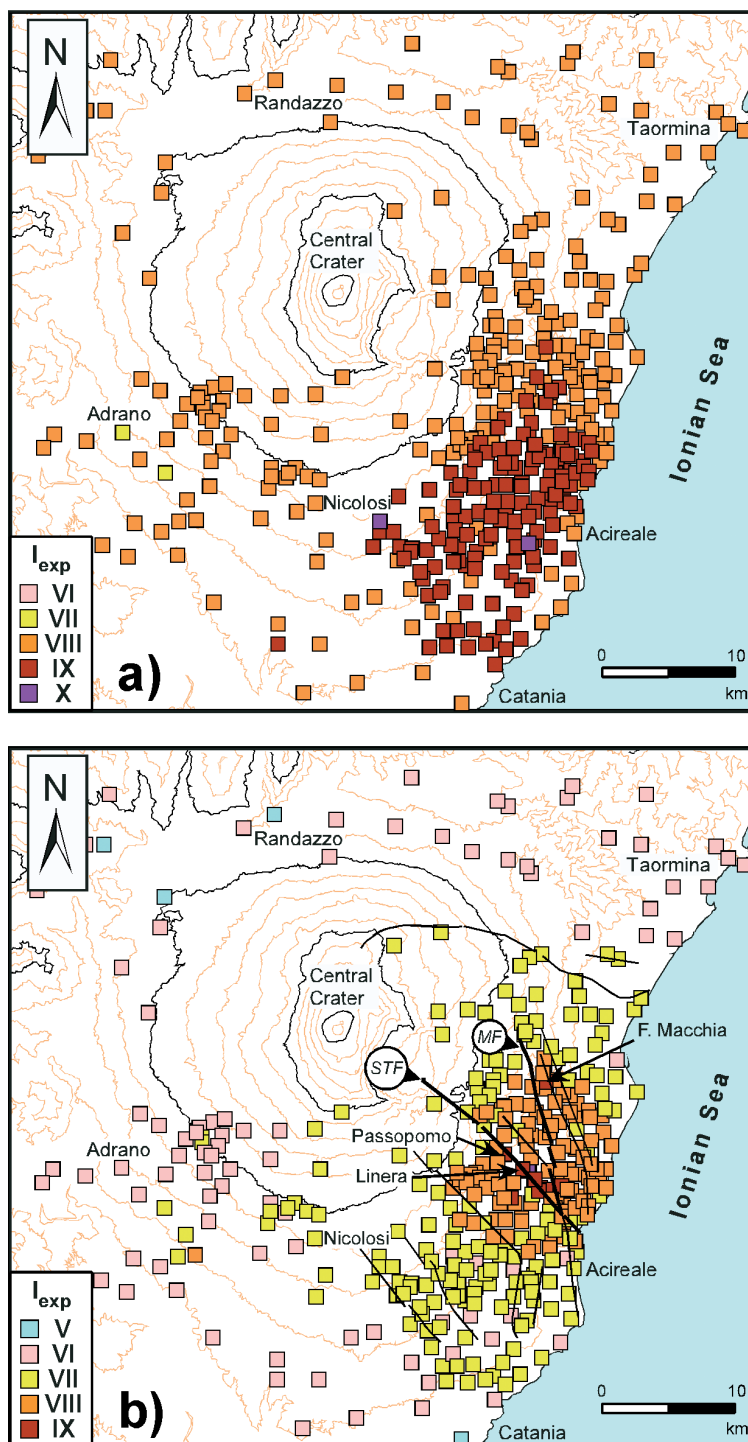


Fig. 7 - Seismic hazard maps expressed in terms of expected intensity (I_{exp}) with a probability of exceedance of 10% for an exposure time of 50 years. Compiled by a) the integrated data set (1000-2005) and b) only the Etna one (1832-2005). The pattern of the seismogenic structures in the eastern flank is also represented: in bold the S. Tecla (STF) and Moscarello (MF) faults discussed in the text.

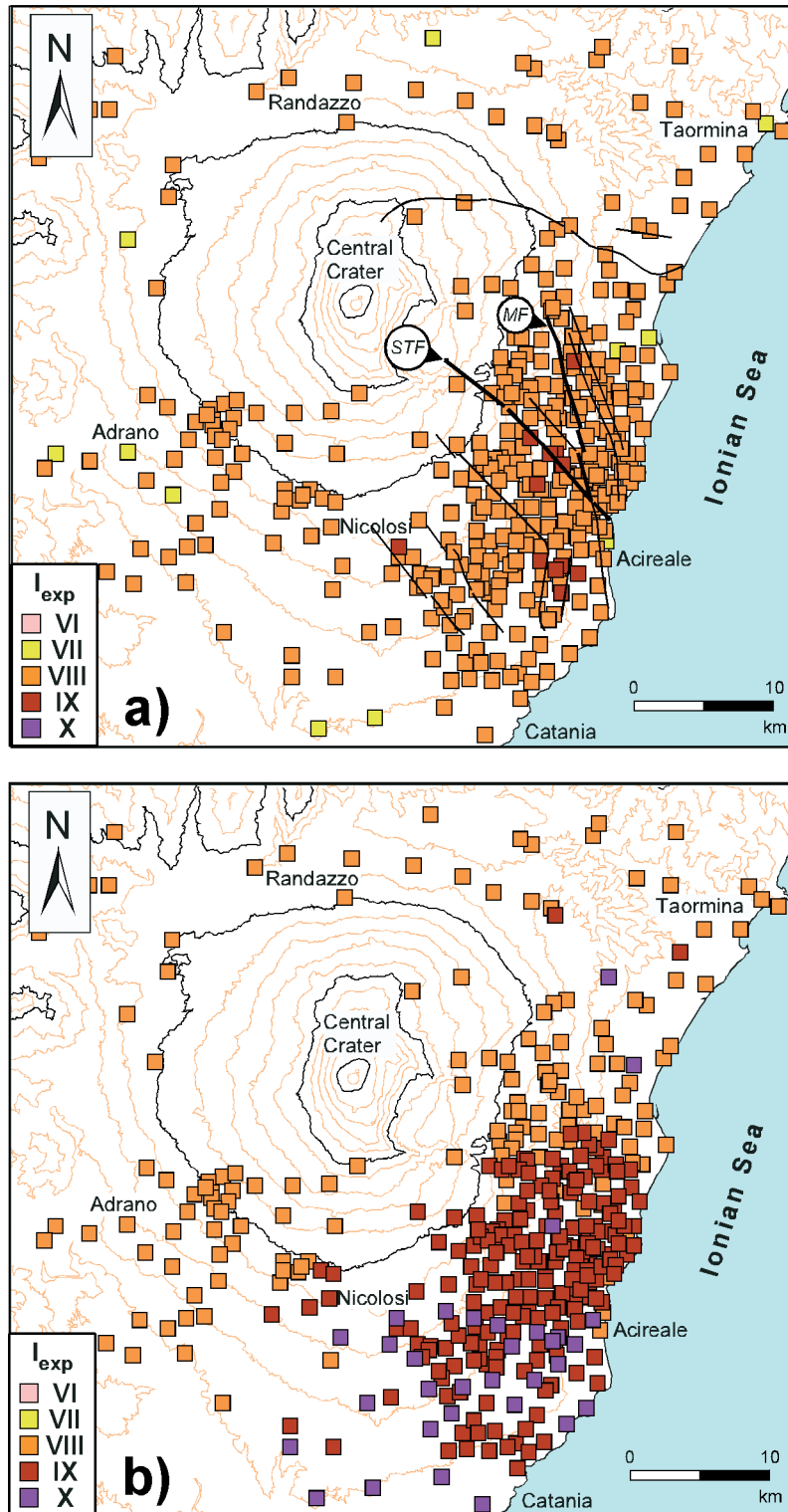


Fig. 8 - Seismic hazard maps (I_{exp}) with a probability of exceedance of 10% for exposure times of a) 30 and b) 70 years. The S. Tecla (STF) and Moscarello (MF) faults are marked in bold.

Table 2 - Occurrence probability for intensity classes from VI to XI MCS for some localities representative of different hazard situations in the Etna area. The values plotted in the hazard maps are shown in the column I_{exp} , and represent 10 % probability of exceedance in 50 yrs.

Locality	Exceedance probability						I_{exp}
	VI	VII	VIII	IX	X	XI	
Acicatena	0.91	0.61	0.29	0.18	0.08	0.04	IX
Aci Consolazione	0.90	0.58	0.29	0.18	0.13	0.04	X
Belpasso	0.81	0.54	0.17	0.07	0.02	0.00	VIII
Biancavilla	0.93	0.59	0.08	0.01	0.00	0.00	VII
Bongiardo	0.99	0.89	0.58	0.12	0.01	0.00	IX
Bronte	0.82	0.50	0.13	0.01	0.00	0.00	VIII
Catania	0.91	0.50	0.17	0.09	0.09	0.04	VIII
Fiandaca	0.99	0.81	0.41	0.12	0.03	0.00	IX
Fondo Macchia	0.99	0.90	0.82	0.27	0.01	0.00	IX
Giarre	0.92	0.43	0.12	0.04	0.01	0.00	VIII
Linera	0.99	0.89	0.52	0.17	0.07	0.00	IX
Linguaglossa	0.89	0.54	0.40	0.08	0.00	0.00	VIII
Milo	0.97	0.68	0.43	0.05	0.01	0.00	VIII
Nicolosi	0.98	0.72	0.32	0.15	0.10	0.04	X
Randazzo	0.80	0.50	0.28	0.01	0.00	0.00	VIII
Santa Venerina	0.98	0.84	0.28	0.05	0.01	0.00	VIII
Zafferana Etnea	0.99	0.79	0.40	0.05	0.01	0.00	VIII

effects of regional earthquakes are already attenuated. The high values of expected intensities ($I_{exp} = IX$) regard various localities such as Linera, Fondo Macchia, Passopomo etc., all located very close to the main seismogenic structures of the volcano, namely the Moscarello and S. Tecla faults (Azzaro, 2004). By comparison, the rest of the eastern flank with part of the southern one, are exposed to a moderate hazard value ($I_{exp} = VII$).

Since seismic hazard in the Etna region is controlled by two distinct types of events (regional and local) having different magnitudes and frequency of occurrence, hazard variations for shorter and longer than 475 years return periods have been also analysed. The I_{exp} values with a fixed probability of exceedance 10% have been computed for exposure times of 30 and 70 years by using the integrated intensity data set (from regional and local catalogues). These values have been selected because they represent the threshold of occurrence, for a significant number of sites, of expected intensities I_{exp} IX and X, respectively. In fact, the hazard map calculated for 30 years (Fig. 8a) shows that the highest values ($I_{exp} = IX$) in the area north of Acireale are due to two seismogenic structures (Moscarello and S. Tecla faults), responsible for the largest earthquakes that have occurred in the Etna region since 1832. This result, consistent with the pattern of Fig. 7b representing the hazard deriving from local events in 50 years, indicates that in some circumstances even short (30 years) exposure times may be relevant ($I_{exp} = IX$) for purposes of seismic rules. On the other hand, for an exposure time of 70 years (Fig. 8b), an extension of the I_{exp} IX area toward north and an increase of I_{exp} X sites in the southern sector of the volcano is observed, suggesting that the influence of the regional earthquakes is predominant.

Finally, in order to represent seismic hazard as a continuous data, homogeneously spread

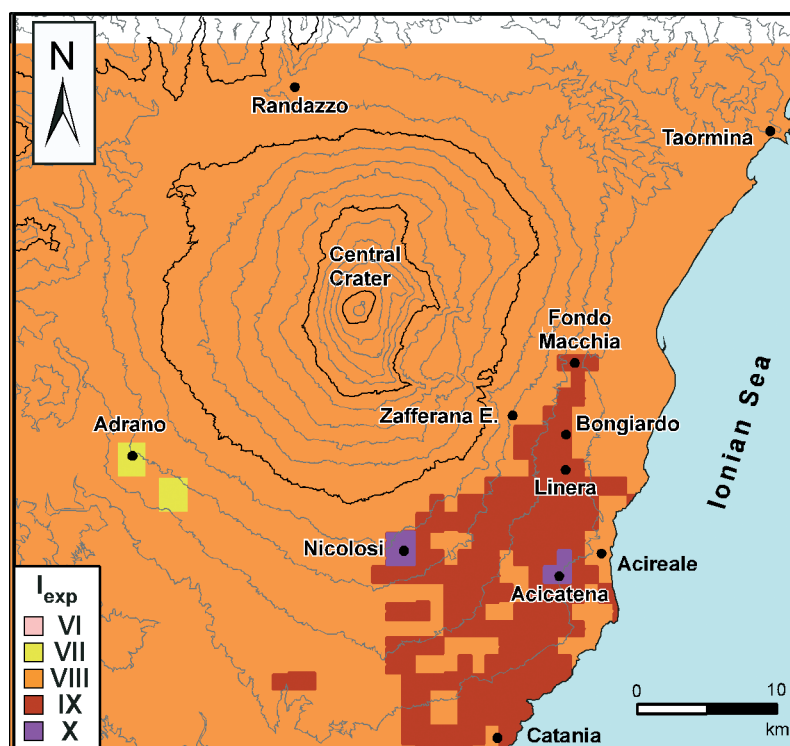


Fig. 9 - Seismic hazard map (I_{exp}) with a probability of exceedance of 10% for an exposure time of 50 years calculated on a grid with node distance of 1 km.

over the whole area, we calculated expected intensities considering a grid with a step of 1 km (Fig. 9). The map is obtained by reconstructing the seismic history for each grid node, using the value of maximum observed intensity inside a circle with radius of 1 km from the node; otherwise, if missing, the probability distribution relative to the possible local intensity values has been computed by the attenuation relationships described above. Therefore, for each grid node, the expected intensities with 10 % probability of exceedance in 50 years are computed. As expected, the map of Fig. 9 confirms the same pattern represented by points of individual localities (Fig. 7a), although the maximum and minimum values are more evident here. In particular, the small areas near Adrano with $I_{exp} = VII$ come from observed intensity data of the 1693 earthquake, while in the surrounding areas (mainly small settlements having poor seismic histories) the slightly higher values derive from calculated intensities.

5. Concluding remarks

PSHA in the Etna region has been performed through the approach proposed by Albarello and Mucciarelli (2002) based on the direct use of local intensity data and by taking into account uncertainty relating to the considered data set (ill-defined macroseismic information,

completeness, etc.). Using an upgraded intensity database, more complete than the one adopted for similar analyses at a national scale, and specific probabilistic attenuation relationships, the seismic site histories have been derived and the hazard calculated in terms of I_{exp} , i.e. the intensity value characterised by a 10% exceedance probability for an exposure time of 50 years.

The results obtained (Fig. 7a) indicate the south-eastern flank of Mt. Etna as the most hazardous sector, with I_{exp} values from IX to X. Slightly lower I_{exp} values (VIII), obtained for the western and northern flanks of the volcano, are mainly due to the greater distance from the epicentres of the regional earthquakes and to the lack of local seismic sources capable of generating strong shallow events. On the other hand, the local seismogenic structures (Moscarello and S. Tecla faults) in the eastern flank, responsible for the strongest Etnean earthquakes, influences the seismic hazard both for the mid-term exposure time (50 years, Fig. 7b) and for a shorter period (30 years, Fig. 8a).

This finding confirms that PSHA analyses carried out on small areas produce detailed mapping of the more hazardous zones, highlighting anomalies and local conditions. In the case of Mt. Etna, the very frequent seismic activity related to the active faults of the Timpe system, influences the hazard on the eastern flank of the volcano, reaching the same values of expected intensity determined by the large, but rare, regional events.

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