

## Earthquakes and faults at Mt. Etna (southern Italy): problems and perspectives for a time-dependent probabilistic seismic hazard assessment in a volcanic region

R. AZZARO<sup>1</sup>, S. D'AMICO<sup>1</sup>, L. PERUZZA<sup>2</sup> and T. TUVÈ<sup>1</sup>

<sup>1</sup> Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Catania, Italy

<sup>2</sup> Istituto Nazionale di Oceanografia e Geofisica Sperimentale, Sgonico (TS), Italy

(Received: June 9, 2010; accepted: March 10, 2011)

**ABSTRACT** We investigated the seismic potential of a given set of faults in the Etna region, by analysing the inter-event times of major earthquakes as given by the earthquake catalogue. Among the active structures of the volcano, the Timpe fault system in the eastern flank is responsible for the largest earthquakes occurred in historical times, with long-term behaviour characterised by earthquake mean recurrence times of  $\sim 20$  years for severe/destructive events (epicentral intensity  $I_0 \geq$  VIII EMS). By means of coseismic effect analyses and thanks to the peculiarity of the earthquake source in this volcanic district, we associated the seismic events to the individual seismogenic sources, obtaining the seismic history of each fault. Mean recurrence time of major events referred to a specific fault can therefore be defined. Then, we calculated the probabilities of occurrence of destructive events both with Poisson and Brownian Passage Time (BPT) models. A time-dependent BPT distribution function has been used to calculate the conditional occurrence probability for each structure of the Timpe seismogenic zone. In a memoryless perspective, the probability of having a major earthquake on individual faults is about 7% in 5 years, while it changes from fault to fault if the probability is conditioned to the time elapsed since the last event. As a result, impending earthquakes are expected on the S. Tecla fault (11%), and on the Moscarello and Fiandaca faults ( $\sim 6$ -9%), all involved in the complex dynamics of the eastern flank of Mt. Etna. These results are consistent with those obtained independently through the site approach, calculated by the SASHA code.

**Keywords:** Mt. Etna, Sicily, fault-based seismic hazard, time-dependent estimate, Brownian Passage Time.

### 1. Introduction

Fault-based and time-dependent approaches to seismic hazard maps have become popular in recent decades (e.g. WGCEP, 2003) also in areas with a low strain rate, such as Italy (Pace *et al.*, 2006; Akinci *et al.*, 2009; Peruzza *et al.*, 2010). Criticisms, [see for example Mulargia and Geller (2003)] concern the fact that they are founded on assumptions that are too simplistic (e.g., periodic model and characteristic event theory), or biased by the inadequacy of the data sets (e.g., for fault incompleteness, lack of inter-event times). Nevertheless, these studies should be a valuable complement to seismic regulation maps, as they are intended to establish priority criteria

for seismic risk reduction strategies.

A probabilistic seismic hazard assessment (PSHA) recently carried out in the Mt. Etna region (Azzaro *et al.*, 2008) indicated that the seismicity due to the activity of the “local” faults represents a significant contribution to seismic hazard, even with respect to the large regional events occurring in eastern Sicily, if short exposure times are considered. Indeed, local communities living on Etna’s eastern flank, the most densely urbanised part of the volcano, repeatedly suffer social and economic losses due to the frequent occurrence of damaging earthquakes, whose effects are somehow neglected or underestimated in the hazard assessment given on an exposure time of 50 years, the standard reference at national scale.

In the framework of the activities developed by a research project funded by the Italian Civil Protection Department and focused on the definition of the hazards related to the flank dynamics of Mt. Etna (Progetto V4 Flank, 2007-2009), we decided to use the Etna region as a lab: most of the seismogenic structures at Mt. Etna can be defined by coseismic surface displacement, and their frequent activity is documented by a long list of historically well-known earthquakes. Therefore, we applied a time-dependent approach based on the Brownian Passage Time (BPT) distribution, in order to obtain an earthquake rupture forecast for a selected group of faults, well identified in the field and with a centennial documented history of coseismic surface faulting (Azzaro, 1999). In this paper, we present the first results of the time-dependent analysis, with the main problems we faced for data validation, and show a comparison with more traditional estimates obtained under Poissonian assumptions.

## 2. Conceptual background and input data

From the seismotectonic point of view, the main features for hazard analyses in the Etna region are the general shallowness of the seismic sources (0.5-2 km) and the low values of magnitude [ $M \leq 4.7$ , Azzaro (2004)], resulting in earthquakes which very frequently produce - on average 1.6 events per year from XIX century to date - severe damage or even destruction when located close to inhabited centres. The Timpe tectonic system, in the eastern flank of the volcano, is the source area responsible for most of the strongest earthquakes known to have occurred in the last 205 years: from a total of twelve events that occurred at Etna with epicentral intensities  $I_0$  larger than degree VIII EMS [estimated according to the European Macroseismic Scale, see Grünthal (1998)], ten of them are located here (Fig. 1), thus indicating a mean recurrence time of about 20 years.

Another fundamental aspect for hazard assessment at Etna, especially for a fault-based approach, is that the strong attenuation of the seismic intensity spreading from the causative fault (Azzaro *et al.*, 2006) along with the occurrence of coseismic surface faulting (Azzaro, 1999), makes the association earthquake-fault well constrained. Starting from this latest point, we reconstructed the seismic histories at the scale of individual faults since the early-1800s (Fig. 2); unfortunately, paleoseismological investigations carried out in the Timpe area (Azzaro *et al.*, 2000b) do not provide suitable data to extend the analysis over a longer period.

A major problem, in the perspective of a time-dependent analysis, includes the question of whether fault behaviour at Etna is controlled by the volcanic activity and the related point of the constant or variable tectonic loading of the faults. Studies on the correlations of earthquakes with eruptive phases have still not reached conclusive results (Nercessian *et al.*, 1991; Gresta *et al.*,

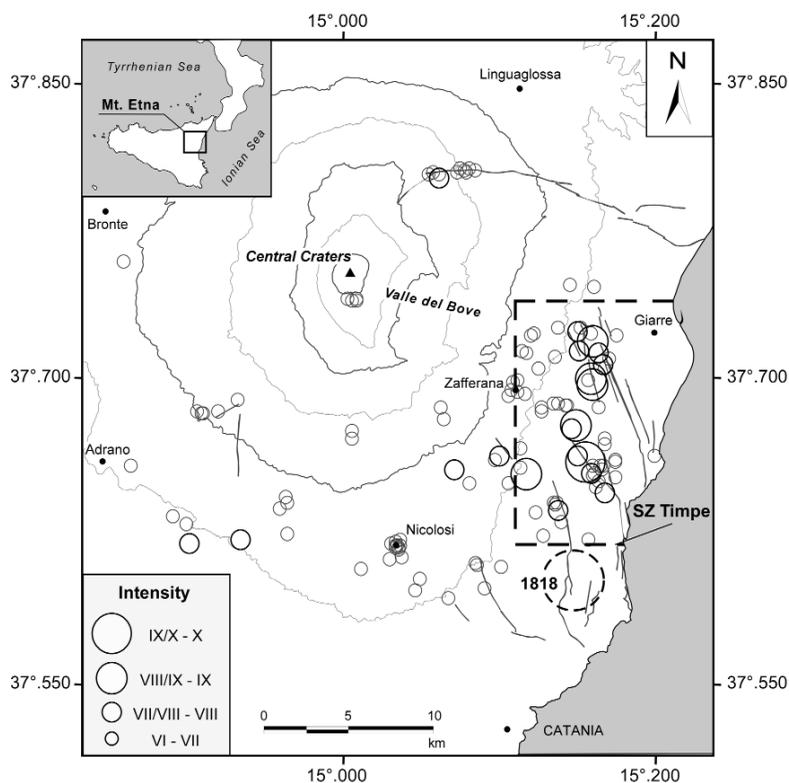


Fig. 1 - Distribution of the main seismicity ( $I_0 \geq VI$  EMS) at Mt. Etna from 1800 to 2008 (data from Azzaro *et al.*, 2000a; Azzaro and Castelli, 2009). The 1818 earthquake has been discarded from our analysis since it is a crustal event not associated with the local seismicogenic sources (Azzaro, 2004; Gruppo di lavoro CPTI, 2004).

1994; Azzaro and Barbano, 1996; Vinciguerra *et al.*, 2001; Smethrust *et al.*, 2009), and destructive earthquakes in the Timpe area occur both during flank eruptions (1865, 1879, 1911, 2002) and not [1805, 1894, 1914; earthquakes data from Azzaro *et al.* (2000a); eruptions from Branca and Del Carlo (2004)]. Conversely, large-scale flank instability at Etna appears as a continuous mode of strain, affecting the eastern sector as a whole both in the short- and long-term (Rasà *et al.*, 1996; Monaco *et al.*, 1997; Bonforte and Puglisi, 2006; Bonforte *et al.*, 2011; Chiocci *et al.*, 2011). Therefore, as is widely accepted, the deformation measured in the low eastern flank presents a continuous component of movement more typical of a tectonic process than magma-induced, transient stresses, and the Timpe system is part of a structurally homogeneous domain characterised by a general east-west extension (Lo Giudice *et al.*, 1982; Bousquet and Lanzafame, 2004), it is also reasonable to assume that faults are constantly (on average) loaded in time, as required by our time-dependent modelling.

### 2.1. The historical earthquake catalogue

The seismic data set that we used for the analysis is essentially the Macroscopic Catalogue of Mt. Etna Earthquakes [CMTE, Azzaro *et al.* (2000a)]. It is a parametric catalogue specifically

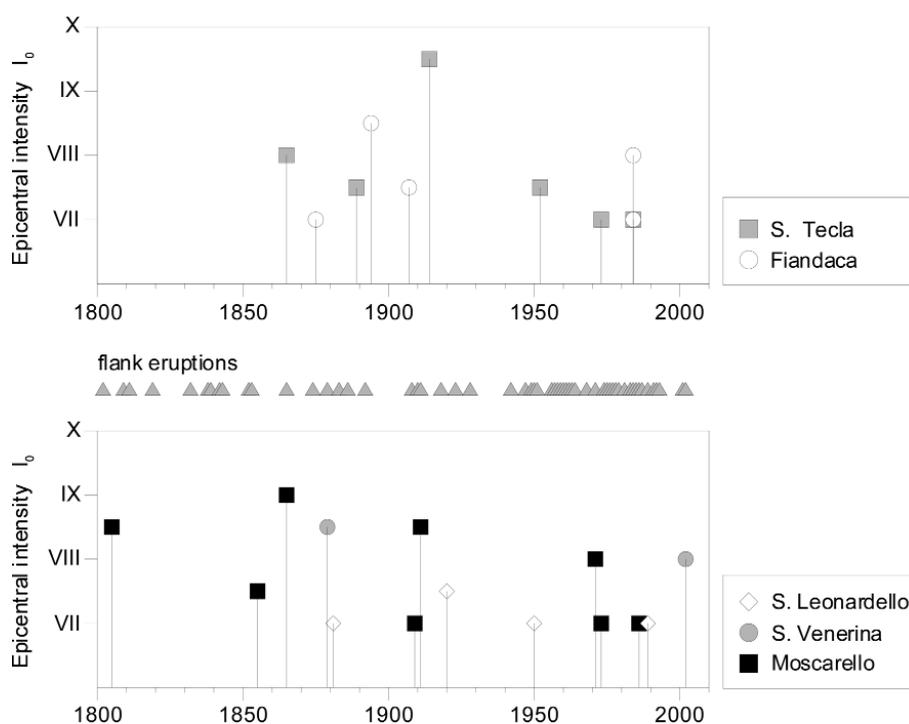


Fig. 2 - Seismic histories of the faults in the SZ Timpe reconstructed from the earthquakes with epicentral intensity  $I_0 \geq VII$  EMS associated with coseismic surface ruptures along strike [data from Azzaro (2004)].

compiled for this region which, unlike the Italian seismic catalogue (Gruppo di lavoro CPTI, 2004), does not adopt any intensity threshold (or equivalent magnitude) or space-time windows to select only the mainshocks, but includes fore- and aftershocks too. For major events the catalogue also indicates a seismogenic fault, on the basis of the interpretation of faulting phenomena, described in the coeval chronicles (Azzaro, 1999), or by analysing the distribution of more relevant macroseismic effects (i.e. damage) with respect to the structural pattern. As a result, CMTE provides a homogeneous and not declustered data set of earthquakes (1790 events in the time-span 1832-2008) suitable for time-dependent analyses. Completeness analysis obtained with a well-known software package (Wiemer, 2001), indicates that the catalogue is complete for earthquakes with epicentral intensity  $I_0 \geq VI$  EMS, i.e., for events above the damage threshold, equivalent to a macroseismic magnitude  $M_m$  3.2 according to the relationship by Azzaro and Barbano (1997). Additional data for the analysis have been taken from the preliminary results of a historical investigation aimed at extending the catalogue to the previous two centuries (Azzaro and Castelli, 2009).

For the following elaborations, we selected the earthquakes located in the seismic zone of the Timpe fault system (hereinafter called SZ Timpe, see Fig. 3), limiting our attention to the strongest earthquakes with epicentral intensities  $I_0$  ranging from VIII to IX-X EMS (i.e., from severe damage up to destruction), that correspond to a magnitude range  $M_m$  4.0-4.7. The final data cover the time-span from 1805 to 2008 and consist in nine earthquakes from 1832-2008

Table 1 - Earthquakes with  $I_0 \geq VIII$  EMS associated with the faults of the SZ Timpe, and related parameters [data from the CMTE, Azzaro *et al.* (2000a)]. The 1805 event results from specific historical investigations from Azzaro and Castelli (2009). The second earthquake that occurred in 1865 (on August 19), marked by an asterisk, was removed from the analysis as a possible non-independent event.

Fault	Date	Epical intensity $I_0$	Lat	Lon	Macroseismic magnitude $M_m$	Instrumental magnitude $M_d$
Fiandaca	1894-08-08	VIII-IX	37.653	15.110	4.3	3.9
	1984-10-25	VIII	37.660	15.095	4.1	
Moscarello	1805-07-11	VIII-IX	37.718	15.150	4.3	4.5 3.5
	1865-07-19	IX	37.702	15.153	4.5	
	1911-10-15	VIII-IX	37.699	15.154	4.3	
	1971-04-21	VIII	37.714	15.148	4.1	
S. Tecla	1865-08-19*	VIII	37.641	15.165	4.1	4.9
	1914-05-08	IX-X	37.659	15.149	4.7	
S. Venerina	1879-06-17	VIII-IX	37.678	15.143	4.3	4.4
	2002-10-29	VIII	37.674	15.143	4.1	

CMTE, plus the 1805 event taken out from the backwards extension of the catalogue (Table 1). It should be stressed that all the events are accompanied by extensive coseismic surface faulting.

### 3. Poissonian statistics on mean recurrence time

Mean recurrence time of severely damaging earthquakes ( $I_0 \geq VIII$  EMS) should be obtained from the historical rate of events, or by statistics on intertimes. The first calculation is performed by dividing the total time length of the catalogue by the number of events, as previously stated for the SZ Timpe; the second one is obtained by summing all the inter-event times divided by the sample number (in our case 8 intertimes, Fig. 4). The two results agree if the effect of “open” intervals (time lag between the starting date of the catalogue and the first earthquake, and between the last event and the catalogue end) is negligible, but intertimes in general provide more accurate results and statistical parameters of sample distribution (e.g., standard deviation).

For seismic hazard assessment under stationary assumptions, a declustered catalogue is required to ensure that independent events are considered. Catalogue declustering is not a trivial issue (see e.g. Kagan and Jackson, 1991; Zhuang *et al.*, 2002) and space-time filtering algorithms for volcanic districts have not been properly implemented. Apart from the space-time window to be used in the Etna region for this purpose, the adopted intensity threshold has identified earthquakes with indeed long intertimes (from 3 to 60 years in Table 1); we discarded only one event in 1865 from the analysis, which could not be considered independent from the one occurring the previous month. Our data set of eight intertimes might be considered not fully robust from a statistical point of view, although it represents an excellent sample when dealing for example, with paleoseismological data [see e.g., Mucciarelli (2007) and references herein]. For these reasons, we will perform Poissonian statistics on intertimes referred to the entire SZ Timpe and to individual faults, in order to derive earthquake probabilities at both scales.

A test of numerical resampling through a bootstrap procedure has been carried out in order to define the confidence intervals of the statistical parameters obtained. The bootstrap analysis

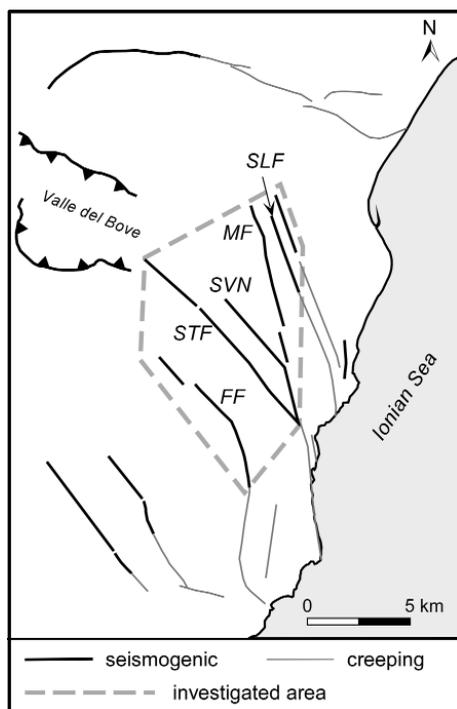


Fig. 3 - Seismotectonic model of Mt. Etna [modified from Azzaro (2004)]. Abbreviations of the studied faults inside the SZ Timpe: FF = Fiandaca; MF = Moscarello; SLF = S. Leonardello; STF = S. Tecla; SVN = S. Venerina.

involves choosing random samples with replacement from a data set and analysing each sample the same way. Sampling with replacement means that every sample is returned to the data set after sampling, so a particular intertime from the original data set could appear multiple times in a given bootstrap sample. The number of elements in each bootstrap sample equals the number of elements in the original data set. In our analysis, a resampling cycle of a 1000 times was performed and the final results represent the average of the statistical parameters, (mean recurrence time, standard deviation, standard error) obtained for each bootstrap sample. An additional verification has been made by the jack-knife sampling procedure, but it has produced the same results.

### 3.1. Intertimes inside the SZ Timpe

Table 2a reports the intertime statistics for the earthquakes with  $I_0 \geq VIII$  occurring everywhere inside the SZ Timpe, i.e., considering the time intervals of the selected events independently from their causative faults. The results from the data set indicate a mean recurrence time of 24.6 years with a standard deviation of 21.4 years; by comparison, the historical mean recurrence time (catalogue time-span divided by the earthquakes number) of the data set is  $\sim 20$  years. The aperiodicity factor  $\alpha$  is 0.87, typical of a quasi-Poisson process. The bootstrap analysis confirms these results, showing a mean recurrence time of 24.4 years, a standard deviation of 19.3 and an aperiodicity of 0.79 characteristic of a moderately Poissonian pattern.

### 3.2. Intertimes on faults

Since the main goal of this study is to investigate the process of earthquake occurrence at the

Table 2 - Statistical distribution of the intertimes (in years) for earthquakes with  $I_0 \geq VIII$  EMS referred to: a) the entire SZ Timpe; b) individual fault. The aperiodicity value  $\alpha$  is the ratio of standard deviation on mean recurrence time.

<b>a) SZ Timpe</b>	<b>Dataset</b>	<b>Bootstrap</b>
Number of intertimes	8	8
Mean recurrence time $\mu$	24.62	24.43
Standard deviation $\sigma$	21.41	19.31
Standard error	7.57	6.83
Aperiodicity $\alpha$	0.87	0.79
<b>b) Individual fault</b>		
Number of intertimes	6	6
Mean recurrence time $\mu$	71.28	71.02
Standard deviation $\sigma$	29.78	25.39
Standard error	12.16	10.36
Aperiodicity $\alpha$	0.42	0.36

scale of individual faults where elapsed times since the last event can be accounted for, we computed the mean recurrence time for intertimes of earthquakes occurring on the same structure as defined by the fault seismic histories shown in Fig. 2 and Table 1. All the faults except the Moscarello fault, have only one intertime; we grouped them all to obtain an acceptable sample size of six intertimes. By doing this, we assume that there are no significant differences between the faults, such as the main seismotectonic features common to the SZ Timpe [fault length, slip-rate, maximum observed earthquake etc, see Azzaro (2004)].

At the fault scale, the mean recurrence time is 71.3 years (Table 2b); the aperiodicity coefficient  $\alpha$  drops to values typical for periodic processes (0.42). Also in this case, the bootstrap analysis confirms the results obtained from the data set, with a mean recurrence time of 71.0 years and the aperiodicity coefficient  $\alpha$  assuming an even more periodic character (0.36).

Note that, if we follow the common practice in PSHA of partitioning the earthquake rate, calculated for a seismic zone on the number of faults existing inside it, we will obtain an underestimation of the fault seismic potential. By partitioning the SZ Timpe earthquake rate on the faults in Fig. 3, we forecast a longer mean recurrence time (98 years obtained from 24.6 by 4 faults, 123 years if the partition is made on the 5 mapped faults) with respect to the value calculated by the mean of intertimes of events effectively occurred on the individual fault (71.3 years in Table 2b).

### 3.3. Poisson probability

Considering the above-mentioned mean recurrence times, we computed the occurrence probability ( $P_{POI}$ ) of an earthquake with  $I_0 \geq VIII$  in an exposure time of 5 years according to the Poissonian assumption, by

$$P_{POI}(t) = 1 - e^{-t/T} \quad (1)$$

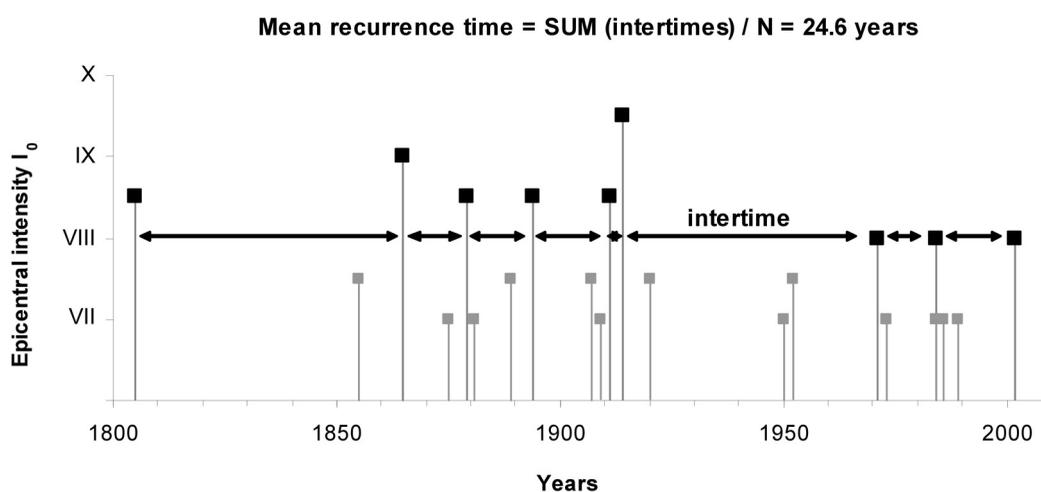


Fig. 4 - Seismic history of the entire SZ Timpe obtained by integrating the individual fault contribution shown in Table 1 and Fig. 2, and computation of the mean recurrence time from the inter-event times (intertimes). In grey, earthquakes with  $I_0 < VIII$  EMS not used in our analysis.

where  $T$  is the mean recurrence time and  $t$  is the exposure time.

Fig. 5a illustrates the values of probability obtained for a strong or destructive event in the perspective of a Poissonian process. In general, the occurrence probability of having one severe damaging earthquake somewhere inside the SZ Timpe is very high even with a very short exposure time (5 years), reaching 18.4%; it decreases to 6.8% if we assign the probability to one specific individual fault.

The mean recurrence time at the fault scale gives us an opportunity to explore how many faults inside that region are compatible with the observed seismicity. We, therefore, calculated the aggregate probabilities ( $P_{aggr}$ ) of having at least one  $I_0 \geq VIII$ , by

$$P_{aggr} = 1 - (1 - P_{F1})(1 - P_{F2}) \dots (1 - P_{Fn}) \tag{2}$$

where  $P_{F1} \dots P_{Fn}$  are the probabilities for the faults from 1 to  $n$ . During historic times only four faults were capable of generating earthquakes with  $I_0 \geq VIII$  (Table 1), while 5 structures are recognized in the field.

Starting from the value of 6.8% in 5 years referred to a single fault, the aggregated probability obtained by the activation of at least one over the 4 historically active faults (24.5%) is higher than the Poissonian hazard from the entire SZ Timpe (18.4%), but it is consistent with the estimates obtained for an exposure time of 5 years with a completely independent approach, based on the method SASHA developed by D'Amico and Albarello (2008). This approach performs a distribution free probabilistic hazard assessment by using the macroseismic intensity data available for a given locality (the so-called seismic site history), taking into account the

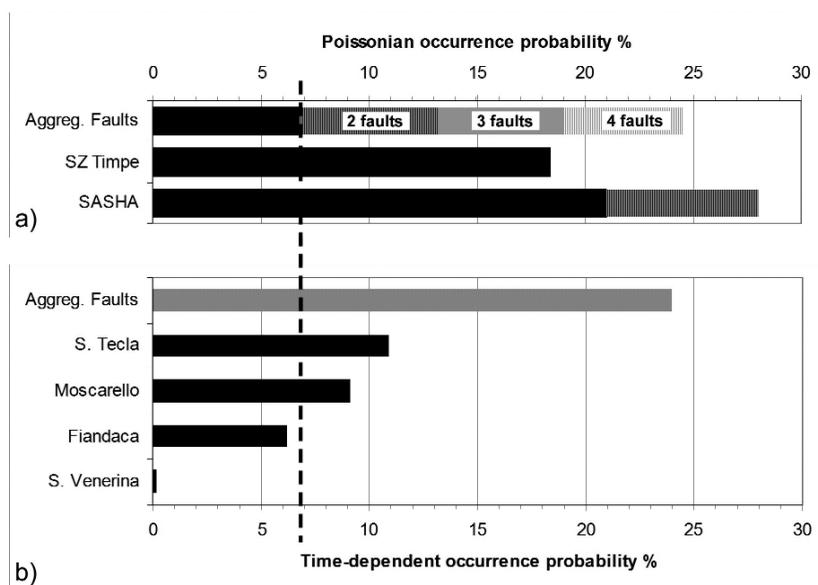


Fig. 5 - Occurrence probability for strong or destructive earthquakes ( $I_0 \geq VIII$ ) calculated according to: a) a Poissonian process, referred to any fault in the SZ Timpe in an exposure time of 5 years (2-3-4 faults indicate the aggregated probabilities, see text); b) the BPT time-dependent approach, referred to a specific fault in the next 5 years (2011-2015). The dotted line represents the Poissonian occurrence probability in 5 years.

different levels of completeness and uncertainty. In our application, we used as input data, the epicentral intensities  $I_0$  of the earthquakes associated with faults in the ZS Timpe, thus the integrated fault seismic history shown in Fig. 4. The SASHA approach gave probabilities of  $I_{ref} \geq VIII$  as high as 28% in 5 years, if uncertain intensity assignments ( $I_0 = VII-VIII$ ) are treated, and 21.4% if only  $I_0 \geq VIII$  are used. Fault-based probability (24.5%) is, therefore, inside this fluctuation, while zone-based probability (Poissonian SZ Timpe, 18.4%) is outside.

In the next section, we will demonstrate how time-dependent perspective respects and modulates this budget inside the Timpe SZ.

#### 4. BPT model on Timpe's faults

The renewal theory is the specific branch of the probability theory that generalizes the Poisson processes for arbitrary holding times. Renewal is a model where intertimes are distributed identically and are mutually independent; both Poisson and BPT models belong to renewal processes; the second one is able to represent time-dependency in a simple way, accounting for the time elapsed since the last event. The time-dependent analysis for estimating the occurrence probability of strong or destructive earthquakes on the faults of the SZ Timpe at a given date has been carried out by applying a BPT model. The relatively small data sample (6 intertimes if referred to individual faults) does not enable a choice among different distributions: we adopted the BPT distribution function, as it proves to be one of the most physically-motivated

distributions (Matthews *et al.*, 2002).

The distribution in the time  $t$  is given by:

$$P(t) = \sqrt{\frac{T_{mean}}{2\pi\alpha^2 t^3}} e^{-\frac{(t-T_{mean})^2}{2T_{mean}\alpha^2 t}} \quad (3)$$

where  $T_{mean}$  is the mean recurrence time and  $\alpha$  the aperiodicity coefficient.

In the computation, we used the mean recurrence time obtained by merging the observed intertimes on faults, as described in chapter 3.2 (Table 2b) whereas for the aperiodicity  $\alpha$  we introduced the correction proposed by Zöller *et al.* (2008), by:

$$\alpha = c_v \approx \sqrt{\frac{b}{3-b}} \quad (4)$$

where  $b$  is the  $b$ -value in the Gutenberg-Richter relationship.

Calibration of  $b$ -values has been performed jointly with an analysis of lateral variation of intertime distributions at Mt. Etna. They will be presented separately, because they are beyond the scope of this paper. Briefly, the  $b$ -value has been calculated by sampling an instrumental data set of about 4,000 earthquakes recorded at Mt. Etna from 1999 to 2009 (Gruppo Analisi Dati Sismici, 2010) on the nodes of a 1.25 km spaced grid. Completeness magnitude value for this catalogue is  $M_c \sim 1.5$  (Alparone *et al.*, 2010). The analysis indicated that the SZ Timpe is characterised by two different  $b$ -values, ranging from 0.86 in the southern and central sectors to 1.0 in the northernmost one. Then, the aperiodicity coefficients adopted in the BPT distributions are, respectively, 0.64 for the Fiandaca-S. Tecla-S. Venerina faults and 0.72 for the Moscarello fault.

The conditional probability of having an event in a defined time-span, is given by:

$$P(T_{elap} \leq T \leq T_{elap} + \Delta T | T > T_{elap}) = \frac{P(T_{elap} \leq T \leq T_{elap} + \Delta T)}{1 - P(0 \leq T \leq T_{elap})} \quad (5)$$

where  $T_{elap}$  is the time elapsed since the last event and  $\Delta T$  the time interval for which the probability is calculated (expressed in years).

Fig. 5b shows the time-dependent, hazard estimates, given in terms of earthquake rupture forecast for events with  $I_0 \geq VIII$  EMS, calculated for the next 5 years since the end of 2010 (January 2011- December 2015). Faults listed in Table 1 are represented with different bars and, by comparison, the Poissonian probability (6.8%) referred to any individual structure in a generic time-span of 5 years is also reported (dotted vertical line). The highest probabilities calculated in the period 2011-2015 (Table 3a) are related to the S. Tecla and Moscarello faults, with values of 10.9% and 9.1%, respectively; again, the Fiandaca fault has a time-dependent probability (6.2%) comparable with the value of the Poissonian assumption (6.8%). Conversely, the S. Venerina fault

Table 3 - Time-dependent conditional probabilities calculated for a) individual faults capable of generating earthquakes with  $I_0 \geq VIII$  EMS; b) the same four faults, by aggregating  $P$ . The values obtained from the Poisson approach and the SASHA methods are also indicated for comparison.

<b>a) Individual fault</b>	<b>Probability (%)</b>
S. Tecla	10.9
Moscarello	9.1
Fiandaca	6.2
S. Venerina	0.2
<b>b) Aggregated faults</b>	
BPT	24
Poisson	24.5
SASHA	21-28

presents a very low value, equal to 0.2%, as it recently slipped in 2002. These fluctuations in probability values have to be handled with care, as the statistics on intertimes is based on only 6 samples, and uncertainties in  $b$ -value assignment have only been partially exploited. Nevertheless, the differences in probability refer to a relatively short exposure interval (5 years), and they imply remarkable variations in fictitious equivalent return times, defined as:

$$T_{fictitious} = \frac{-t}{\ln[1 - P(Char\_event|telapsed)]}, \quad (6)$$

where  $P(Char\_event|telapsed)$  is the conditional probability obtained with Eq. (5). Note that the fictitious Poissonian return time for the S. Tecla fault is about 1/3 shorter than the simple Poissonian estimate ( $\sim 43$  years at the end of 2010 versus  $\sim 71$  years). In 2011, the S. Venerina fault appears to be in a “safer” condition, with a fictitious return time of thousands of years; its conditional probability is expected to recover rapidly as time goes by, and in about 20 years – if no earthquake occurs on this fault – it will again reach the Poissonian level. We believe that such a difference has a notable impact, if prioritisation schemes in seismic risk reduction strategies have to be adopted.

Finally, we calculated the aggregate probabilities for these structures as in chapter 3.3. Starting from the values that refer to the individual faults, the value of the aggregated probabilities calculated for the next 5 years on the aforementioned 4 faults is 24% (Table 3b). This result is again consistent with the estimates obtained over an exposure time of 5 years from the analysis of the fault seismic histories with the SASHA method (21-28%). These computations confirm the very high hazard inside the SZ Time even for short-term forecasts; the traditional Poissonian statistics based on intertimes of the whole SZ should underestimate it (18%). Further improvements in a fault-based and time-dependent method for hazard assessment should derive by the integration of more sophisticated ground attenuation models [obtained by deterministic

modelling of local response, as for example in the Catania area by Faccioli and Pessina (2000)].

## 5. Concluding remarks

This analysis is the first effort to introduce fault-based and time-dependent methods on the seismic hazard assessment of the Mt. Etna region, especially in the eastern flank characterised by frequent severe/destructive earthquakes, active faulting and relevant dynamics as a whole (Azzaro, 2004; Bonforte and Puglisi, 2006; Bonforte *et al.*, 2011). Good historical data enable us to have a more than 200-year long underclustered earthquake catalogue, and a reliable earthquake-fault association. We, therefore, computed the mean recurrence time of major events (epicentral intensity  $I_0 \geq$  VIII EMS) by statistics of intertimes for events assigned to the same fault. This seismicity rate is higher than the one obtained traditionally by partitioning the earthquake rate of the whole area on the mapped faults. Using a unique mean recurrence time for all the Timpe faults, two  $\alpha$  aperiodicity coefficients calibrated on the  $b$ -value of well-monitored instrumental seismicity, and the elapsed times since the last event on a fault, we modelled some BPT time-dependent processes and obtained earthquake probabilities for each fault. This method represents an alternative approach to estimate earthquake occurrence; retrospective testing of these hypotheses is currently underway.

Analyses of intertime distributions, and  $b$ -value lateral variations support the choice of considering a BPT process, basically tectonically driven, acceptable for a first approximation, for major earthquakes occurring inside this volcanic district. The probability of having a major event on an individual fault inside the SZ Timpe is about 7% in 5 years, if a Poisson process is invoked. It rises by about 1/2 when the probability is conditioned from the time elapsed since the last event: at the end of 2010, impending earthquakes are expected on the S. Tecla fault (10.9%); the Moscarello fault (9.1%) has a BPT probability higher than the Poissonian one, while the Fiandaca fault (6.2%) shows a comparable value: the S. Venerina one is the least-probable structure (0.2%), as it slipped in 2002. The time-dependent aggregate probability (24%) of having a major earthquake in the next 5 years on at least one of the four historically activated faults is consistent with the results obtained with the SASHA approach (21-28%), but it is significantly higher than the traditional zone-based Poissonian approach (18%).

Even if analyses resorting to more complex processes, and taking into account the eruptions cycles are needed, this study suggests that in a very active area such as Mt. Etna, a time-dependent approach may contribute to identify the faults with higher probabilities of generating strong earthquakes, clearly important for land planning at a local scale. It should be a valuable complement intended to establish priority criteria for seismic risk reduction action.

We plan further investigations to corroborate these preliminary considerations into a more refined framework of stress-conditions.

**Acknowledgments.** This research has benefited from funding provided by the Italian Presidenza del Consiglio dei Ministri - Dipartimento della Protezione Civile (DPC). Scientific papers funded by DPC do not represent its official opinion and policies. The authors are grateful to D. Albarello, S. Gresta and D. Pantosti for having made useful criticisms and suggestions during the preparation of this work. We also wish to thank the two anonymous reviewers for their valuable and detailed comments.

## REFERENCES

- Akinci A., Galadini F., Pantosti D., Petersen M., Malagnini L. and Perkins D.; 2009: *Effect of time dependence on probabilistic seismic-hazard maps and deaggregation for the Central Apennines, Italy*. Bull. Seismol. Soc. Am., **99**, 585-610.
- Alparone S., D'Amico S., Maiolino V. and Ursino A.; 2010: *Sismicità all'Etna dal 1989 al 2010: evidenze sull'evoluzione spazio-temporale della attività sismica*. In: Slejko D. and Riggio A. (a cura di), Gruppo Nazionale di Geofisica della Terra Solida, 29° Convegno Nazionale, Riassunti estesi della Comunicazione, Stella Arti Grafiche Trieste, pp. 5.
- Azzaro R.; 1999: *Earthquake surface faulting at Mount Etna volcano (Sicily) and implications for active tectonics*. J. Geodyn., **28**, 193-213.
- Azzaro R.; 2004: *Seismicity and active tectonics in the Etna region: constraints for a seismotectonic model*. In: Bonaccorso A., Calvari S., Coltelli M., Del Negro C. and Falsaperla S. (eds), Mt. Etna: volcano laboratory, American Geophysical Union, Geophysical monograph, **143**, pp. 205-220, doi: 10.1029/1436M13.
- Azzaro R. and Barbano M.S.; 1996: *Relationship between seismicity and eruptive activity at Mt. Etna volcano (Italy) as inferred from historical record analysis: the 1883 and 1971 case histories*. Ann. Geofis., **39**, 445-461.
- Azzaro R., and Barbano M.S.; 1997: *Intensity-magnitude relationship for the Mt. Etna area (Sicily)*. Acta Volcanol., **9**, 15-21.
- Azzaro R. and Castelli V.; 2009: *Materiali per un catalogo di terremoti etnei del periodo 1600-1831*. In: Slejko D. and Rebez A. (a cura di), Gruppo Nazionale di Geofisica della Terra Solida, 28° Convegno Nazionale, Riassunti estesi della Comunicazione, Stella Arti Grafiche Trieste, pp. 79-80.
- Azzaro R., Barbano M.S., Antichi B. and Rigano R.; 2000a: *Macroseismic catalogue of Mt. Etna earthquakes from 1832 to 1998. Upgrade 1999-2008*. Acta Volcanol., **12**, 3-36, <<http://www.ct.ingv.it/ufs/macro/>>.
- Azzaro R., Barbano M.S., D'Amico S. and Tuvè T.; 2006: *The attenuation of seismic intensity in the Etna region and comparison with other Italian volcanic districts*. Ann. Geophys., **49**, 1003-1020.
- Azzaro R., Barbano M.S., D'Amico S., Tuvè T., Albarello D. and D'Amico V.; 2008: *First studies of probabilistic seismic hazard assessment in the volcanic region of Mt. Etna (Southern Italy) by means of macroseismic intensities*. Boll. Geof. Teor. Appl., **49**, 77-91.
- Azzaro R., Bella D., Ferrelli L., Michetti A.M., Santagati F., Serva L. and Vittori E.; 2000b: *First study of fault trench stratigraphy at Mt. Etna volcano, Southern Italy: understanding Holocene surface faulting along the Moscarello fault*. J. Geodyn., **29**, 187-210.
- Bonforte A. and Puglisi G.; 2006: *Dynamics of the eastern flank of Mt. Etna volcano (Italy) investigated by a dense GPS network*. J. Volcanol. Geotherm. Res., **153**, 357-369.
- Bonforte A., Guglielmino F., Coltelli M., Ferretti A. and Puglisi G.; 2011: *Structural assessment of Mount Etna volcano from Permanent Scatterers analysis*. Geochem. Geophys. Geosyst., **12**, Q02002, doi: 10.1029/2010GC003213.
- Bousquet J.C. and Lanzafame G.; 2004: *The tectonics and geodynamics of Mt. Etna: synthesis and interpretation of geological and geophysical data*. In: Bonaccorso A., Calvari S., Coltelli M., Del Negro C. and Falsaperla S. (eds), Mt. Etna: Volcano Laboratory, American Geophysical Union, Geophysical monograph, **143**, pp. 29-47.
- Branca S. and Del Carlo P.; 2004: *Eruptions of Mt. Etna during the past 3,200 years: a revised compilation integrating the historical and stratigraphic records*. In: Bonaccorso A., Calvari S., Coltelli M., Del Negro C. and Falsaperla S. (eds), Mt. Etna: volcano laboratory, American Geophysical Union, Geophysical monograph, **143**, pp. 1-27.
- Chiocci L.F., Coltelli M., Bosman A. and Cavallaro D.; 2011: *Continental margin large-scale instability controlling the flank sliding of Etna volcano*. Earth Planet. Sci. Lett., **305**, 57-64.
- D'Amico V. and Albarello D.; 2008: *SASHA: a computer program to assess seismic hazard from intensity data*. Seismol. Res. Lett., **79**, 663-671.
- Faccioli E. and Pessina V. (eds); 2000: *The Catania Project: earthquake damage scenarios for high risk area in the Mediterranean*. CNR-Gruppo Nazionale per la Difesa dai Terremoti, Roma, 225 pp.
- Gresta S., Marzocchi W. and Mulargia F.; 1994: *Is there a correlation between larger local earthquakes and the end of eruptions at Mount Etna volcano, Sicily?* Geophys. J. Int., **116**, 230-232.
- Grünthal G. (ed); 1998: *European macroseismic scale 1998 (EMS-98)*. European Seismological Commission,

- subcommission on Engineering Seismology, working Group Macroseismic Scales. Conseil de l'Europe, Cahiers du Centre Européen de Géodynamique et de Séismologie, **15**, Luxembourg, 99 pp.
- Gruppo Analisi Dati Sismici; 2009: *Terremoti recenti localizzati con la rete sismica della Sicilia Orientale*. INGV, Catania, <<http://www.ct.ingv.it/DFS/analisti/catalogolist.php/>>.
- Gruppo di lavoro CPTI; 2004: *Catalogo Parametrico dei Terremoti Italiani, versione 2004*. INGV, Bologna, <<http://emidius.mi.ingv.it/CPTI/>>.
- Kagan Y.Y. and Jackson D.D.; 1991: *Long-term earthquake clustering*. Geophys. J. Int., **104**, 117-134.
- Lo Giudice E., Patanè G., Rasà R. and Romano R.; 1982: *The structural framework of Mount Etna*. Mem. Soc. Geol. It., **23**, 125-158.
- Matthews M.V., Ellsworth W.L. and Reasenberg P.A.; 2002: *A Brownian model for recurrent earthquakes*. Bull. Seismol. Soc. Am., **92**, 2233-2250.
- Monaco C., Tapponnier P., Tortorici L. and Gillot P.Y.; 1997: *Late Quaternary slip rates on the Acireale-Piedimonte normal faults and tectonic origin of Mt. Etna (Sicily)*. Earth Planet. Sci. Lett., **147**, 125-139.
- Mucciarelli M.; 2007: *A test for checking earthquake aperiodicity estimates from small samples*. Nat. Hazards Earth Syst. Sci., **7**, 399-404.
- Mulargia F. and Geller R.J.(eds); 2003: *Earthquake science and seismic risk reduction*. NATO Science Series IV. Earth and Environmental Sciences, Vol. 32, Kluwer Academic Publishers, Dordrecht, 338 pp., ISBN 1-4020-1777-4.
- Nercessian A., Hirn A. and Sapin M.; 1991: *A correlation between earthquakes and eruptive phases at Mt. Etna: an example and past occurrences*. Geophys. J. Int., **105**, 131-138.
- Pace B., Peruzza L., Lavecchia G. and Boncio P.; 2006: *Layered seismogenic source model and probabilistic seismic-hazard analyses in central Italy*. Bull. Seismol. Soc. Am., **96**, 107-132.
- Peruzza L., Pace B. and Cavallini F.; 2010: *Error propagation in time-dependent probability of occurrence for characteristic earthquakes in Italy*. J. Seismol., **14**, 119-141, doi: 10.1007/s10950-008-9131-1.
- Progetto V4 Flank; 2007-2009: *Pericolosità connessa alla dinamica di fianco all'Etna*. INGV-DPC research project, <[http://ctwall/flank-lava/index.php?option=com\\_content&view=article&id=12&Itemid=21](http://ctwall/flank-lava/index.php?option=com_content&view=article&id=12&Itemid=21)>.
- Rasà R., Azzaro R. and Leonardi O.; 1996: *Aseismic creep on faults and flank instability at Mt. Etna volcano, Sicily*. In: McGuire W.C., Jones A.P. and Neuberg J. (eds), *Volcano Instability on the Earth and Other Planets*, Geological Society Special Publication, **110**, pp. 179-192.
- Smethurst L., James M.R., Pinkerton H. and Tawn J.A.; 2009: *A statistical analysis of eruptive activity on Mount Etna, Sicily*. Geophys. J. Int., **179**, 655-666.
- Vinciguerra S., Latora V., Biccato S. and Kamimura R.T.; 2001: *Identifying and discriminating seismic patterns leading flank eruptions at Mt. Etna Volcano during 1981-1996*. J. Volcanol. Geotherm. Res., **106**, 211-228.
- Wiemer S.; 2001: *A software package to analyze seismicity: ZMAP*. Seismol. Res. Lett., **72**, 373-382.
- WGCEP (Working Group on California Earthquake Probabilities); 2003: *Earthquake probabilities in the San Francisco Bay Region: 2002-2031*. U.S. Geol. Surv. Tech. Rep. OFR 03-214.
- Zöller G., Hainzl S. and Holschneider M.; 2008: *Recurrent large earthquakes in a fault region: what can be inferred from small and intermediate events?* Bull. Seismol. Soc. Am., **98**, 2641-2651, doi: 10.1785/0120080146.
- Zhuang J., Ogata Y. and Vere-Jones D.; 2002: *Stochastic declustering of space-time earthquake occurrences*. J. Am. Statistical Ass., **97**, 369-380.

Corresponding author: Raffaele Azzaro

Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Catania  
Piazza Roma 2, 95125 Catania, Italy  
Phone: +39 095 7165800; fax: +39 095 7165826; e-mail: azzaro@ct.ingv.it