ESTIMATING THE EXPECTED SEISMICITY RATES OF VOLCANO-TECTONIC EARTHQUAKES AT MT. ETNA (ITALY) BY A GEOMETRIC-KINEMATIC APPROACH

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Introduction. Seismic hazard studies have been undertaken at Etna volcano in the last years with the aim of estimating the potential of local fault's activity in generating destructive earthquakes. The target is the mid-term assessment (30, 20, 10 and 5 yrs), as the identification of zones that are exposed to the recurrent seismic shaking may be important for land planning at a local scale, and it represents a valuable complement to establish priority criteria for seismic risk reduction action.

The methodologies applied at Mt. Etna area include probabilistic approaches based on the use of historical macroseismic data (the "site approach" by the software code SASHA, see Azzaro *et al.*, 2008) and fault-based time-dependent models in which occurrence probabilities of major earthquakes are estimated through the Brownian Passage Time (BPT) function and the time lapsed since the last event (Azzaro *et al.*, 2012b, 2013b). Mean return period of major earthquakes - strong to destructive events with epicentral intensity $I_0 \geq$ VIII EMS, considered as "proxies" of "characteristic" earthquakes – have been obtained by the fault seismic histories, i.e. the associations "earthquake-seismogenic fault" derived from the historical catalogue of Etnean earthquakes (CMTE Working Group, 2014). Inter-time statistics of major earthquakes have been applied to the Timpe tectonic system, considered as a homogeneous seismotectonic domain (Azzaro *et al.*, 2013b), obtaining a mean recurrence time (T_{mean}) of 71.3 years, and an aperiodicity factor α ($\sigma T_{mean}/T_{mean}$) = 0.42, typical of semi-periodic processes.

In the present study we present the preliminary results of an analysis aimed at verifying the variability of the mean occurrence times of major earthquakes generated by the main tectonic systems at Etna (Pernicana and Timpe faults) by using a geological approach based on geometric-kinematic parameters (3D dimensions, slip-rates etc) representative of fault activity.

Method and input data. The analysis has been carried out through the software code ErrorPropagation (hereinafter EP), a Matlab® routine produced in the framework of the projects DPC-INGV *S2* in order to quantify the seismic activity from geometry and slip-rates of a fault (Peruzza *et al.*, 2010; Pace *et al.*, 2013). We used the Beta version 0.15 implemented for this work with new earthquake scaling relationships for volcanic contexts.

The adopted approach is based on the assumption of seismic moment conservation. It imposes the condition that the total amount of seismic moment released by an individual seismogenic fault does not exceed the seismic moment released by the maximum expected magnitude alone. The budget is obtained by fixing the seismic moment rate of the maximum expected earthquake and by scaling the occurrence of each magnitude class properly, and can be adopted for both gaussian and G-R linear distributions.

In the probabilistic procedure for calculating the seismic hazard, the mean recurrence time (T_{mean}) of the maximum magnitude (M_{max}) expected on a fault, together with the quantification of its variability, are the basic ingredients to compute occurrence earthquake probabilities, both under Poissonian assumptions as well as in a time-dependent perspective. The best situation for a given fault segment is to have a long list of associated events, so that mean and variability derive directly from observations. The real situations in Italy of multiple characteristic events occurring on the same fault segment are definitely few, mostly represented by recent active sources along the central Apennines (e.g., Paganica fault, Galli *et al.*, 2010; Cinti *et al.*, 2011; Moro *et al.*, 2013). More favourable conditions are present at Etna, where some ten major earthquakes (M_L 4.3-5.2) repeatedly occurred along fault segments of the Timpe system (Azzaro *et al.*, 2012b).

A widely used practice invokes the criterion of "segment seismic moment conservation" proposed by Field *et al*. (1999), where the T_{mean} can be obtained by estimating the M_{max}, provided that three-dimensional geometry and slip rate of a seismogenic structure are known. Peruzza *et al*. (2010) extended this approach by introducing the estimated T_{mean} and α via errors propagation which occur in estimating maximum magnitude and slip-rate. Applying this methodology, Peruzza *et al*. (2011) demonstrated that the probability of occurrence of an event with $M> 6$ for the Paganica fault before the April 6, 2009 earthquake, considering an exposure time of 5 years, was the highest of central Apennines (~3.5%).

Actually the EP code uses as input information for each seismogenic source the following parameters:

1) fault name,
2) kinematics,
3) length along strike,
4) width along dip,
5) minimum and maximum slip-rate,
6) observed characteristic/maximum magnitude (optional),
7) standard deviation of the observed characteristic/maximum magnitude (optional),
8) elapsed time since the last characteristic/maximum earthquake (optional).

In detail the code uses different empirical and analytical relationships between the geometry of each input source and the characteristics of the expected earthquake, in order to quantify several values of M_{max} and associated T_{mean}. The EP code, therefore, formally propagates the errors of magnitude and slip-rate obtaining, for each seismogenic source, the most likely value of recurrence interval and the associated error. Finally, it uses the selected values to calculate the hazard rates, for a given exposure time, following a BPT probability density function (time-dependent) and a Poissonian distribution.

Fault parameters and earthquake scaling relationships. The analysis and integration of different types of data such as tectonics, active faulting and long-term seismicity have produced a first seismotectonic model of the Etna region including information on segmentation, kinematics and seismic behaviour (Azzaro, 2004). Later, geometry and slip-rates of active faults have been constrained by geological/geomorphological field investigations (Azzaro *et al*., 2012a), while geodetic data modelling provided information on the extension at depth of faults as well as slip-rates and kinematics in the short-term (Azzaro *et al*., 2013a). Finally, the magnitude of the historical earthquakes has been calibrated by means of new *ad-hoc* relationships in terms of M_L and M_w (Azzaro *et al*., 2011). In short, most of the input parameters needed for the EP code are available.

A scheme of the faults considered in our analysis is shown in Fig. 1, while the values of input parameters are reported in Tab. 1.

Tab. 1 - Fault and seismic parameters used in the analysis. Abbreviations: FF = Fiandaca fault; STF = S. Tecla fault; SVF = S. Venerina fault; MF = Moscarello fault; SLF = S. Leonardello fault; PF2 = Pernicana fault, central segment; kinematics 8 = extensional volcanic context.

Fault	Kinematics	Length (km)	Width (km)	Min slip-rate (mm/yr)	Max slip-rate (mm/yr)	M_{max} (observed)	σ M_{max}	Elapsed time (yrs)
FF	8	7.7	3.5	0.9	1.1	4.8	0.36	120
STF	8	7.6	5	4.2	4.4	5.3	0.36	100
SVF	8	5.6	5	0.9	1.1	4.8	0.36	135
MF	8	8	3.5	1.4	2.7	5.1	0.36	149
SLF	8	4	3.5	2.5	2.7	4.4	0.36	113
PF2	8	4.5	5.7	3.3	5.2	4.3	0.3	4

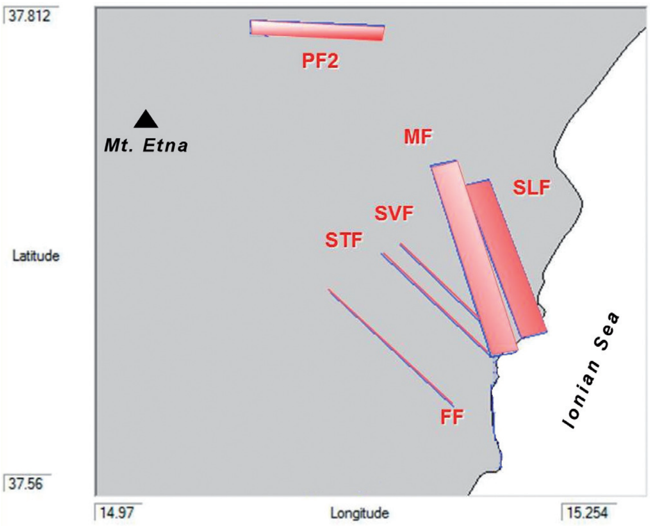

Fig. 1 – Pattern of the seismogenic fault segments modelled in this study; the boxes represent the projection at the surface of the fault planes, the lines indicate vertical planes (modified from Azzaro *et al*., 2013a). For abbreviations see Tab. 1.

The only ingredient missing from the aforementioned list is a relationship between magnitude and rupture length suitable for the Etnean earthquakes, since the equations derived for purely tectonic domains are proven to be inapplicable for Etna, for the different magnitude range and because tend to overestimate the earthquake fault dimension (Azzaro, 2004). To this end, we extrapolated a new empirical relationship specific for the Etna region by using the coseismic surface faulting dataset by Azzaro (1999), updated to 2013. The result is represented in a logarithmic scale in Fig. 2, where our relationship is compared with the one obtained by Villamor *et al*. (2001) for the Taupo volcanic zone (New Zealand). Considering the different magnitude range the relationships have been calibrated from, and the adopted correlation of x-axes due to the use of different dimensional parameters (subsurface fault length for Etna, and rupture area for volcanic NZ sources) obtained taking into account aspect ratio relationships (Peruzza and Pace, 2002), the agreement is actually satisfactory. Note analogies and discrepancies with respect to the relationships suggested by the review paper Stirling *et al*. (2013) [two different equations for thick crust volcano-tectonic contexts: Wesnousky (2008) and Mason (1996); normal fault], and

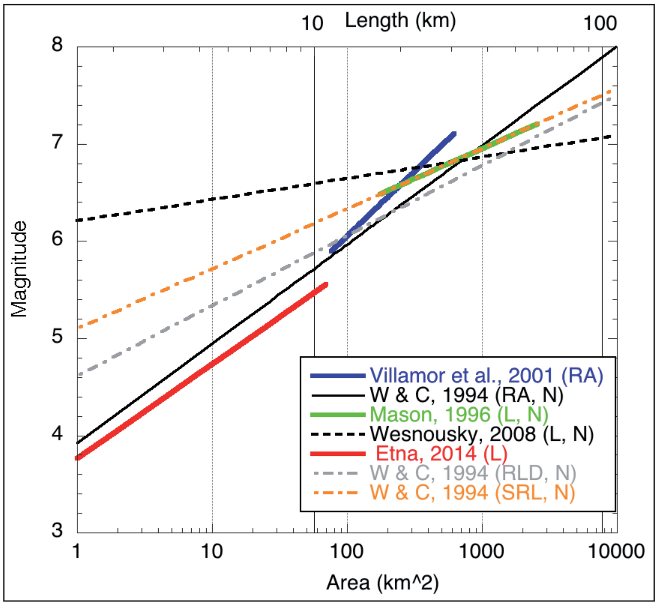

Fig. 2 – Plot of magnitude vs. surface rupture length equations for the Etna region (this study) and Taupo volcanic zone (Villamor *et al*., 2001), compared with worldwide relationships for tectonic domains (Wells and Coppersmith, 1994; Mason, 1996; Wesnousky, 2008).

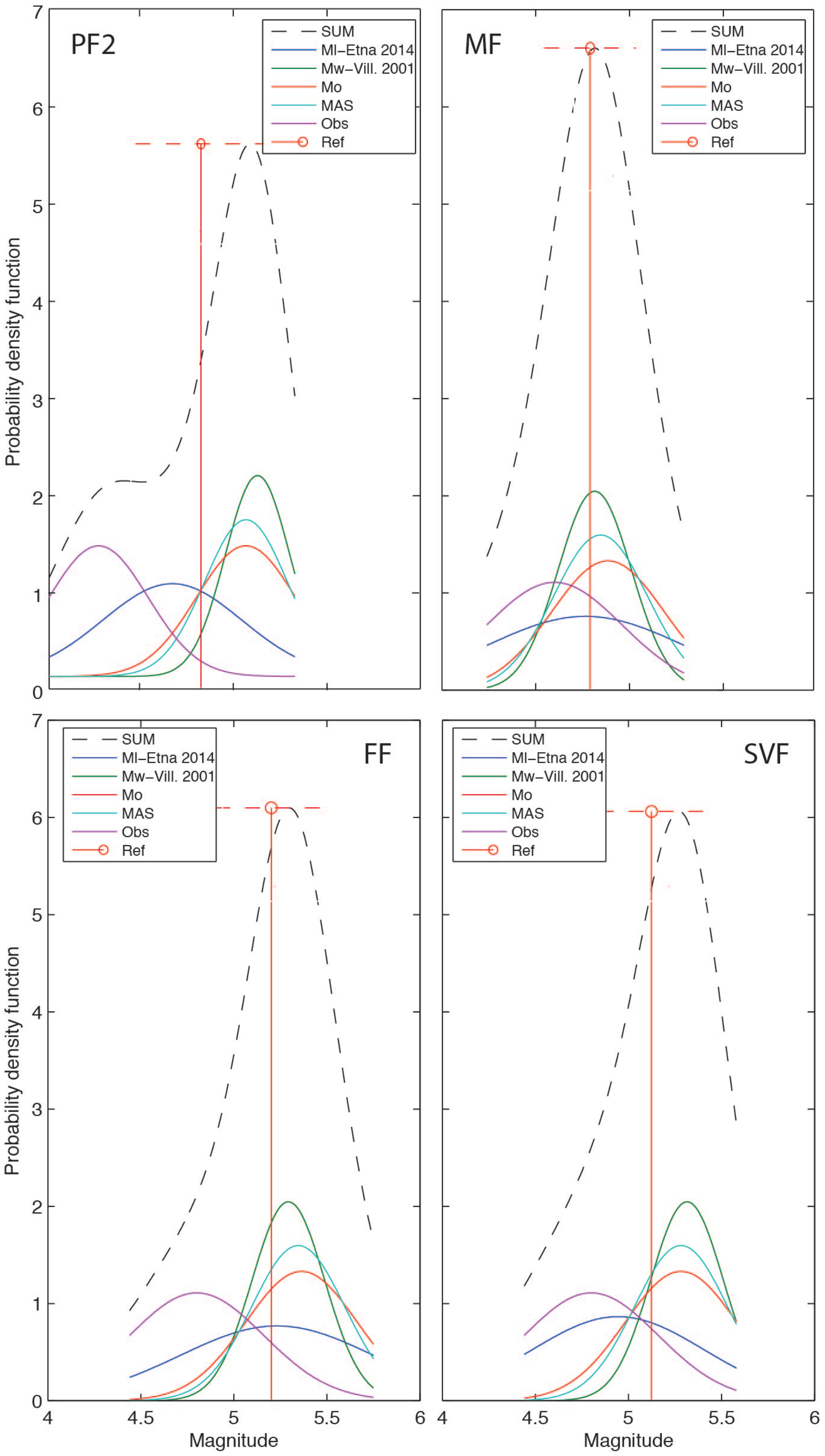

Fig. 3 – Maximum magnitudes (M_{max}) estimated by the EP code for some of the studied faults (abbreviations as in Tab. 1); the dimensions of the curves are in agreement with the relative uncertainties.

with respect to the worldwide used relationship (Wells and Coppersmith, 1994) here given as a function of rupture area, subsurface rupture length and surface rupture length (all referred to normal faults). It is important to highlight that the Wells and Coppersmith (1994) relationships are extrapolated outside its definition ranges and applied to volcano-tectonic environments. These considerations suggested us introducing the Villamor *et al.* (2001) relationship in the area-based computations of EP code, but leaving the Wells and Coppersmith (1994) ones.

The EP code, in addition to the $M_{max}s$ calculated by the above defined empirical scaling relationships, defines for each fault other two expected M_{max}: one from the general formula of magnitude as a function of the scalar seismic moment (M0 in Fig. 3), starting from a constant strain drop value (here 2×10^{-5}); and the other (MAS in Fig. 3) by using the aspect ratio relationships derived by Peruzza and Pace (2002) on a slightly modified Wells and Coppersmith (1994) data set.

Preliminary results and conclusions. The output of the EP code applied to the Etna case is reported in Tab. 2, where the most likely values of characteristic expected magnitude (M_{char}) with the associated standard deviation σ, the corresponding mean recurrence times (T_{mean}) and the aperiodicity factor α, are indicated for each fault.

Tab. 2 - Output of EP code for the studied faults. The characteristic magnitude (*Mchar*) is calculated according to the Etna *SRL-M* relationship shown in Fig. 2. Fault abbreviations as in Tab. 1.

Fault	M_{char} (calculated)	σ M_{char}	T_{mean} (yrs)	α
FF	5.2	0.3	264	0.54
STF	5.4	0.2	67	0.47
SVF	5.1	0.3	182	0.52
MF	5.3	0.2	138	0.59
SLF	4.8	0.3	45	0.52
PF2	4.9	0.4	27	0.65

The obtained α values suggest fault behaviours potentially modelled by a time-depended approach.

Fig. 3 reports the calculated M_{max} values for four faults, following all the different approaches with the associated uncertainty and, if available, the observed (historical) M_{max}. The upper curve ('SUM' in Fig. 3) represents the summation of the M_{max}'s, treated as probability density functions, in order to evaluate a reference "mean" value ('Ref' in Fig. 3). This representation is useful to evaluate whether the observed M_{max} value is in agreement or not with the values of maximum rupture calculated (M_{char}) from the geometry/kinematic. It is important to stress that the M_{max} values calculated by the different methods are comparable, also with the observed historical earthquakes except the case of PF2 and partially the SVF. As regards PF2, the partial discrepancy between the M_{max} calculated by the proposed Etna scaling relationship and the others values, can be ascribed to the "strange" fault geometry showing a length along dip (*W*) larger than the one along strike (*L*).

The results of this work, actually in progress, suggest that a geological approach based on geometric-kinematic parameters to estimate the expected seismicity rates can be adopted with success on the volcanic context of Etna. A comparison between our results with scalar moment rates estimated from seismic and geodetic data will provide important constraints on the fault parameters and validate the goodness of the methodology.

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