# Ground motion attenuation for volcanic zones in Europe

**E. Faccioli, M. Vanini & M. Villani**
*Department of Structural Engineering, Politecnico di Milano, Italy*

**SUMMARY:**
To comply with the seismotectonic regionalization framework set forth in European project SHARE, we address the task of providing ground motion attenuation equations (GMPE) appropriate for volcanic zones in Europe, lying essentially in Central and Southern Italy, Iceland, and the Azores (Portugal). The study is conducted using as reference data a limited set of accelerograms recorded at close distances in the latter zones from events in the 3.5 ÷ 4 Mw magnitude range. Attenuation predicted through numerical simulations using the $\omega$-square source model (consistently with an earlier study), as well as through a recent GMPE that takes focal depth into account is compared with the data. While numerically based predictions provide acceptable response spectrum estimates at distances <15 km, the empirical GMPE do an overall better job and capture the observed distance attenuation rate, higher than standard geometrical spreading.

*Keywords: attenuation of spectral ordinates, volcanic earthquakes, numerical simulations, shallow focal depth*

## 1. INTRODUCTION

As shown in a new seismotectonic regionalization map of Europe ('**Figure 1**'), active volcanoes – identified by red symbols - are associated with seismically active zones essentially in Iceland, in Italy, in the Azores archipelago and, to a lesser extent, in the Aegean Sea. The map in question, produced in the European Project SHARE (http://diss.rm.ingv.it/SHARE/), was developed for the main purpose of providing a rational basis for the choice of Ground Motion Prediction Equations (GMPEs) appropriate for each region. Active volcanic zones occupy only small extensions of land, and the seismic activity generated in them tends to be obscured by that of the much larger seismic provinces in which they lie. Nevertheless, the scientific community has recognized that the attenuation of ground motion from earthquakes occurring in volcanic zones deserves (at least in principle) special consideration, because of the shallow focal depths and of the peculiarity of near-surface geology. This contribution, stemming from the senior author's involvement as an external expert in SHARE, addresses precisely the task of defining/selecting GMPEs appropriate for volcanic zones, within the unified approach to seismic hazard estimation in Europe which is the core task of the project.

We begin with volcanic zones in Italy, since the effects of local earthquakes therein have been often damaging and are historically well documented (see e. g. the Macroseismic Database of Italy (http://emidius.mi.ingv.it/DBMI11/). In such zones, earthquakes typically in the 3.5 < M < 5.0 magnitude range have been observed to generate locally strong ground motion, causing building damage in a limited area close to the epicenter, associated to a fast attenuation of the shaking severity with distance. We recall, among other examples:
- the 1971 ($M_w$ 4.9) Tuscania earthquake 80 km NW of Rome, occurring in the Quaternary Roman Magmatic province, presently regarded as inactive, which caused severe damage and MCS intensity as high as VIII-IX in Tuscania (http://emidius.mi.ingv.it/DBMI11/), located as shown in '**Figure 2**', and
- the October 29, 2002 ($M_w$ 4.8) earthquake near Mt. Etna (Sicily), the highest active volcano in Europe. This event, despite its moderate magnitude, caused damage to many buildings including some reinforced concrete ones. The zone affected extended for about 4 km, with maximum MCS intensity

VIII. The event was recorded by both SM accelerographs and BB velocity meters (www.earth-prints.org/bitstream/2122/2086/1/etnacov4.ppt).
In volcanic zones the strong ground motion within an area of small extension and the rapid decay with distance are controlled on one hand on the shallow focal depth of the events, typically less than 5 km. On the other hand, the strong attenuation in the upper layers of volcanic geological formations also depends on the presence of highly fractured rocks possibly filled by gas or viscous fluids, which tend to lower the capability of transmitting the high-frequency ground-motion (see e.g. Patanè et al., 1994).

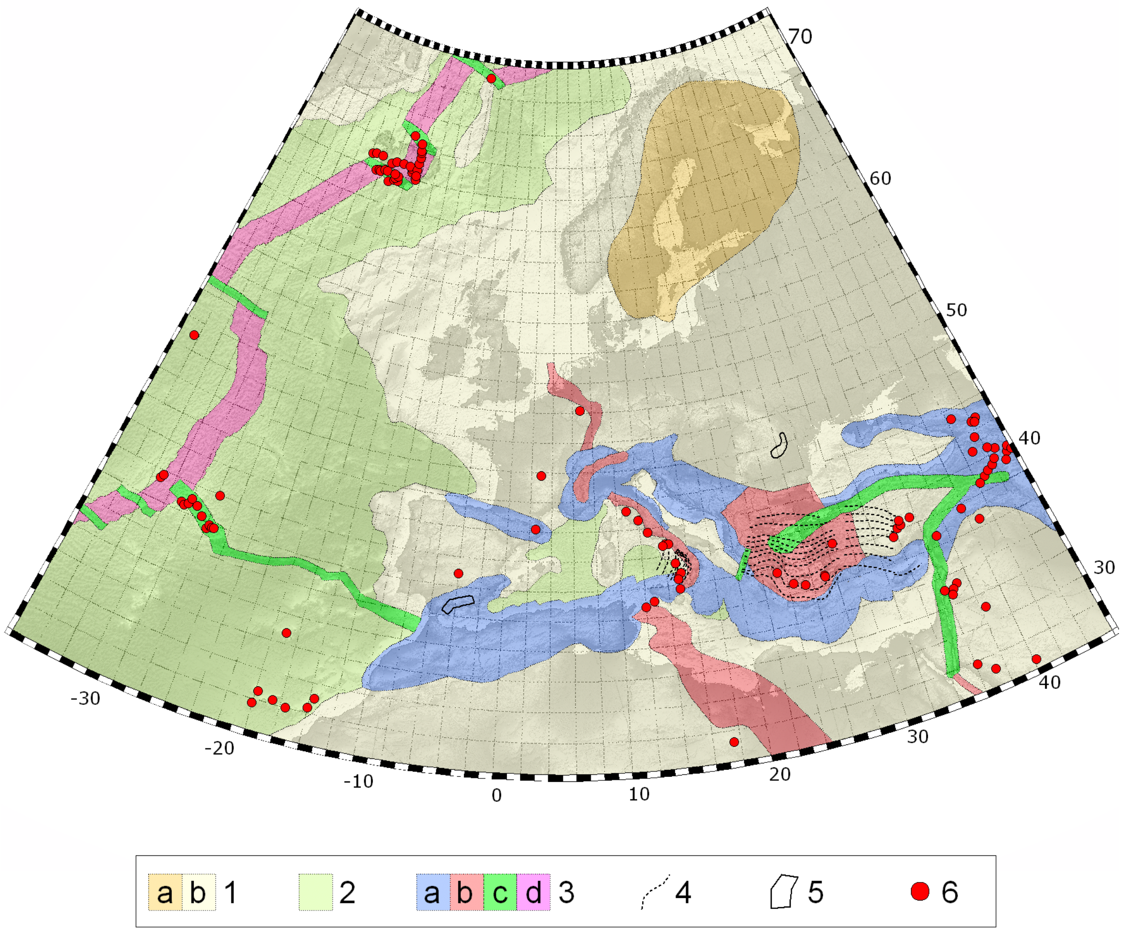


**Figure 1.** Seismotectonic map of the Euro-Mediterranean area developed in the SHARE European project (August 2011). 1: Stable Continetal Regions (SCR) where 1(a) indicates "shield" and 1(b) "continental crust". 2: oceanic crust; 3: Active Shallow Crustal Regions (ASCR) with 3(a) compression-dominated areas, 3(b) extension-dominated areas, 3(c) major strike-slip faults and transforms and 3(d) mid oceanic ridges; 4: subduction zones shown by contours at 50 km depth interval of the dipping slab; 5: areas of deep-focus non-subduction earthquakes; 6: active volcanoes and other thermal/magmatic features. (Courtesy R. Basili)

With few exceptions (e. g. Hawai), seismic hazard in active volcanic regions around the world has in the past been evaluated without using specific predictive relations or adjustments accounting for the peculiar propagation characteristics of these regions. In earlier seismic hazard maps of Italy (Slejko et al., 1998) attenuation in the main volcanic areas has been accounted for, in a rough way, by simply reducing the predicted ground-motion by a fraction of the standard deviation. However, specific GMPEs had more recently been introduced for volcanic zones in the elaboration of the current seismic hazard map for Italy (Montaldo et al., 2005). Such attenuation relations were based on numerical simulations using a point source $\omega$ -square model with a geometric spreading inversely proportional to focal distance and the factor $\kappa$ for near site attenuation, following the approach adopted in De Natale et al. (1988) to model weak earthquake motions recorded in 1982-84 in the Campi Flegrei volcanic field near Naples. The GMPEs in question, numerically generated through random vibration theory for magnitude ranging between 3.0 and 6.5 and focal distance $\leq$ 20 km, had not been checked for consistency with SM data because records available from the published databases were not considered sufficient.

Upon searching the databases almost ten years later, we found that the limitation arising from the scarcity of SM data could be partially removed. Thus, we revisited the numerical simulation approach of De Natale et al. (1988) as a starting point towards establishing GMPEs applicable to volcanic zones, and satisfying the requirements of project SHARE (Delavaud et al., 2012). The following sections describe how this task was addressed. On one hand, a non-parametric attenuation description (in the form of tables) was developed for this purpose from numerical simulations. On the other hand, the applicability of a recent, empirical GMPE that can handle shallow focal depths was also tested against the data for comparison.

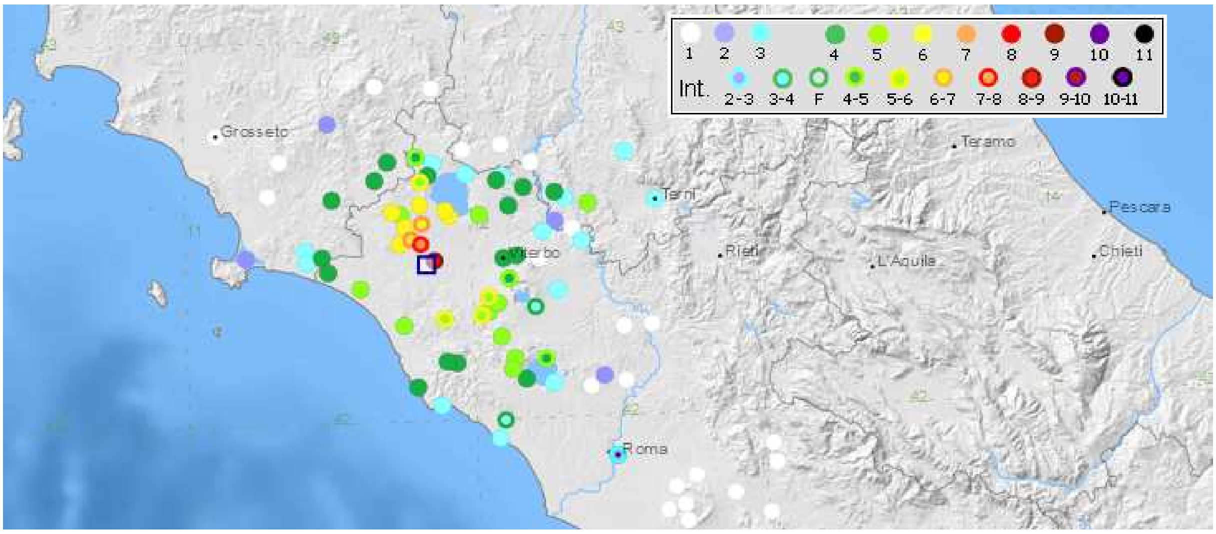


**Figure 2.** 1971 Tuscania, Central Italy, earthquake ($M_w$ 4.9): map of felt MCS intensity, from http://emidius.mi.ingv.it/DBMI11/.

## 2. DATA

To enhance the applicability of the results of this study to a broader context, after collecting an initial set of data from Italy we extended the search of SM records to the other active volcanic zones of Europe, i. e. the Azores archipelago (in Portugal) and Iceland. We could thus identify a small number of suitable records from the latter regions, limiting the search to earthquakes with shallow focal depth (not exceeding about 7 km for consistency with the Italian data).

From the SM database ITACA (http://itaca.mi.ingv.it/ItacaNet/), an initial dataset of 36 records from the volcanic zones of Central and Southern Italy was selected and analyzed, including some from events of magnitude as low as 3+. The records selected come from the Mt. Amiata geothermal area in Southern Tuscany, and the Mt. Etna volcano in Sicily. Using the horizontal waveforms, we estimated seismic moment $M_0$, stress drop $\Delta\sigma$, and corner frequency $f_c$ from the low frequency spectral levels, through the Brune model (Brune, 1970) and the expressions given in Andrews (1986). The near-site attenuation parameter $\kappa$ was estimated from the slope of Fourier acceleration spectra at high frequencies plotted in log-linear scale, following Andreson and Hough (1984). Since for practically all the events considered only a single station record was available, the estimates of the foregoing parameters are inevitably affected by considerable uncertainty.

Table 1 shows the Italian SM records that were finally retained (as a basis for the simulations) with the estimated parameters, while '**Figure 3**' (left panel) depicts the location of the earthquake epicenters and the SM stations from the Mt. Etna area. Note that ground category A applies for all recording sites, lying typically on lava flows or other volcanic rocks, except for the Catania Piana (CAT) accelerograph site, located on deep soil sediments, a short distance outside the volcanic structure of Mt. Etna.

**Table 1.** Selected SM records from volcanic areas in Central and Southern Italy, from ITACA database. Stations PNS and PNC are from Mt. Amiata volcanic and geothermal area, while stations BNT, SVN and CAT lie in Mt. Etna area. $R_{epi}$ and $R_{hypo}$ are the epicentral and hypocentral distances. Mean estimates of source parameters (including moment magnitude, stress drop $\Delta\sigma$, and corner frequency $f_c$) after Brune model, from the two horizontal components, are given. Local magnitude $M_L$, focal depth and $R_{epi}$ are from record header information.

| Station name | Ground type (EC8) | date | Code | $M_L$ | Focal depth [km] | $R_{epi}$ [km] | $R_{hypo}$ [km] | PGA [cm/s$^2$] | Mean estimates from Brune's model | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | $M_w$ | $\Delta\sigma$ [bar] | $f_c$ [Hz] |
| Piancastagnaio | A | 01/04/2000 | PNS | 3.9 | 2 | 1.64 | 3.19 | 107.13 | 3.8 | 99.51 | 2.9 |
| Piancastagnaio Natali | A | 01/04/2000 | PNC | 3.9 | 2 | 2.25 | 3.56 | 155.98 | 3.8 | 95.47 | 3 |
| Bronte | A | 27/10/2002 (01:58) | BNT#1 | 4.4 | 6 | 12.93 | 14.67 | 12.87 | 3.9 | 69.64 | 2.61 |
| Bronte | A | 22/04/2001 | BNT#2 | 3.9 | 0 | 14.28 | 14.31 | 8.75 | 3.5 | 53.64 | 3.5 |
| Bronte | A | 27/10/2002 (02:50) | BNT#3 | 4.8 | 0 | 23.08 | 23.1 | 8.44 | 4.0 | 85.86 | 2.43 |
| Bronte | A | 27/10/2002 (01:28) | BNT#4 | 4.1 | 0 | 31.04 | 31.05 | 4.03 | 3.8 | 46.62 | 2.4 |
| S. Venerina | A | 21/10/2005 | SVN#1 | 3.2 | 5 | 2.23 | 5.87 | 67.05 | 3.6 | 159.15 | 4.71 |
| S. Venerina | A | 28/10/2005 | SVN#2 | 3.1 | 3 | 1.34 | 3.68 | 48.2 | 3.3 | 80.1 | 5.1 |
| S. Venerina | A | 30/10/2005 | SVN#3 | 3.1 | 6.6 | 6.17 | 12.06 | 18.17 | 3.4 | 80.14 | 4.97 |
| S. Venerina | A | 01/08/2007 | SVN#4 | 3 | 4 | 6.17 | 7.59 | 13.8 | 3.5 | 59.19 | 4 |
| Catania Piana | D | 29/10/2002 | CAT#1 | 4.5 | 6 | 19.68 | 20.58 | 9.5 | 3.9 | 51.14 | 2.4 |
| Catania Piana | D | 27/10/2002 | CAT#2 | 4.8 | 0 | 35.74 | 35.74 | 3 | 3.7 | 28.24 | 2.35 |
| Catania Piana | D | 22/07/2004 | CAT#3 | 2.9 | 0 | 27.91 | 27.91 | 0.86 | 3.4 | 15.53 | 2.7 |



**Figure 3.** Selected events (red stars for epicenters) and SM selected stations (blue squares): from the Mt. Etna volcano area (left panel), in Eastern Sicily, and from the Azores Islands (right panel).

Table 2 shows the SM records collected from the ESMD database (Ambraseys *et al.*, 2002) for the Azores and Iceland, processed with the same criteria and method as Italian data. All the Azores data were recorded at station HOR on soft soil, while the Iceland data were recorded on rock. '**Figure 3**', right panel, shows the epicenters and SM stations in the Azores. '**Figure 4**' shows an example of recorded time histories, with an event from Mt Etna collection and an event from the Azores islands, having comparable $M_L$ and epicentral distance. Note the lower amplitudes in the Mt Etna record, probably due to the different soil conditions (hard ground compared to soft one).

**Table 2.** Selected SM records from the Azores Islands (in Portugal) and Iceland. Mean estimates after Brune model, from the two horizontal components, are given.

| Earthquake Name | Date | Focal depth [km]* | $M_L$ | Station Code | Local Geology | $R_{epi}$ [km] | PGA [%g] | Mean estimates from Brune's model | | | Fault Dist. [km]** | Focal depth [km]** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AZORES | | | | | | | | $M_w$ | $\Delta\sigma$ [bar] | $f_c$ [Hz] | | |
| Faial (aftershock) | 19/07/1998 20.05.49 | 6 | 3.4 | HOR | soft soil | 12 | 1.325 | 3.7 | 80 | 3.25 | 13.79 | 7 |
| Azores | 24/02/1999 10.10.18 | 7 | 3.5 | HOR | soft soil | 18 | 0.183 | 3.2 | 17 | 3.72 | 18.48 | 4 |
| Azores | 12/10/2001 2.36.19 | 7 | 3.5 | HOR | soft soil | 13 | 0.601 | 3.5 | 38 | 3.16 | 15.68 | 9 |
| Faial (aftershock) | 04/08/1998 3.27.34 | 2 | 3.8 | HOR | soft soil | 17 | 1.244 | 4.0 | 103 | 2.64 | 17.36 | 4 |
| ICELAND | | | | | | | | | | | | |
| Mt. Hengill Area | 14/03/1996 5.34.56 | - | 3.6 | 102 | rock | 4 | 8.318 | 3.8 | 82 | 2.90 | 6.534 | 5 |
| N of Hveragerdi | 12/04/1997 23.04.44 | - | 3.8 | 102 | rock | 8 | 4.047 | 3.8 | 88 | 3.00 | 10.659 | 7 |

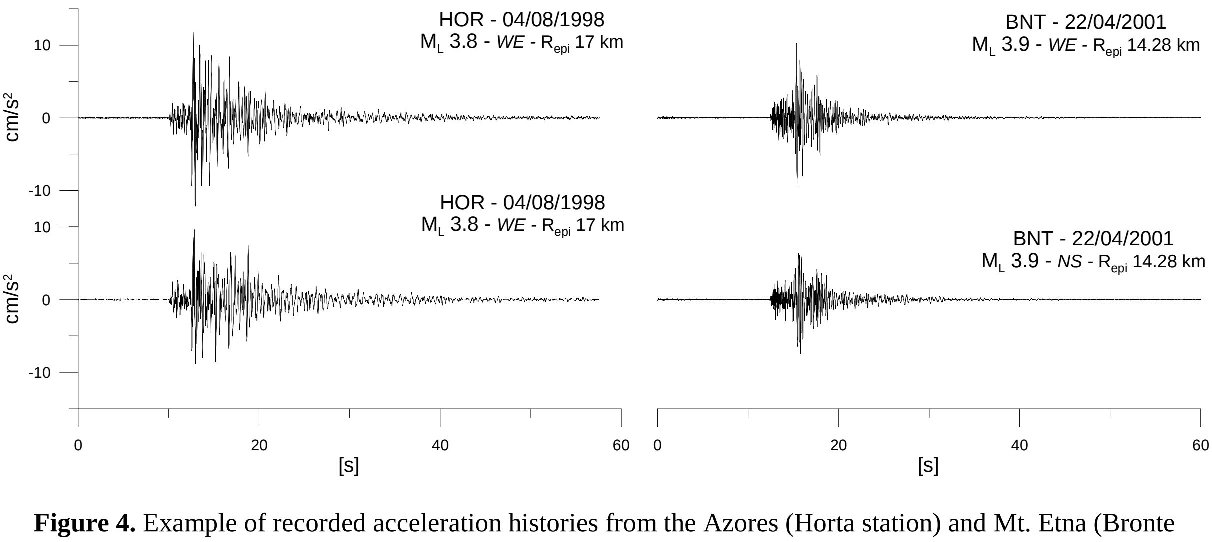


**Figure 4.** Example of recorded acceleration histories from the Azores (Horta station) and Mt. Etna (Bronte station) with similar magnitude and distance but different site conditions.

## 3. NUMERICAL SIMULATION APPROACH

We started from the work in De Natale *et al.* (1988), who analysed 40 digitally recorded velocity histories of small earthquakes ($0.7 \le M_L \le 3.2$), at distances typically 3 to 6 km, from the Campi Flegrei volcanic field near Naples, Italy. The authors were able to accurately reproduce the observed PGA and PGV dependence on seismic moment using the stochastic method of Boore (Boore, 1983). Thus, we numerically generated acceleration time histories using the same method, where the motion attenuates as the inverse of focal distance and undergoes a high frequency decay $e^{-\pi\kappa f}$, $\kappa$ being the near site attenuation parameter, consistently with Brune (1970). Therein, anelastic attenuation (described by a $Q$-factor) had been disregarded, due to the small epicentral distances involved, and we conformed to the same assumption. From the synthetic accelerograms, attenuation tables for peak values and response spectral ordinates were obtained. In the numerical simulations, $\Delta\sigma$ values between 5 and 90 bar were introduced, as well as an S wave velocity $\beta$ = 2.0 km/s and $\kappa$ = 0.015. For each magnitude, distance and $\Delta\sigma$ value, 50 accelerograms were stochastically generated. Seven $\Delta\sigma$ values were chosen in the indicated range, after analyses of the SM records selected (see Table 1 and Table 2). The simulations were performed for 21 hypocentral distances between 0.01 and 78 km (spaced at constant intervals in log scale) and for 5 magnitude values (3.5, 4.0, 4.5, 5.0, 5.5). Since the magnitude and distance ranges covered by the simulations considerably exceed those of the data, the applicability of the results will need further checking.

Most of the variability associated to the predicted strong motion parameters is generated by the range of the assumed stress drop values. This range has been based on the comparison between data and synthetics in terms of response spectral ordinates (see '**Figure 5**'). Thus, the selected stress drop values are between 5 and 90 bar. For a fixed stress drop, the variability arising from the randomness of the Gaussian noise used in the simulations is limited, and significantly lower than the sigma of current data-based GMPEs.

'**Figure 5**' compares the median attenuation curves obtained from the simulations for different acceleration response spectrum ordinates (and three different stress drops) with those estimated by the recent GMPE of Faccioli et al. (2010) and with the observed spectral accelerations of the records in Table 1 and Table 2. The GMPE in Faccioli et al. (2010) uses the distance from fault rupture ($R_{rup}$) as distance measure, which reduces to $R_{hypo}$ for $M$< 5.5, and is therefore appropriate to handle the shallow focal depths of earthquakes in volcanic zones. The same would not generally be true for GMPEs that use the Joyner and Boore distance as distance measure, and are therefore insensitive to focal depth, such as Akkar and Bommer (2010).

While for $T \leq 0.2$ s the agreement between simulated curves and recorded data is satisfactory up to about 15 km focal distance (i.e. the range of interest) especially for $M$~4.0, at longer periods the simulations underestimate the data and indicate that the $R_{hypo}^{-1}$ attenuation is not adequate. On the other hand the empirical GMPE (Faccioli *et al.*, 2010), with a magnitude dependent attenuation rate, clearly does better in reproducing the data trends, owing to a decay rate that increases with distance. The less satisfactory performance observed for $M_w$ 3.5 at $T$ = 0.2 s may be explained by recalling that $M_w$ 4.5 is the lower magnitude in the reference dataset used in the derivation of this GMPE.

## 4. PREDICTION OF RESPONSE SPECTRAL ORDINATES

As mentioned, for each magnitude, each distance and for each spectral ordinate the variability in the response spectral acceleration has been sampled through the variability of the stress drop (7 values between 5 and 90 bar) and the inherent stochastic variability of the Boore method (Boore, 1983). The sample thus consisted of 350 simulated accelerograms for each magnitude-distance pair.

To select an appropriate probability distribution for the representative shaking parameters, the simulated data have been statistically analyzed by performing visual tests, that graphically compare the data and the probability density function of the selected distributions, and standard goodness-of-fit tests. The visual tests showed that both lognormal and gamma distributions can fit the data, but the tests of hypotheses rejected both distributions for $T$ < 0.5 s, while for $T \geq 0.5$ s the tests were passed. A lognormal distribution was finally adopted.

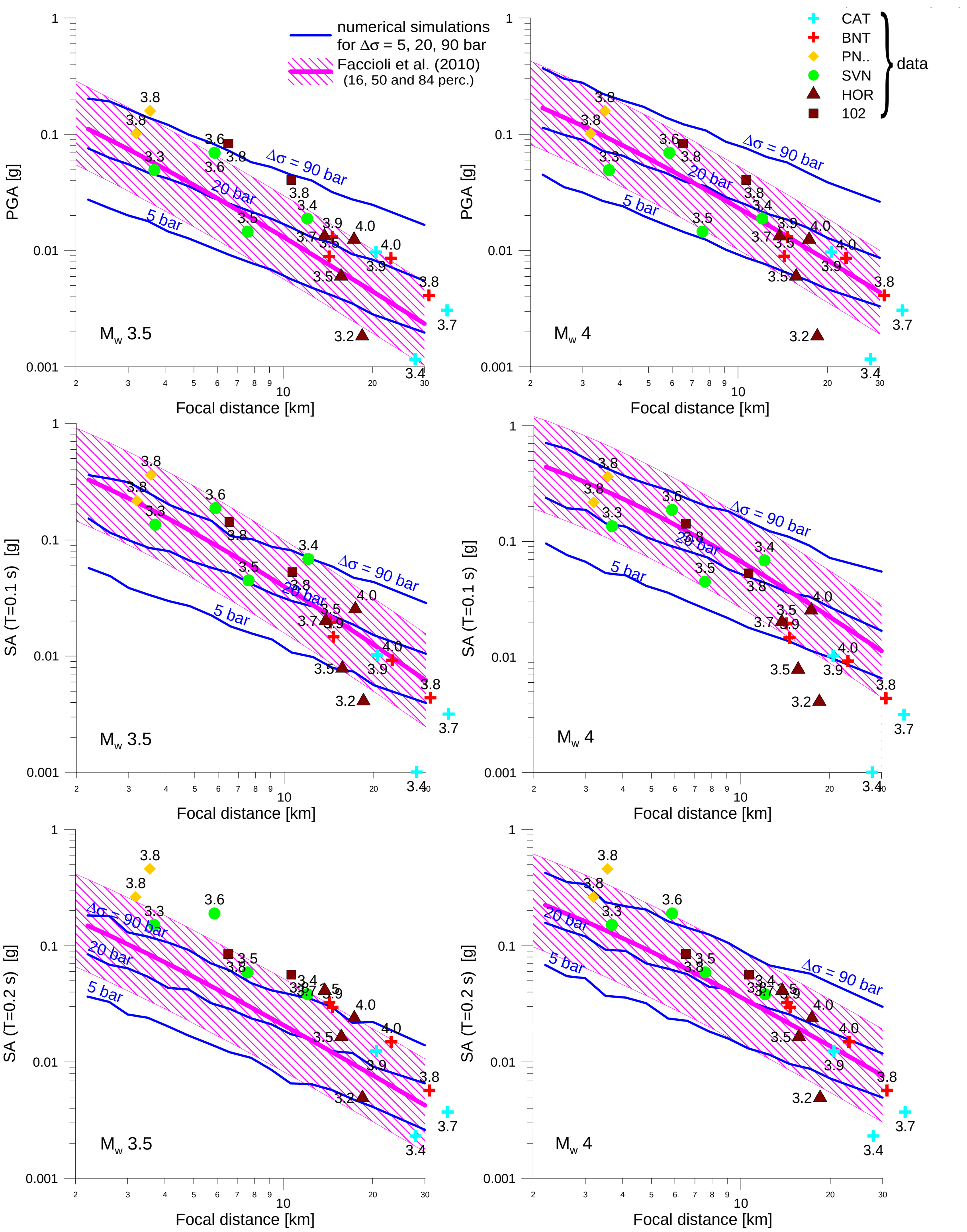


**Figure 5.** Comparison between the attenuation curves for acceleration response spectrum ordinates SA with 5% damping at period $T$ = 0.0, 0.1, and 0.2 s, obtained from the numerical simulations for different stress drop values (blue curves) as in De Natale *et al.* (1988), the curves estimated by the GMPEs of Faccioli *et al.* (2010) (median and dispersion band, in magenta) and the observations from the records in Table 1 and Table 2 (yellow symbols for PNS and PNC, green for SVN, light blue for CAT, red for BNT and brown for HOR, Azores, and 102, Iceland, data). Numbers close to symbols indicate estimated $M_w$ magnitudes. Panels to the left and to the right are for $M_w$=3.5 and $M_w$=4, respectively.

The s. e. of the logarithm of the predicted spectral accelerations as a function of the period were computed for all distances and magnitudes. It was observed that the dependence of the s. e. on distance is negligible, while magnitude plays a significant role. Thus, the final s. e. was considered to be a function of period and magnitude.

### 4.1. Attenuation with distance

The simulation based attenuation curves (median and dispersion band) with focal distance have been computed for each spectral ordinate in the range of 0 s $\leq T \leq$ 4 s, and for all magnitudes. As illustrated in '**Figure 6**', the dispersion bands vary considerably with magnitude, keeping however always smaller than those predicted by Faccioli *et al.* (2010).

It is evident that the attenuation numerically simulated through the $\omega$-square model, even if applicable only for limited focal distances, is to some extent contrary to expectations, since it is slower than that typified by Faccioli *et al.* (2010) for Active Shallow Crustal Regions.

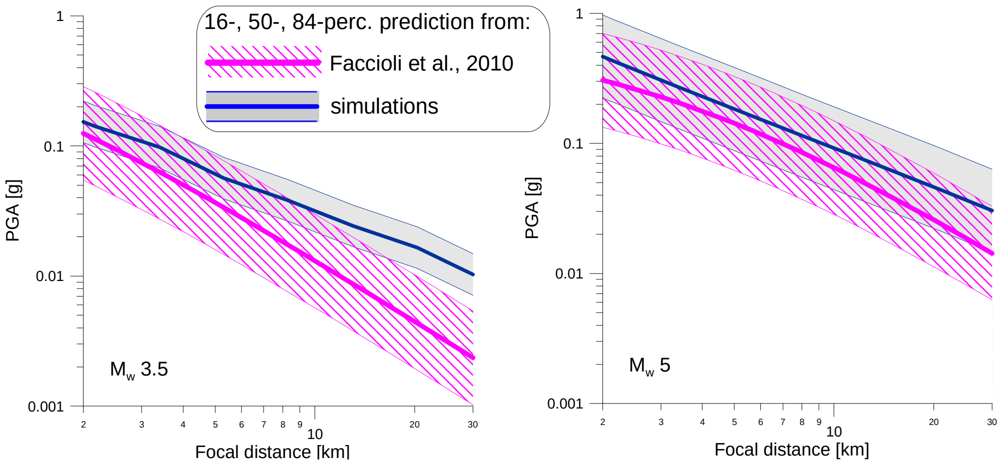


**Figure 6.** Attenuation curves (median and dispersion band) obtained from this study (for $T$=0 s and magnitudes $M_w$ 3.5 and 5), and from Faccioli *et al.* (2010). Because of the low magnitude values involved, the fault distance (metric of Faccioli *et al.*, 2010) was assumed equal to the focal distance.

### 4.2. Predicted vs, observed response spectra

'**Figure 7**'compares the response spectra computed from the records in Table 1 for the SVN and PNC stations and in Table 2 for the Iceland earthquakes with the simulation based spectra of this study, and also with the spectra predicted by the GMPE in Faccioli et al. (2010). The agreement is satisfactory in most cases. Both the Faccioli et al. (2010) GMPE and the simulated spectra of this study (especially at the 84.1-percentile level) seem able to capture the main features of the observed ground motion.

For a few sites (namely CAT and BNT), significant differences between predictions and observations both in amplitude and in spectral shape. For CAT, site effects were considered partly responsible for the discrepancies as the site is on very deep soft sediments instead of hard ground. To cast light on this problem, a 1D linear deconvolution of the recorded time histories has been performed, in order to remove site amplification effects. The results are not shown for brevity, but the spectra obtained after the deconvolution, even adopting a $\kappa$ value as high as 0.05, still different substantially from the observed ones. The anomalous low frequency content in the records of a class of earthquakes in the Mt. Etna area has been discussed elsewhere (Milana *et al.*, 2008). Moreover, for CAT and BNT focal distances are higher than for other events, affecting significantly their attenuation behavior. This confirms that the simulation method adopted may not be suitable for focal distances exceeding ~ 15 km.

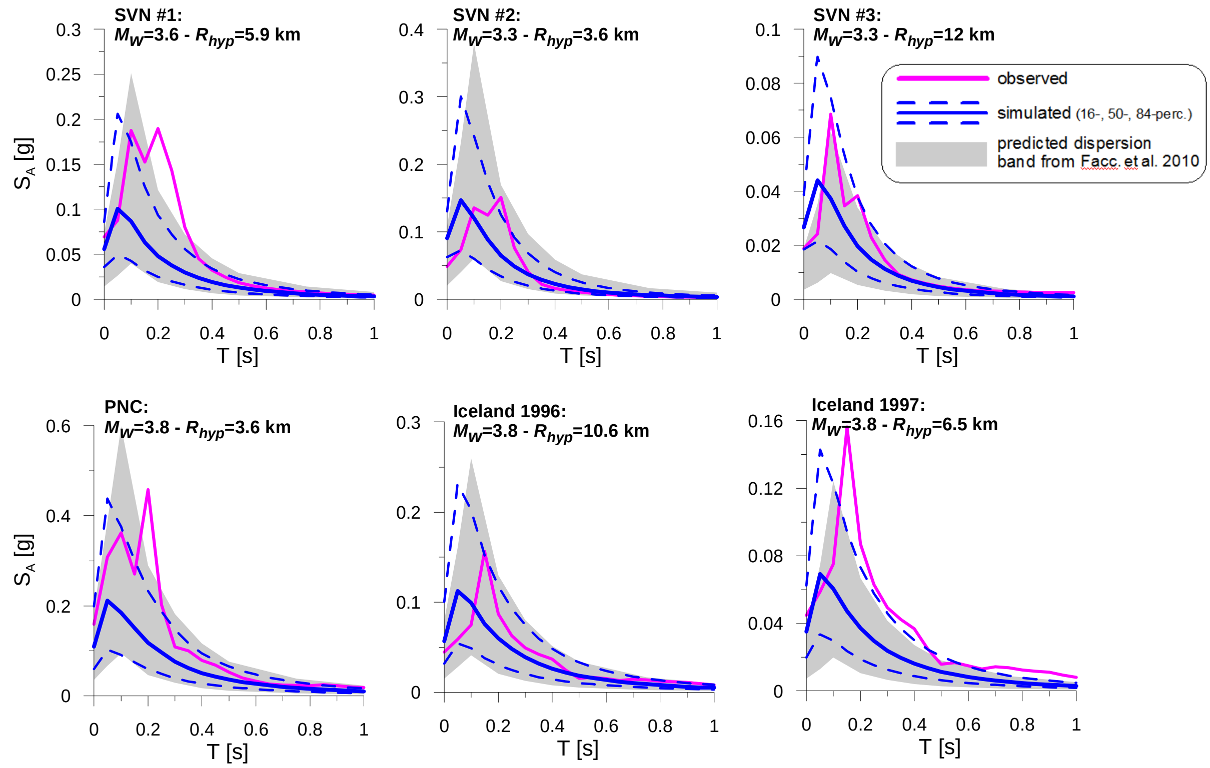


**Figure 7.** Comparison of the 0.05 damped acceleration response spectra from the SM accelerograms recorded at SVN and PNC of Table 1 and the two Iceland earthquakes (Table 2), represented as the geometric mean of the two horizontal components, with the median and dispersion band from the present simulation based spectra (blue curves) and with those predicted by Faccioli *et al.* (2010) (grey shaded band). Simulations performed with $\kappa$= 0.015.

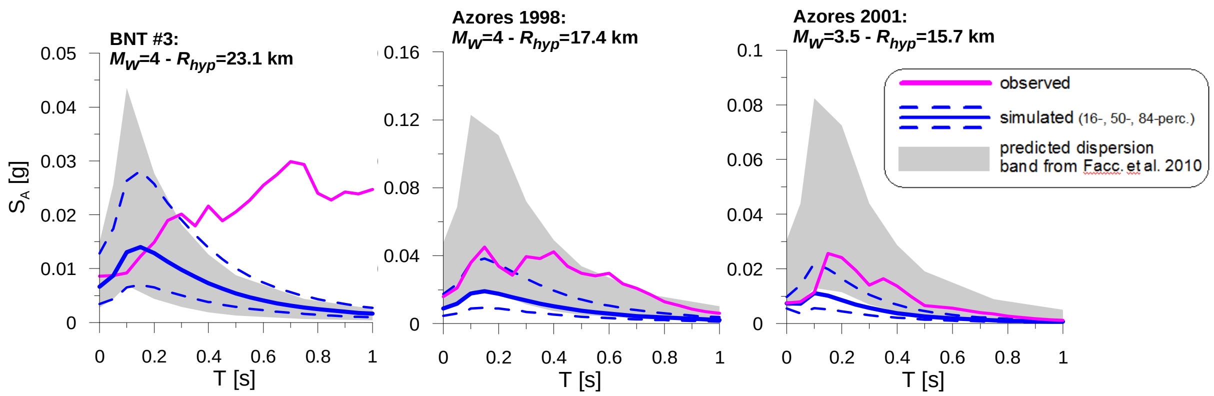


**Figure 8.** Comparison of the 0.05 damped acceleration response spectra from the records at BNT (Mt. Etna) of Table 1 and the four Azores earthquakes of Table 2, represented as the geometric mean of the two horizontal components, with the median and dispersion band derived from present simulation based spectra (blue curves) and those predicted by the Faccioli *et al.* (2010) model (grey shaded band). Simulations performed with $\kappa$=0.05.

'**Figure 8**' compares the simulation based spectra with those observed for the Mt. Etna BNT station and during the Azores earthquakes. In both cases the synthetics were generated with $\kappa = 0.05$, since for BNT this value is closer to that estimated from the data, while for the Azores station, lying of soft soil, a value of 0.05 has been considered more appropriate. The predictions using Faccioli *et al.* (2010) have been performed for soil type A in the case of BNT and for soil type C for the other stations. Neglecting the noted anomalous behavior of BNT, the agreement between the observed spectra from the Azores with those predicted through the numerical GMPEs of this study is reasonable, and it becomes somewhat better by using Faccioli *et al.* (2010). The tendency of the spectral ordinates predicted in this study to be on the low side with respect to the data confirms that the numerical attenuation model is mostly appropriate for rock sites.

## 5. CONCLUSIONS

Our study on the attenuation of spectral acceleration parameters in volcanic zones of Europe has shown that the limited SM observations available can be reasonably well predicted by recent global GMPEs with distance decay rate dependent on magnitude, provided they take focal depth into account ( such as by using $R_{hypo}$ or $R_{rup}$ as distance measure), as in Faccioli *et al.* (2010). This is because earthquakes in volcanic areas considered herein have depths mostly not exceeding 6 or 7 km.

On the other hand, an approach based on stochastic simulations using an $\omega$-square model (point source) with near site attenuation ($\kappa$ factor), suggested by earlier studies conducted in Italy, proved less satisfactory, mostly due to the inadequacy of the attenuation rate imposed by standard ($R^{-1}$) geometrical spreading.

## REFERENCES


Akkar, S. and Bommer, J.J. (2010). Empirical equations for the prediction of PGA, PGV and spectral accelerations in Europe, the Mediterranean region and the Middle East. Seismological Research Letters, **81:2**, 195–206.

Ambraseys, N., Smit, P., Sigbjornsson, R., Suhadolc, P. and Margaris, B. (2002). Internet-Site for European Strong-Motion Data, European Commission, Research-Directorate General, Environment and Climate Programme. http://www.isesd.hi.is.

Anderson, J.G. and Hough, S. (1984). A model for shape of Fourier amplitude spectrum of acceleration at high frequencies, Bull. Seism. Soc. Am., **74**, 1969-1994.

Andrews, D.J. (1986). Objective determination of source parameters and similarity of earthquakes of different size, Earthquake source mechanics, Maurice Ewing Series 6, AGU, Washington D.C., 259-267.

Boore, D.M. (1983). Stochastic simulation of high frequency ground motions based on seismological models of the radiated spectra, *Bull. Seism. Soc. Am.*, **73**, 1865-1894.

Boore, D.M. and Atkinson, G.M. (2008). Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01 s and 10.0 s, *Earthquake Spectra*, **24:1**, 99-138.

Brune, J.N. (1970). Tectonic stress and the spectra of seismic shear waves, *J.G.R.*, **75**, 4997-5009.

De Natale, G., Faccioli, E. and Zollo, A. (1988). Scaling of peak ground motions from digital recordings of small earthquakes at Campi Flegrei, Southern Italy, *Pageoph*, **126:1**, 37-53.

Delavaud, E., Cotton, F., Akkar, S., Scherbaum, F., Danciu, L., Beauval, C., Drouet, S., Douglas, J., Basili, R., Sandikkaya, A., Segou, M., Faccioli, E. and Theodoulidis, N. (2012). Toward a ground-motion logic tree for probabilistic seismic hazard assesement in Europe, *J. of Seismology*, DOI 10.1007/s10950-012-9281-z.

Faccioli, E., Bianchini, A. and Villani, M. (2010). New ground motion prediction equations for *T*>1 s and their influence on seismic hazard assessment, *Proc. of the University of Tokyo Symposium on Long-Period Ground Motion and Urban Disaster Mitigation*, March 2010.

Milana, G., Rovelli, A., De Sortis, A., Calderoni, G., Coco, G., Corrao, M. and Marsan, P. (2008). The role of long-period ground motions on magnitude and damage of volcanic earthquakes on Mt. Etna, Italy, *Bull. Seism. Soc. Am*, **98:6**, 2724-2738.

Montaldo V., Faccioli, E., Zonno, G., Akinci, A. and Malagnini, L. (2005). Treatment of ground-motion predictive relationships for the reference seismic hazard map of Italy, *J. of Seismology*, **9**, 295-316.

Patané, D., Ferrucci, F. and Gresta, S. (1994). Spectral feature of microearthquakes in volcanic areas: attenuation in the crust and amplitude response of the site at Mt. Etna, Italy, *Bull. Seism. Soc. Am.*, **84**, 1842-1860.

Slejko, D., Peruzza, L. and Rebez, A. (1998). The seismic hazard maps of Italy, *Ann. Geofis.*, **41**, 183-214.