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Ground-Motion Variability for Single Site and Single Source through Deterministic Stochastic Method Simulations: implications for PSHA

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Abstract

The ground motion median and standard deviation of empirical Ground Motion Prediction Equations (GMPEs) are usually poorly constrained in the near-source region due to the general lack of strong motion records. Here we explore the use of a deterministic-stochastic simulation technique, specifically tailored to reproduce directivity effects, to evaluate the expected ground motion and its variability at a near-source site and seek a strategy to overcome the known GMPEs limitations.

To this end, we simulated a large number of equally-likely scenario events for three earthquake magnitudes (M7.0, M6.0 and M5.0) and various source-to-site distances. The variability of the explored synthetic ground motion is heteroscedastic, with smaller values for larger earthquakes. The standard deviation is comparable with empirical estimates for smaller events and reduces by 30-40% for stronger earthquakes.

We then illustrate how to incorporate directivity effects into PSHA analysis. This goal is pursued by calibrating a set of synthetic GMPEs and reducing their aleatory variability (~50%) by including a predictive directivity term that depends on the apparent-stress parameter obtained through the simulation method. Our results show that, for specific source-to-site configurations, the nonergodic PSHA is very sensitive to the additional epistemic uncertainty that may augment the exceedance probabilities when directivity effects are maximized.

30   The proposed approach may represent a suitable way to compute more accurate hazard estimates.

31   **Key words:** *seismogenic sources, finite fault simulations, near source, directivity effects, ground*

32   *motion variability, seismic hazard, Southern Italy*

33

Introduction

35   Practical seismic hazard applications require the ground motion component to be explored for

36   various possible events that could affect a site of interest. The hazard assessment can either be

37   carried out through probabilistic or deterministic approaches with the main difference between the

38   two methods residing in the time variable, which is absent in the deterministic method (Bommer,

39   2002). A probabilistic approach typically explores all possible earthquake magnitudes, above a

40   given minimum, sampled from an established Frequency-Magnitude Distribution (FMD), usually in

41   the form of a Gutenberg-Richter power law generated by all possible seismic sources. Conversely,

42   deterministic approaches usually explore one or few controlling events generated by one or few

43   seismic sources. The controlling event or events could be the Maximum Credible Earthquake (e.g.

44   Mualchin, 1996), or the earthquakes that may cause a pre-defined level of damage or malfunction

45   (e.g. for nuclear facilities the Seismic Level 1 or Seismic Level 2; IAEA, 2002, 2010).

46   Recommendations on how to carry out these analyses are included in regulations for designing new

47   buildings or critical infrastructures or for retrofitting purposes (e.g. ASCE, 2005, 2010; BSSC,

48   2009). Other fields of interest, however, are also the preservation of cultural heritage and the

49   actions undertaken for civil protection purposes (e.g. training and plans for emergency response and

50   post-earthquake recovery).

51   For both the probabilistic and deterministic approaches, the accuracy of the predicted ground-

52   motion amplitude is a fundamental issue (McGuire, 1995; Chapman, 1995; Bazzurro and Cornell,

53   1999; McGuire, 2001), especially when the analyzed site and the seismic source are very close one

54   to another. In such a case, the ground motion median and standard deviation evaluated from any

55   Ground Motion Prediction Equation (GMPE) are usually poorly constrained due to the general lack

of strong motion records in near-source conditions. In addition, the ground motion variability associated with a single fault is even more difficult to be assessed because multiple records of earthquakes generated by the same fault rarely exist. Finite-fault simulations can represent a valid alternative to overcome the limitations of GMPEs, especially in the near-source region, where the ground motion is dominated by effects due to the finiteness of the source, such as directivity, fault hanging-wall/foot-wall relative position to the site, radiation-pattern, and slip distribution. Directivity effects, in particular, have the largest impact on the ground motion variability at low and intermediate frequencies, causing amplification at sites in the forward direction of the rupture (Ruiz-García, 2011).

The use of numerical simulations is recently increasing and a number of initiatives worldwide are promoting their application for hazard assessment purposes (Graves et al., 2010; Dreger and Jordan, 2015). The CyberShake Project promoted by the Southern California Earthquake Center (Graves et al., 2010), extensively utilizes 3D numerical simulations coupled with kinematic source models to compute low-frequency ground motions (up to 0.5Hz) and assess deterministic and probabilistic seismic hazard in Southern California. The related hazard maps differ from the classical ones based on empirical GMPEs for including long-period effects, such as basin and directivity effects. Although these methods improve the ground motion description, they require very high-performance computational resources to be applied on a routinely basis.

One possible strategy to inject simulated ground motion into Probabilistic Seismic Hazard Analysis (PSHA) is by means of the computation of generalized attenuation functions (GAFs). GAFs replace the empirical predictions with large sets of numerical simulations from which derive the first two moments of the ground motion parameters probability distributions (Convertito, 2006; Faccioli, 2013; Villani et al., 2014). The GAFs can be generated with different simulation codes (purely deterministic, stochastic, hybrid) depending on the target of the hazard analysis, but they should be validated beforehand by the comparison with observed records (Goulet et al., 2015). Convertito (2006) used a high-frequency deterministic technique for the prediction of the ground motion in a

82 characteristic earthquake and showed the effect of the source radiation pattern and directivity at

83 several sites around the fault. Villani et al. (2014) used 3D numerical simulations to demonstrate

84 how near-source high-resolution representation of hazard, which accounts for combined 3D effects

85 (site effects, basin effects, and topographic features), is more realistic than those purely based on

86 traditional GMPEs.

87 In this work, we explore the use of a deterministic-stochastic simulation method (DSM, Pacor et al.,

88 2005) to predict the ground motion close to the source, assess its variability, and calibrate synthetic

89 attenuation models - including directivity effects - to be incorporated into PSHA. This study is

90 timely in order to integrate the selection of GMPEs for the current update of the Italian seismic

91 hazard map (MPS16, see Data and Resources).

92 To this end, we set up a case study for the city of Cosenza, southern Italy, a densely populated city

93 with a rich heritage of historic buildings, located in one of the Italian regions characterized by the

94 highest seismic hazard (as for the MPS04, the Italian official seismic hazard map, Figure 1a;

95 Gruppo di Lavoro MPS, 2004), a long history of damaging earthquakes (Figure 1c), and a site

96 where only few strong motion data are available (Luzi et al., 2008; Pacor et al., 2011).

97 The expected ground motion is evaluated for bedrock and free-field conditions, at a single target

98 site located in the proximity of a single fault (SFSS: Single-Fault Single-Site scenarios) assumed as

99 capable of generating from moderate to strong earthquakes. As a modeling strategy, we generate a

100 large number of rupture scenarios by varying both the location and kinematic parameters of

101 individual ruptures. We simulate earthquakes of three magnitude values, M7.0, M6.0, and M5.0, as

102 well as source-to-site distances of 0 to 10 km (Figure 1b), thereby exploring the range of the major

103 contribution to PSHA at Cosenza as resulting from the disaggregation analysis of the MPS04

104 (Figure 1d; Meletti et al., 2007; Martinelli and Meletti, 2008; Stucchi et al., 2011).

105 The median values and variability of ground motion distributions simulated for SFSS conditions are

106 analyzed to test the performance of the simulation method in reproducing directivity effects in

107 various source-to-site configurations and compared with those predicted by two reference GMPEs

108 (BSSA, Boore et al., 2014; BI2014, Bindi et al., 2014)

109 Finally, we discuss some of the possible implications of our results for the PSHA by testing the

110 influence of directivity effects in the near source region.

Sampling the Aleatory Variability of SFSS Scenarios

112 Although the number of involved elements in the SFSS estimate is minimal (one fault, one site),

113 each of them involves several parameters which need to be based on prior information affected by

114 aleatory uncertainty. This represents a typical hazard problem that can be tackled through the Event

115 Tree (ET) approach (Ericson, 2005) and has already been adopted in a number of geophysical

116 applications (e.g.: Newhall and Hoblitt 2002; Lorito et al., 2015; Selva et al, 2016). Here, we use a

117 simplified ET-like representation of our experiment where each ET branch represents possible

118 realizations of earthquake rupture models exploring various characteristics of earthquake source and

119 target site. For simplicity, we assume a uniform probability distribution of discrete values for all the

120 parameters of each branch. The procedure to introduce and manage SFSS variability is exemplified

121 in Figure 2. Extended descriptions of each ET branch used in the Cosenza case study follow.

122 Alternative models to the one adopted here represent an epistemic uncertainty that is commonly

123 tackled through the implementation of logic trees or ensemble modeling (Marzocchi et al., 2015).

124 However, the thorough treatment of epistemic uncertainty is beyond the scope of this work.

ET implementation

Branch #1: Parent Fault and its context

127 The case study is set in the area source (AS) 929 "Calabria tirrenica" of the seismic zonation ZS9

128 (Meletti et al., 2008) at the base of MPS04 (Gruppo di Lavoro MPS, 2004), a tectonically active

129 region of southern Italy dominated by E-W extensional tectonics (e.g. Meletti et al., 2008) and

130 prevailing N-S maximum horizontal stress (Carafa and Barba, 2013).

131 A single Parent Fault (PF) is defined here by a rectangular fault plane adopted from the DISS 3.1.1

132 (DISS Working Group, 2010; Basili et al., 2008) and consisting of a north-south striking, west-

5

133 dipping, normal fault (Figure 1a and Table 1). The target site (city of Cosenza; CSZ) is located on

134 the hanging wall of this fault.

Branch #2: Child Faults Generation

136 A Child Fault (CF) is a fault that inherits orientation and sense of movement from the PF defined in

137 Branch #1 and other static parameter according to a selection of possible earthquake magnitudes.

138 We adopt three earthquake moment magnitudes: M5.0, M6.0, and M7.0, that encompass the range

139 of magnitudes (M = 5.5-6.0) that dominates the ground motion (Peak Ground Acceleration) at

140 Cosenza for near-site seismic sources at short (475 years) and long (2476 years) average return

141 periods (ARP) (Figure 1d). For each magnitude value we obtain the equivalent seismic moment

142 using the classical relationships by Kanamori and Anderson (1975) and Hanks and Kanamori

143 (1979) and deriving fault area and slip from seismic moment, assuming a rigidity of 30 GPa. Length

144 and width (rounded values) are then determined by assuming an aspect ratio of ~1.5 (Table 2).

Branch #3: Scenario Set

146 This branch explores the range of possible source-to-site configurations. In our case, the CFs are

147 irregularly distributed over the PF (Figure 1b) with a smaller spacing for the shallower sector to

148 better explore the closest distances from the site. For M7.0 we consider only one CF, with the top

149 edge at 1 km depth, covering almost the entire PF plane. For M6.0 we consider five identical CFs,

150 distributed at a regular spacing of half fault length, from north to south, along the uppermost part of

151 the M7.0 CF. For M5.0 there are 23 identical CFs distributed at five irregular depth levels (Table 2).

Branch #4: Scenario Events

153 Since the specific kinematic features of any future rupture on the CFs defined at Branch #2 and #3

154 are unknown, we generate a large number of possible scenario events for each magnitude (Table 3).

155 The aleatory variability of the rupture process is incorporated by varying rupture kinematics within

156 plausible a-priori defined parameter ranges (Table 1). Several scenario events are obtained by

157 varying the position of the nucleation points and considering rupture fronts that radially propagate

158 with three different constant velocities V_r (Table 1). The M7.0 CF is subdivided along strike into

159 three sub-faults for each of which we simulate nine nucleation points at a regular spacing of 3 km

160 along strike and 4.5 km along dip (Table 3). In such a way, both unilateral and bilateral directivity

161 effects can be properly modeled. Being the M6.0 CFs smaller, we simulate only nine nucleation

162 points uniformly distributed on the fault plane at a regular spacing of 4 km along strike and 3 km

163 along dip (Table 3). For the M5.0 CFs we simulate only three nucleation points with a regular

164 spacing of 1 km in the middle of the fault plane (Table 3).

165 Fault slip is assumed as uniformly distributed over each CF plane. Although this hypothesis may

166 seem very simplistic, we use it because in the simulation method adopted in this study the slip

167 distribution has a second-order effect on the ground motion amplitude (Pacor et al., 2005) if

168 compared to the other kinematic parameters (i.e. nucleation point and rupture velocity).

169 **Branch #5: Propagation Medium Properties**

170 We use a 1D multilayer model (Table 4) considered representative of the study area in agreement

171 with seismic imaging studies for southern Italy (Barberi et al., 2004; Orecchio et al., 2011;

172 D'Amico et al., 2011). The anelastic attenuation (Table 1) is obtained through a constant quality

173 factor from Rovelli et al. (1988). For simplicity we use only the expected values of each layer.

174 Given the very short source-to-site distance (R_{JB}< 15 km), we use an inverse-distance geometrical

175 spreading factor (1/R) to model the path effects (Table 1).

176 **Branch #6: Site Conditions**

177 All simulations are performed at bedrock and free-field conditions assuming three values for the

178 attenuation at high frequency, described by the k_0 parameter (Table 1) and selected among typical

179 values for rock sites (Anderson and Hough, 1984; Boore and Joyner, 1997; Parolai and Bindi,

180 2004).

181 **Branch #7: Receivers Geometry**

182 The distribution of virtual receivers deployed in the region of interest includes two sites (Figure 1):

183 CSZ is located in the middle of the M7.0 CF, and s001 is located close the northernmost edge of the

184 fault. Simulations for the M7.0 are performed for both CSZ and s001 to analyze the ground-motion

185 variability due to bilateral and quasi-unilateral directivity effects, respectively. R_{JB} is equal to zero

186 for both sites. For the M6.0 CFs R_{JB} varies between 0-7 km. For the M5.0 CFs R_{JB} is equivalent to

187 the epicentral distance and varies between 0-15 km (Table 2).

SFSS scenario output and analysis

189 A remarkable number of acceleration time series is generated for each earthquake magnitude (Table

190 3) to ensure the statistical significance of SFSS simulated ground motions. The expected seismic

191 shaking can thus be represented by the distributions of Intensity Measure Types (IMTs) commonly

192 used for engineering purposes rather than using values inferred from single scenario events.

193 However, the ET scheme produces several scenarios and it is thus necessary to sample a restricted

194 dataset of synthetic waveforms able to reflect the overall ground-motion variability, which meet the

195 various engineering requirements. In general, once the simulation results are obtained, a

196 comparative scheme has to be adopted to ensure the reliability of synthetic IMTs (e.g. comparing

197 synthetic distributions with pre-existing empirical models or, when available, with recorded data).

Simulation Method

199 The Deterministic Stochastic Method (DSM, Pacor et al., 2005) is an extension of the stochastic

200 point source simulation method of Boore (1983, 2003) and it is designed to reproduce the

201 directivity effects due to the rupture propagation along an extended fault. Despite the simplistic

202 modeling of the physics of rupture generation and propagation, DSM was successfully used for

203 estimating ground motion variability located near active faults (Carvalho et al., 2008; Ameri et al.,

204 2008). In several studies, DSM was able to reproduce the main features of the observed short-period

205 ground motions (Cultrera et al., 2010), with results comparable to those computed by hybrid

206 techniques (Ameri et al., 2009, Ameri et al., 2011).

207 In the DSM, the source model is described by a rupture radially propagating with constant velocity

208 from a nucleation point along a finite fault, and by a slip distribution. DSM exploits the isochrones

209 theory (Bernard and Madariaga, 1984; Spudich and Frazer, 1984) to compute the envelopes of the

210   acceleration signals, to define the apparent corner frequency, and to estimate the source-to-site

211   distance.

212   For each site the envelope is built by summing the contributions to ground motion from the

213   corresponding isochrone on the fault. A random phase modulates the amplitude of the medium

214   response to ensure that the envelopes are calculated as incoherent summation of the energy emitted

215   by each point of the fault. The duration and shape of the envelope are functions of the rupture

216   model (fault dimensions, rupture nucleation point, and rupture velocity) and of the relative fault-to-

217   receiver position. The envelope varies from site to site and describes how the site perceives the

218   energy released from the source.

219   For a given site, the spectral content of the synthetic seismogram is then defined through the finite-

220   fault reference spectrum FFR(f), given by:

221     $FFR(f) = S(f) \cdot A(f) \cdot K(f)$ (1)

222   where *S(f)* is the apparent source acceleration spectrum, *A(f)* is the attenuation operator, and *K(f)* is

223   the site response function.

224   A(f) includes the geometrical spreading and the frequency-dependent attenuation term in the form:

225     $A(f) = G(R)exp\left[\frac{-\pi fR}{Q(f)\beta}\right]$, where G(R) is the geometrical spreading attenuation, β is the shear-wave

226   velocity, Q is the apparent quality factor (values reported in Table 1). As the simulations are

227   performed at bedrock, the only site effect considered is the high-frequency attenuation introduced

228   through the Anderson and Hough's (1984) model given by K(f) = exp(-k_0πf), where k_0 is the

229   parameter describing the spectral decay.

230   The radiation pattern $R_{\theta\phi}$, the source-to-site distance R, and the corner frequency are inferred by

231   deterministic envelopes in order to take into account the effects of the rupture propagation along a

232   finite fault (Pacor et al., 2005). The source-to-site distance and the radiation pattern adopted to scale

233   the reference spectrum at each receiver are determined through a spatial average over the entire

234   fault, followed by a temporal average, weighted by the envelope function itself (global average).

235   The spatial average can also be performed over the reduced fault area associated with the maximum

236   pulse of energy arriving at a given site, defined by the maximum isochrone velocity (local average).

237   The apparent source acceleration spectrum S(f) has the shape of the classical omega-square model

238   (Brune 1970):

239    $S(f) = C \cdot M_0 (2\pi f)^2 \dfrac{1}{1+\left(\frac{f}{fa}\right)^2}$ (2)

240   where C is a constant given by $\frac{\Re_{\theta\varphi}F}{4\pi\rho\beta^3}$, (where $\Re_{\theta\varphi}$ is the radiation pattern; F is the free-surface

241   amplification, and ρ is the density), M_0 denotes the seismic moment, and f_a is the apparent corner

242   frequency. Differently from the point-source model, the corner frequency is defined as the inverse

243   of the envelope duration and it differs from site to site (apparent corner frequency). By means of the

244   apparent corner frequency, the directivity effects are directly included in the simulation,

245   reproducing the expected azimuthal variation of corner frequency and spectral amplitudes due to the

246   source rupture propagation. Consequently, the ground motion simulated at sites along the direction

247   of the rupture front propagation experience (forward/backward) directivity-induced

248   amplification/attenuation effects. Note that, due to the relationship between stress drop and corner

249   frequency (Brune, 1970), from the apparent corner frequency it is possible to evaluate an apparent

250   stress parameter that can be used to measure to what extent the site is affected by directivity effects.

251   Similarly, the earthquake stress parameter can be obtained from the corner frequency of the event,

252   given by the inverse of the rupture duration.

253   In the context of the stochastic finite-fault modeling, the largest source of epistemic uncertainty in

254   the ground motion prediction is due to the limited knowledge concerning the stress drop

255   (Motazedian and Atkinson, 2005; Atkinson and Boore, 2006), which is the main "free" input

256   parameter that controls the level of the acceleration spectrum (> 1 Hz). In DSM, this issue is

257   addressed by replacing the epistemic uncertainty on the stress parameter with the aleatory

258   uncertainty given by the variability in the fault dimension, nucleation point, and rupture velocity.

259   Figure 3 shows the range of variability of the apparent stress parameter Δ_{app} and local distance

260   associated to the ET implementation presented in the previous section. The "apparent" stress

261   parameters vary in different ranges for different magnitudes, with the widest range for the M5.0

262   class in which several faults, with different rupture velocities and distance–to-source geometries are

263   involved. Conversely, the local distances are very similar to the hypocentral distance for M5.0

264   while they shorten as the fault dimension increases.

265   In this work, to test the influence of the use of the apparent corner frequency (or apparent stress

266   parameter) in the evaluation of ground motion amplitudes at a single site, we considered three

267   different setups of the DSM (M1, M2, and M3). Each setup has the role to differently weight

268   directivity effects as follows:

269   i)   M1 (maximum directivity effect): prescribes the use of the deterministic envelope

270   duration to define the apparent corner frequency f_a; in this way, the corner frequency

271   depends on rupture velocity, nucleation point, fault dimension, and relative position of

272   the observer with respect to the nucleation point.

273   ii)   M2 (minimum directivity effect): uses the fixed corner frequency, defined by an

274   apparent stress parameter of 30 bar; in this case, the finite-source effects are taken into

275   account only in the distance and radiation pattern computation.

276   iii)   M3 (medium directivity effect): implies the use of a minimum threshold f_{th} for the

277   apparent corner frequency in order to minimize backward directivity effects simulated

278   by M1 and not clearly observed on recorded data; for each magnitude class f_{th} is defined

279   by a constant value for the apparent stress parameter of 30 bar (i.e. for M = 7 f_{th} = 0.07

280   Hz, M3 = M2 if $f_a <= f_{th}$, otherwise M3 = M1).

281   In the three cases, we use the local metrics definition both for $R_{\theta\varphi}$ and R. Compared to the global

282   metrics, the local one produces larger ground-motion variability and, on average, higher amplitudes.

283   **Analysis of the Synthetic Ground Motion Dataset**

284   **Median and standard deviation of the simulated ground motion**

285 Figure 4 shows the box plots of the peak ground acceleration (PGA) and peak ground velocity

286 (PGV) synthetic distributions (geometrical mean of the horizontal components), obtained by the

287 M1, M2, and M3 DSM setups for the three magnitudes classes (log10 units). For M7.0, the ground

288 motion distributions are relative to the bilateral CSZ and the quasi-unilateral s001 sites (Figure 1),

289 both located at a Joyner-Boore distance $R_{JB} = 0$. In the cases of M6.0 and M5.0, the involved R_{JB}

290 varies in the range 0-7 km and 0-15 km, respectively (Figure 1). We aggregate the synthetic

291 ground-motion peak values at 0 or 5 km for M6.0. For M5.0, R_{JB} varies with depth because the PF

292 is inclined. We thus aggregate the R_{JB} distances into two depth groups that contain approximately

293 the same number of realizations. The resulting mean R_{JB} distances are of 5 km and of 10 km,

294 respectively. We introduced this approximation to explore the synthetic ground motion variability

295 for two different source-to-site distances and to compare our results with median and variability

296 ground motion predicted by GMPEs. The median (μ_{DSM}) and standard deviation (σ_{DSM}) of the DSM

297 distributions are reported in Table 5 and Table 6, respectively. Ground motion distributions are

298 shown in the Electronic Supplement. For M7.0 and M6.0, based on visual inspection and statistical

299 tests (i.e. Kolmogorov-Test, χ-square test with 5% confidence interval), the synthetic PGAs follow,

300 on average, a lognormal distribution, independently of the modeling setups (M1, M2, and M3).

301 However, directivity effects can generate distributions characterized by a positive or negative skews

302 (for example the PGA distributions at s001 relative to M7.0). Compared to the PGAs, the PGV

303 values are better described by multimodal distributions. For M5.0 we observe that, independently

304 from the scenario model, the ground-motion parameter distributions can be only approximated by

305 lognormal shapes both at high and low frequencies; a larger number of CFs should be considered to

306 better sample the PF to generate a lognormal distribution.

307 The weight assigned to the directivity effects for the three modeling setups influences the ground

308 motion distributions: in general, the median values are lower for M1 and higher for M3, whereas

309 the associated variability shows opposite trends. These features are especially marked in the case of

310 the quasi-unilateral site (s001) for M7.0, and for the more distant faults of M6.0 and M5.0 in which

forward and backward directivity effects dominate, due to the particular source-to-site

configurations. For all the three magnitudes, the variability in M1 is about 40% and 30% larger than

in the M2 and M3 configurations, respectively. When the contribution of the apparent corner

frequency is limited, either by a fixed corner frequency (M2) or by a threshold in the apparent

corner frequency (M3), the ground-motion variability is mainly controlled by the variability of local

distance and radiation pattern. In these cases, the contribution of the backward directivity is

minimized or partially reduced, thus increasing the median values and reducing the range of

simulated values. As the magnitude decreases, the synthetic ground motion variability increases: the

standard deviations vary from 0.18 for M7.0 to 0.38 for M5.0 (Table 6).

In our modeling, the synthetic variability represents the ground motion variability expected at a

single site over many scenario events on a given fault and includes: i) the source term, given by

various kinematic scenarios; ii) the site term, related to the three considered bedrock conditions; iii)

the synthetic-to-synthetic term, due to the simulation of forward and backward directivity effects at

the same site. For the smallest events, a further source of variability is related to the uncertainties of

the CFs locations over the PF, thus generating a large dispersion in the simulated ground motion.

This finding is in agreement with recent empirical heteroscedastic GMPEs that found a decrease of

the scatter with increasing magnitude (e.g., Bommer et al., 2007; Boore et al., 2014). Among the

possible causes, errors in the location and magnitude determination of smaller events, in particular

aftershocks, might contribute to the larger scatter for smaller events (Strasser et al., 2008).

Figure 5 shows the synthetic cumulative distribution functions (CDFs) of PGA, computed at CSZ

considering the three magnitude classes and the M1 setup; this will help to better understand how

uncertainties of different input simulation parameters contribute to the ground-motion variability.

For M6.0 and M5.0, the analyses are carried out considering the largest distance bin. In Figure 5a,

the three CDFs are related to each rupture velocity: we grouped the scenarios with a fixed Vr and

variable nucleation point position and k_0. In Figure 5b, the CDFs are calculated for the three k_0

336   values. In Figure 5c the scenarios are grouped considering three nucleation areas, each of them

337   corresponding to one third of the parent fault.

338   The variation of rupture velocity and k_0 contributes to the ground motion variability. The CDFs in

339   Figure 5a are shifted to larger PGA values as the selected Vr increases. A similar trend is observed

340   for k_0 values but in a small extent. The effect of the nucleation area (Figure 5c) is more complicated

341   because it depends on the position of CSZ compared to the CFs. On the one hand, the M7.0

342   nucleation areas 1 and 3 produce very similar PGA distributions, which are lower than the one of

343   area 2. On the other hand, for M6.0 the opposite occurs and areas 1 and 3 generate the largest

344   ground motions. In general, uncertainties in the hypocenter position produce a large variability of

345   ground motion as can be observed for M5.0, where the CDFs are also distinguished in relation to

346   the depth of the hypocenters.

347   **Comparison with GMPEs**

348   In this section we compare the synthetic ground motion medians and variances with the predictions

349   from global (BSSA, Boore et al., 2014) and Pan-European (BI2014, Bindi et al., 2014) GMPEs, for

350   the rock-soil category and for various magnitude-distance (M-R) pairs (Table 2, and Figure 6a).

351   Here we have two objectives: one is to test the reliability of our simulations, while ensuring that the

352   combinations of input parameters produce ground-motion levels that are consistent with the

353   observations for similar conditions; the other is to assess to what extent the ground-motion

354   variability and median values of empirical models may represent directivity effects. Independently

355   from the DSM setups (M1-3), the synthetic ground motion median values fall within the empirical

356   median plus/minus one standard deviation, thus supporting the reliability of our modeling (Figure

357   6a). The standard deviations of the synthetic ground motions are consistent with the empirical ones

358   for the M6.0 and M5.0 and the M1 configuration, for which more than one fault is involved and the

359   directivity effects are strongest. In all the other cases the synthetic variability is lower.

360   In the SFSS case and M7.0, the synthetic variability is expected to be lower than the empirical one

361   obtained from global models that include contributions from multiple sites, paths, and sources

362 (ergodic assumption). For example, Yagoda-Biran et al. (2015) showed that the variance in ground

363 motions related to repeated large earthquakes (single fault) is reduced by about 45% and 80% with

364 respect to the between-event variability τ of the global model.

365 Figure 6b shows the Probability Density Function (PDF) of PGA as predicted by the BI2014 and

366 BSSA at CSZ and s001 together with PDFs obtained from M1, M2, and M3 setups for M7.0,

367 considering a lognormal distribution. Since only a single fault is involved, the total sigma of the

368 empirical PDFs is computed using the fault-variance defined in Yagoda-Biran et al. (2015) as $\tau^2/2$

369 instead of the between-event variance. For comparison, we also consider the sigma estimated for a

370 single seismic source zone in Italy by Luzi et al. (2014) which is about 30% lower than the overall

371 sigma for the entire Italian territory. The PGA distribution generated for maximum directivity

372 effects (M1 setup) is very close to the empirical distributions in terms of median values and

373 variability both at CSZ and s001, when the sigma of a single source is considered.

374 The weight given to the directivity effects strongly influences the median and the associated

375 standard deviations of the simulated ground motions, demonstrating how near-source effects are not

376 adequately represented by traditional GMPEs. Forward directivity effects, in particular, could be an

377 enhancement of the ground motions of about 60-100% (M3 setup for quasi-unilateral site).

378 **Synthetic ground motion models**

379 DSM simulations are used to derive a SFSS ground motion attenuation model accounting for

380 directivity effects by means of the apparent stress parameter. In this way we carried out our

381 analyses to account for source-specific and path-specific effects. We adopted this approach with the

382 dual aim of investigating the contribution of the kinematic ruptures into the overall simulation

383 variability and evaluating the impact into a simple PSHA performed for the SFSS case study.

384 Villani and Abrahamson (2015) followed a similar approach by identifying repeatable site and path

385 effects into simulated ground motion variability and assessing the influence of different

386 assumptions (ergodic, partially ergodic, and fully nonergodic) for the seismic hazard computation.

387   The SSFS model is calibrated for PGA using the hypocentral distance metrics evaluated from the

388   nucleation points considered in the ET scheme. In this model, the empirical model BI2014

389   describes the attenuation at distances larger than those covered by simulations.

390   As a first step, for each magnitude class and DSM setup, we fit the simulated PGAs using a simple

391   distance-dependent function in the form:

392

393    $\log(PGA) = c_1 + c_2 \log \frac{R}{d} + \varepsilon$ (3)

394    $R = \sqrt{R_{hypo}^2 + h_{eff}^2}$ (4)

395   where R_{hypo} is the hypocentral distance and h_{eff} is the effective depth parameter that includes near-

396   source saturation effects (Atkinson, 2015); d is the joint distance between synthetic and empirical

397   median values and ε represents the residuals of the fit, c_2 is a free parameter, c_1 is constrained to

398   assume the median value of BI2014 at the joint distance d. We adopt the Atkinson's (2015)

399   relationships, such as $h_{eff} = \max(1, 10^{(-1.72+0.43M)})$, for the M7.0 case; in the other two cases we

400   adopt the same values ($h_{eff} = 7.32$) suggested by Bindi et al. (2014).

401   Regression coefficients c_1, and c_2, and h_{eff} and d values are reported in Table 7a, together with the

402   standard deviations σ_{reg} for all magnitude classes and simulation setups.

403   Figure 7 shows the comparison between BI2014 and synthetic PGAs ground motion in terms of

404   median values and standard deviations. The synthetic median values are generally higher than the

405   empirical ones, especially when backward directivity effects are removed (M3). The only

406   exception is for the M1 setup with M6.0, where the backward directivity effects dominate because

407   of the particular source-to-site configurations. Conversely, the overall synthetic variability is not

408   changed with respect to what previously observed. The dispersion remains heteroscedastic with the

409   largest values (ever higher than the empirical one) for the M1 setup.

410   To reduce the standard deviation, we introduce the apparent stress parameter (Δ_{app}) as an

411   explanatory variable in the previous model. The M1 residuals clearly depend from this parameter,

412   as illustrated in Figure 8a, indicating that the simple functional form of Eq. 3 is not able to capture

413   the strong directivity effects due to particular combinations of kinematic and geometrical factors.

414   From this example, two remarkable biases with opposite sign are detectable: negative below the

415   16th percentile (~15 bars) and positive above the 84h percentile (~30 bars) of the Δ_{app} distribution.

416   Negative residuals result from scenario events with ruptures starting in the uppermost part of the

417   fault and propagating with the lowest rupture velocity (Vr = 2.4 km/s); positive residuals are mainly

418   due to up-dip ruptures with the highest rupture velocity (Vr = 2.7 km/s). The residual trend around

419   the median value (~20 bars) of the Δ_{app} distribution is unbiased, showing how this cluster is

420   essentially governed by source-to-site distances and the directivity effects are minimized.

421   As a second step of our regression analysis, we fit the residuals of Eq. 3 through the directivity term

422   depending on Δ_{app} according to the following model:

423    $$\mathcal{E} = c_3 + c_4 \log(\Delta_{app}) + \mathcal{E}^* \tag{5}$$

424   where c_3 is the mean offset of the data with respect to the synthetic attenuation model and

425    $c_4\log(\Delta_{app})$ is the contribution of the apparent stress parameter. In Figure 8b we show that the

426   residual trend is almost unbiased and the dispersion is strongly reduced. Regression coefficients c_3

427   and c_4 are reported in Table 8, together with the standard deviation σ^* for each sampled magnitude

428   and the M1 setup. The most significant result in the strong reduction of the standard deviation of the

429   model of Eq. 3 is the sigma reduction for M7.0. The variability is about 1/3 of the empirical one; it

430   retains the heteroscedastic feature although to a lesser extent. Sigma for M7.0 is about 50% ($\sigma^* =$

431    $0.47\sigma_{reg}$) of the variability only considering the hypocentral distance, whereas a major reduction is

432   obtained for lower magnitudes ($\sigma^* = 0.65\sigma_{reg}$ for M6.0 and $\sigma^* = 0.72\sigma_{reg}$ for M5.0).

433   Synthetic ground motion models corrected for the directivity term in the M1 setup are shown in

434   Figure 9 and compared to BI2014 for three percentiles (16th, 50th, and 84th) of the Δ_{app} distributions:

435   the median values vary by 30% for M7.0 or by 40% for the lower magnitudes, with respect to the

436   predictions at the 50th percentile.

437   **PSHA sensitivity analysis**

438   We employ the set of synthetic attenuation models derived in the previous section to perform a

439   simplified PSHA sensitivity analyses at CSZ accounting for the area source AS929 of the ZS9

440   model (Meletti et al., 2008; Figure 10a), whose seismic activity is described by a doubly-truncated

441   Gutenberg-Richter distribution (with a-value, b-value, and Mmax as shown in Figure 10b), focal

442   depth, and dominant faulting mechanism as used in MPS04 (Gruppo di Lavoro MPS, 2004). The

443   integration domain of the hazard integral for CSZ was limited at 30 km distance to isolate only the

444   single-fault contribution. All the PSHA computations were carried out with the program

445   CRISIS2015 (Ordaz et al., 2013).

446   In order to exemplify the impact onto the hazard assessment of the synthetic GMPEs accounting for

447   directivity effects, the annual probabilities of exceedance (APEs) for PGA are computed comparing

448   the performance of the attenuation models developed in this study with the reference GMPE

449   BI2014 (Figure 11a). We use for the hazard calculations the sigma values obtained by synthetic

450   residuals regressions (σ_{reg} and σ^*). Such assumption leads toward a total removal of the ergodic

451   assumption for prevailing path-specific effects, such as those modeled in our stochastic-based

452   simulations.

453   First, we adopt the model depending on hypocentral distance (Eq. 3). As a result of the comparison

454   of hazard curves when the ergodic assumption is removed (grey lines), we observe an increased

455   APE for PGA (Figure 11a). This is due to the overall enhancement of the median ground motion

456   produced by the synthetic models. The highest hazard curve is for the modeling setup that

457   minimizes backward directivity. APEs accounting for maximum directivity effects are lower than

458   the previous case beyond 1 m/s^2. When a point-like source is used to represent the ground motion,

459   the APEs are lower with respect to the other nonergodic hazard curves.

460   Then, we apply the synthetic attenuation model depending on both distance and apparent stress

461   parameter (Eq. 5). In Figure 11b we show an example of the APEs for this case (nonergodic

462   assumption). For each magnitude class we select three values of apparent stress parameters

463   corresponding to the 16th, 50th and 84th percentiles of the distributions plotted in Figure 9. Then, we

apply a simplified PSHA logic tree to handle the epistemic uncertainties on the values of the apparent stress parameters. We build three branches where each of them represents a different combination of weights. In case of equally-weighted curves each attenuation model has the same likelihood, whereas in the other two cases, a higher weight is attributed to the synthetic model defined either by the 16th or the 84th percentile. We observe how the global effect of the sigma reduction leads to a decrease of APEs with respect to the ergodic assumption (BI2014). The only exception is due to the increase in the epistemic uncertainty of the median when forward directivity effects are accounted for.

Discussion and Conclusions

A reliable characterization of the aleatory variability of the ground motion is an important factor in PSHA because it controls the shape of the hazard curves at low frequencies of exceedance (Restrepo-Vélez and Bommer, 2003; Bommer and Abrahamson; 2006).

The common practice in PSHA is to adopt the total standard deviation of ground-motion models. However, such models are developed using a broad range of earthquake types, stations, and tectonic regions. Therefore, the temporal variability of the ground motion for a single source-to-site combination for a given ARP is assumed to be the same as the spatial variability in ground motion observed in rich earthquake datasets (i.e. the ergodic assumption; Anderson and Brune; 1999). This assumption is particularly inappropriate when path-specific effects dominate the ground motion. In such a case, systematic source-specific and site-specific effects should be removed from the seismic hazard estimates (Al Atik et al., 2010). This problem can only be tackled by collecting repeated observations of earthquakes located in a small region nearby the target site. In addition, the GMPE uncertainty distribution generally follows a lognormal distribution and the misfit between observed and predicted ground motions is commonly assumed to be homoscedastic, i.e. independent from the explanatory variable, such as magnitude or distance. However, in several cases the observed decreasing scatter with increasing magnitude suggests that heteroscedastic models should be used (Ambraseys et al., 2005; Akkar and Bommer, 2007a,b; Bommer et al., 2007 among others).

490 In this work, we evaluated the ground motion variability related to a SFSS configuration through

491 deterministic-stochastic earthquake simulations to investigate the impact of synthetic attenuation

492 models in seismic hazard assessment. According to hazard disaggregation from the Italian seismic

493 hazard map (MPS04: Meletti et al., 2007; Martinelli and Meletti, 2008) for the site of interest (CSZ;

494 Figure 1), our simulations span the entire range of the most contributing earthquake magnitudes in

495 near-source conditions (source-to-site distance shorter than 10 km) for short (M5.5 for 475 years)

496 and long (M6.5 for 2476 years) ARPs.

497 We modeled only M5.0, M6.0, and M7.0 earthquakes generated by various ruptures laying on the

498 same fault plane. Other earthquakes, especially the smaller ones, can likely be generated by other

499 faults not considered in this work, such as conjugated and secondary faults, splay faults, and tear

500 faults. Other major faults could also exist in the region. These potential seismic sources can further

501 increase the variability of the expected ground motion at the site with respect to what we have

502 analyzed here. A complete site-specific hazard assessment should also take these potential sources

503 into account. An additional source of variability may also come from the slip distribution,

504 especially for the larger earthquakes, but this aspect was not modeled in our study.

505 We found that, although synthetic ground-motion median values are relatively centered within the

506 range of values predicted by empirical GMPEs (either BI2014 or BSSA), there are some significant

507 differences in the ground-motion variability. The PGA and PGV simulated for SFSS scenarios often

508 deviate from the lognormal distribution commonly used to describe the ground-motion variability.

509 Skewed synthetic distributions are also detected, thereby showing how much directivity effects of

510 large events (M7.0) should be accounted for in a reliable ground motion characterization in the

511 near-source distance range (Figure 4 and more details of these distributions in the Electronic

512 Supplement of this work). The synthetic ground motion variability (σ_{DSM}) of the explored scenario

513 events is heteroscedastic, with smaller values for larger earthquakes (Figure 6a). The GMPE

514 variability (σ_{GMPE}), on the other hand, is linked with source, propagation, and site characteristics, as

515 well as earthquake data availability; the σ_{DSM} in our case study is linked to the modeled scenario

516   events in terms of source-to-site distance and directivity. The tails of the ground motion

517   distributions have significant overlaps. This indicates that, although we are looking at the same fault

518   source, it is significantly likely that ground motion levels expected for higher magnitude

519   earthquakes could also be exceeded by smaller earthquakes.

520   From the synthetic dataset, we calibrated a set of synthetic attenuation models including directivity

521   effects by means of the apparent stress parameter. The associated variability is reduced of more

522   than 50% with respect to the simple model described by Eq. 3, which depends on distance only. The

523   standard deviation of this model represents the variability of ground motion expected at a single site

524   from a single fault, where several rupture scenarios may occur.

525   Although the proposed functional form is very simple, we do introduce an additional parameter –

526   the apparent stress Δ_{app} – that implies the treatment of its associated epistemic uncertainty. This is

527   indeed a critical point in hazard assessment because the hazard levels are sensitive to the weighting

528   scheme.

529   As a further development, the predicted ground-motion median and its related variability for the

530   SFSS configuration can be extended to a grid of virtual receivers, using the concept of apparent

531   stress parameter, to calibrate synthetic ground motion equations useful in different fault-to-site

532   configurations.

533   The above considerations and results suggest that DSM simulations are accurate enough to be used

534   in seismic hazard applications and, although they have a higher computational cost than the

535   GMPEs, they provide an added value represented by 1) one-to-one association between seismic

536   source characteristics and their calculated effects; 2) possibility to supply results in any hazard

537   ground motion parameters directly derived from synthetic waveforms; 3) possibility to explore the

538   ground motion variability due to several fault kinematic parameters, directivity, and short source-to-

539   site distances; 4) integration with empirical ground motion models, especially for moderate-to-large

540   magnitudes in the near-source region where recorded data are usually poor or nonexistent; 5) PSHA

541 accounting for heteroscedastic features of the ground motion; 6) total removal of the ergodic

542 assumption for prevailing path-specific effects.

543 **Data and Resources**

544 Accelerometric waveforms and related metadata can be retrieved from the ITalian ACcelerometric

545 Archive ITACA 2.0 at http://itaca.mi.ingv.it (last accessed May 2016); data from the DISS Working

546 Group (2010) can be found at http://diss.rm.ingv.it/diss/ (last accessed May 2016). Data from the

547 Gruppo di Lavoro MPS (2004) can be found at http://zonesismiche.mi.ingv.it (last accessed May

548 2016). PGAs with probability of exceedance in 50 years were calculated by using the CRISIS2015

549 program, made by Universidad National Autónoma de México

550 (https://sites.google.com/site/codecrisis2015/; last accessed May 2016). The figures in this work

551 were mainly drawn with MATLAB and Statistics Toolbox Release 2012b, The MathWorks, Inc.,

552 Natick, Massachusetts, United States. Information about the work in progress about the upgrading

553 version of the current Italian seismic hazard map (MPS16) can be found at

554 http://tinyurl.com/jg99xsc (in Italian, last accessed May 2016).

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References

566 Akkar, S., and J. J. Bommer (2007a). Empirical Prediction Equations for Peak Ground Velocity

567 Derived from Strong-Motion Records from Europe and the Middle East, *B. Seismol. Soc. Am.*, **97,**

568 511-530, doi:10.1785/0120060141.

569 Akkar, S., and J. J. Bommer (2007b). Prediction of elastic displacement response spectra in Europe

570 and the Middle East, *Earthquake Engineering & Structural Dynamics*, **36,** 1275-1301,

571 doi:10.1002/eqe.679.

572 Al Atik, L., N. Abrahamson, J. J. Bommer, F. Scherbaum, F. Cotton, and N. Kuehn (2010). The

573 Variability of Ground-Motion Prediction Models and Its Components, *Seismol. Res. Lett.*, **81,** 794-

574 801, doi:10.1785/gssrl.81.5.794.

575 Ambraseys, N. N., J. Douglas, S. K. Sarma, and P. M. Smit (2005). Equations for the Estimation of

576 Strong Ground Motions from Shallow Crustal Earthquakes Using Data from Europe and the Middle

577 East: Vertical Peak Ground Acceleration and Spectral Acceleration, *B. Earthq. Eng.*, **3,** 55-73,

578 doi:10.1007/s10518-005-0186-x.

579 Ameri, G., A. Emolo, F. Pacor, and F. Gallovic (2011). Ground-Motion Simulations for the 1980 M

580 6.9 Irpinia Earthquake (Southern Italy) and Scenario Events, *B. Seismol. Soc. Am.*, **101,** 1136-1151,

581 doi:10.1785/0120100231.

582 Ameri, G., F. Gallovic, F. Pacor, and A. Emolo (2009). Uncertainties in Strong Ground-Motion

583 Prediction with Finite-Fault Synthetic Seismograms: An Application to the 1984 M 5.7 Gubbio,

584 Central Italy, Earthquake, *B. Seismol. Soc. Am.*, **99,** 647-663, doi:10.1785/0120080240.

585 Ameri, G., F. Pacor, G. Cultrera, and G. Franceschina (2008). Deterministic Ground-Motion

586 Scenarios for Engineering Applications: The Case of Thessaloniki, Greece, *B. Seismol. Soc. Am.*,

587 **98,** 1289-1303, doi:10.1785/0120070114.

588 American Society of Civil Engineers (ASCE) (2005). Minimum Design Loads for Buildings and

589 Other Structures, (ASCE/SEI 7-05), ASCE, Reston, Virginia.

23

590 American Society of Civil Engineers (ASCE) (2010). Minimum Design Loads for Buildings and

591 Other Structures, (ASCE/SEI 7-10), ASCE, Reston, Virginia.

592 Anderson, J. G., and J. N. Brune (1999). Probabilistic Seismic Hazard Analysis without the Ergodic

593 Assumption, *Seismol. Res. Lett.*, **70,** 19-28, doi:10.1785/gssrl.70.1.19.

594 Anderson, J. G., and S. E. Hough (1984). A model for the shape of the Fourier amplitude spectrum

595 of acceleration at high frequencies, *B. Seismol. Soc. Am.*, **74,** 1969-1993.

596 Atkinson, G. M. and D. M. Boore (2006). Earthquake Ground-Motion Prediction Equations for

597 Eastern North America, *B. Seismol. Soc. Am.*, **96**, 2181–2205.

598 Atkinson, G. M. (2015). Ground-Motion Prediction Equation for Small-to-Moderate Events at

599 Short Hypocentral Distances, with Application to Induced-Seismicity Hazards, *B. Seismol. Soc.*

600 *Am.*, **105,** 981-992, doi:10.1785/0120140142.

601 Barberi, G., M. T. Cosentino, A. Gervasi, I. Guerra, G. Neri, and B. Orecchio (2004). Crustal

602 seismic tomography in the Calabrian Arc region, south Italy, *Phys. Earth Planet. In.*, **147,** 297-314,

603 doi:10.1016/j.pepi.2004.04.005.

604 Basili, R., G. Valensise, P. Vannoli, P. Burrato, U. Fracassi, S. Mariano, M. M. Tiberti, and E.

605 Boschi (2008). The Database of Individual Seismogenic Sources (DISS), version 3: Summarizing

606 20 years of research on Italy's earthquake geology, *Tectonophysics*, **453,** 20-43,

607 doi:http://dx.doi.org/10.1016/j.tecto.2007.04.014.

608 Bazzurro, P., and C. Allin Cornell (1999). Disaggregation of seismic hazard, *B. Seismol. Soc. Am.*,

609 **89,** 501-520.

610 Bernard, P., and R. Madariaga (1984). A new asymptotic method for the modeling of near-field

611 accelerograms, *B. Seismol. Soc. Am.*, **74,** 539-557.

612 Bindi, D., M. Massa, L. Luzi, G. Ameri, F. Pacor, R. Puglia, and P. Augliera (2014). Pan-European

613 ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5 %-

614   damped PSA at spectral periods up to 3.0 s using the RESORCE dataset, *B. Earthq. Eng.*, **12,** 391-

615   430, doi:10.1007/s10518-013-9525-5.

616   Bommer, J. J. (2002). Deterministic Vs. Probabilistic Seismic Hazard Assessment: An Exaggerated

617   and Obstructive Dichotomy, *J. Earthq. Eng.*, **6,** 43-73, doi:10.1080/13632460209350432.

618   Bommer, J. J., and N. A. Abrahamson (2006). Why Do Modern Probabilistic Seismic-Hazard

619   Analyses Often Lead to Increased Hazard Estimates?, *B. Seismol. Soc. Am.*, **96,** 1967-1977,

620   doi:10.1785/0120060043.

621   Bommer, J. J., P. J. Stafford, J. E. Alarcon, and S. Akkar (2007). The Influence of Magnitude

622   Range on Empirical Ground-Motion Prediction, *B. Seismol. Soc. Am.*, **97,** 2152-2170,

623   doi:10.1785/0120070081.

624   Boore, D. M. (1983). Stochastic simulation of high-frequency ground motions based on

625   seismological models of the radiated spectra, *B. Seismol. Soc. Am.*, **73,** 1865-1894.

626   Boore, D. M. (2003). Simulation of Ground Motion Using the Stochastic Method, *Pure Appl.*

627   *Geophys.*, **160,** 635-676, doi:10.1007/PL00012553.

628   Boore, D. M., and W. B. Joyner (1997). Site amplifications for generic rock sites, *B. Seismol. Soc.*

629   *Am.*, **87,** 327-341.

630   Boore, D. M., J. P. Stewart, E. Seyhan, and G. M. Atkinson (2014). NGA-West2 Equations for

631   Predicting PGA, PGV, and 5% Damped PSA for Shallow Crustal Earthquakes, *Earthquake Spectra*,

632   **30,** 1057-1085, doi:10.1193/070113eqs184m.

633   Brune. J.N., (1970). Tectonic stress and the spectra of seismic shear waves from earthquakes. *J.*

634   *Geophys. Res.*, **75**, 4997–5009.

635   Building Seismic Safety Council (BSSC) (2009). NEHRP Recommended Seismic Provisions for

636   New Buildings and Other Structures, (FEMA P-750), prepared for the Federal Emergency

637   Management Agency, Washington, DC.

638 Carafa, M. M. C., and S. Barba (2013). The stress field in Europe: optimal orientations with

639 confidence limits, *Geophys. J. Int.*, **193,** 531-548, doi:10.1093/gji/ggt024.

640 Carvalho, A., G. Zonno, G. Franceschina, J. Bilé Serra, and A. Campos Costa (2008). Earthquake

641 shaking scenarios for the metropolitan area of Lisbon, *Soil Dyn. Earthq. Eng.*, **28,** 347-364,

642 doi:10.1016/j.soildyn.2007.07.009.

643 Chapman, M. C. (1995). A probabilistic approach to ground-motion selection for engineering

644 design, *B. Seismol. Soc. Am.*, **85,** 937-942.

645 Convertito, V. (2006). Seismic-Hazard Assessment for a Characteristic Earthquake Scenario: An

646 Integrated Probabilistic-Deterministic Method, *B. Seismol. Soc. Am.*, **96,** 377-391,

647 doi:10.1785/0120050024.

648 Cultrera, G., A. Cirella, E. Spagnuolo, A. Herrero, E. Tinti, and F. Pacor (2010). Variability of

649 Kinematic Source Parameters and Its Implication on the Choice of the Design Scenario, *B. Seismol.*

650 *Soc. Am.*, **100,** 941-953, doi:10.1785/0120090044.

651 D'Amico, S., B. Orecchio, D. Presti, A. Gervasi, L. Zhu, I. Guerra, G. Neri, and R. Herrmann

652 (2011). Testing the stability of moment tensor solutions for small earthquakes in the Calabro-

653 Peloritan Arc region (southern Italy), *Boll. Geof. Teor. Appl.*, **52,** 283-298, doi:10.4430/bgta0009.

654 DISS Working Group (2010). Database of Individual Seismogenic Sources (DISS), Version 3.1.1:

655 A compilation of potential sources for earthquakes larger than M 5.5 in Italy and surrounding areas.

656 http://diss.rm.ingv.it/diss/, Istituto Nazionale di Geofisica e Vulcanologia; DOI:10.6092/INGV.IT-

657 DISS3.1.1.

658 Dreger, D. S., and T. H. Jordan (2015). Introduction to the Focus Section on Validation of the

659 SCEC Broadband Platform V14.3 Simulation Methods, *Seismol. Res. Lett.*, **86,** 15-16,

660 doi:10.1785/0220140233.

661 Ericson, C. A. (2005). Hazard analysis techniques for system safety, John Wiley & Sons.

662 Faccioli, E. (2013). Recent evolution and challenges in the Seismic Hazard Analysis of the Po Plain

663 region, Northern Italy, *B. Earthq. Eng.*, **11,** 5-33, doi:10.1007/s10518-012-9416-1.

664 Goulet, C. A., Abrahamson, N. A., Somerville, P. G., & Wooddell, K. E. (2015). The SCEC

665 Broadband Platform Validation Exercise: Methodology for Code Validation in the Context of

666 Seismic-Hazard Analyses. *Seismol. Res. Lett.*, **86**, 17-26. doi: 10.1785/0220140104.

667 Graves, R., T. H. Jordan, S. Callaghan, E. Deelman, E. Field, G. Juve, C. Kesselman, P. Maechling,

668 G. Mehta, K. Milner, D. Okaya, P. Small, and K. Vahi (2010). CyberShake: A Physics-Based

669 Seismic Hazard Model for Southern California, *Pure Appl. Geophys.*, **168,** 367-381,

670 doi:10.1007/s00024-010-0161-6.

671 Gruppo di Lavoro MPS (2004). Redazione della mappa di pericolosità sismica prevista

672 dall'Ordinanza PCM del 20 marzo 2003 n. 3274,All. 1. Rapporto conclusivo per il Dipartimento

673 della Protezione Civile, aprile 2004, Istituto Nazionale di Geofisica e Vulcanologia (INGV),

674 Milano-Roma, Italy, available at http://zonesismiche.mi.ingv.it/ (last accessed May 2015), 163 pp.

675 (in Italian).

676 Hanks, T. C., and H. Kanamori (1979). A moment magnitude scale, *J. Geophys. Res.*, **84,** 2348,

677 doi:10.1029/JB084iB05p02348.

678 International Atomic Energy Agency (IAEA) (2002). Evaluation of seismic hazards for nuclear

679 power plants: safety guide, IAEA Safety standards series, ISSN 1020–525X; no. NS-G-3.3, IAEA,

680 Vienna.

681 International Atomic Energy Agency (IAEA) (2010). Seismic hazard in site evaluation for nuclear

682 installations: safety guide. IAEA safety standards series, ISSN 1020-525X; no. SSG-9, IAEA,

683 Vienna.

684 Kanamori, H., and D. L. Anderson (1975). Theoretical basis of some empirical relations in

685 seismology, *B. Seismol. Soc. Am.*, **65,** 1073-1095.

686 Locati, M., R. Camassi, and M. E. Stucchi (2011). DBMI11, la versione 2011 del Database

687 Macrosismico Italiano. Milano, Bologna, http://emidius.mi.ingv.it/DBMI11, DOI:

688 10.6092/INGV.IT-DBMI11.

689 Lorito, S., J. Selva, R. Basili, F. Romano, M. M. Tiberti, and A. Piatanesi (2015). Probabilistic

690 hazard for seismically induced tsunamis: accuracy and feasibility of inundation maps, *Geophys. J.*

691 *Int.*, **200,** 574-588, doi:10.1093/gji/ggu408.

692 Luzi, L., D. Bindi, R. Puglia, F. Pacor, and A. Oth (2014). Single‐Station Sigma for Italian

693 Strong-Motion Stations, *B. Seismol. Soc. Am.*, doi:10.1785/0120130089.

694 Luzi, L., S. Hailemikael, D. Bindi, F. Pacor, F. Mele, and F. Sabetta (2008). ITACA (ITalian

695 ACcelerometric Archive): A Web Portal for the Dissemination of Italian Strong-motion Data,

696 *Seismol. Res. Lett.*, **79,** 716-722, doi:10.1785/gssrl.79.5.716.

697 Martinelli, F., and C. Meletti (2008). A WebGIS Application for Rendering Seismic Hazard Data in

698 Italy, *Seismol. Res. Lett.*, **79,** 68-78, doi:10.1785/gssrl.79.1.68.

699 Marzocchi, W., M. Taroni, and J. Selva (2015). Accounting for epistemic uncertainty in PSHA:

700 Logic Tree and ensemble modeling, *B. Seismol. Soc. Am.*, **105**(4), 2151–2159.

701 McGuire, R. K. (1995). Probabilistic seismic hazard analysis and design earthquakes: Closing the

702 loop, *B. Seismol. Soc. Am.*, **85,** 1275-1284.

703 McGuire, R. K. (2001). Deterministic vs. probabilistic earthquake hazards and risks, *Soil Dyn.*

704 *Earthq. Eng.*, **21,** 377-384, doi:10.1016/S0267-7261(01)00019-7.

705 Meletti, C., G. M. Calvi, and M. Stucchi (2007). Progetto S1: proseguimento della assistenza al

706 DPC per il completamento e la gestione della mappa di pericolosità sismica prevista dall'Ordinanza

707 PCM 3274/2003 e progettazione di ulteriori sviluppi, DPC-INGV S1 Project, Final Report,

708 available at http://esse1. mi. ingv. it/data/S1_Rendicontazione_Scientifica_finale_S1. pdf

709 Meletti, C., F. Galadini, G. Valensise, M. Stucchi, R. Basili, S. Barba, G. Vannucci, and E. Boschi

710 (2008). A seismic source zone model for the seismic hazard assessment of the Italian territory,

711   *Tectonophysics*, **450,** 85-108, doi:10.1016/j.tecto.2008.01.003.

712   Motazedian, D. and G. M. Atkinson (2005). Stochastic finite-fault modeling based on a dynamic

713   corner frequency. *B. Seismol. Soc. Am.,* **95**, 995–1010.

714   Mualchin, L. (1996). A technical report to accompany the CALTRANS California seismic hazard

715   map 1996 (based on maximum credible earthquakes), California Department of Transportation

716   Engineering Service Center.

717   Newhall, C., and R. Hoblitt (2002). Constructing event trees for volcanic crises, *B. Volcanol.*, **64,** 3-

718   20, doi:10.1007/s004450100173.

719   Ordaz, M., F. Martinelli, V. D'Amico, and C. Meletti (2013). CRISIS2008: A Flexible Tool to

720   Perform Probabilistic Seismic Hazard Assessment, *Seismol. Res. Lett.*, **84,** 495-504,

721   doi:10.1785/0220120067.

722   Orecchio, B., D. Presti, C. Totaro, I. Guerra, and G. Neri (2011). Imaging the velocity structure of

723   the Calabrian Arc region (southern Italy) through the integration of different seismological data,

724   *Boll. Geof. Teor. Appl.*, **52,** 625-638, doi:10.4430/bgta0023.

725   Pacor, F., G. Cultrera, A. Mendez, and M. Cocco (2005). Finite Fault Modeling of Strong Ground

726   Motions Using a Hybrid Deterministic-Stochastic Approach, *B. Seismol. Soc. Am.*, **95,** 225-240,

727   doi:10.1785/0120030163.

728   Pacor, F., R. Paolucci, L. Luzi, F. Sabetta, A. Spinelli, A. Gorini, M. Nicoletti, S. Marcucci, L.

729   Filippi, and M. Dolce (2011). Overview of the Italian strong motion database ITACA 1.0, *B.*

730   *Earthq. Eng.*, **9,** 1723-1739, doi:10.1007/s10518-011-9327-6.

731   Parolai, S., and D. Bindi (2004). Influence of Soil-Layer Properties on k Evaluation, *B. Seismol.*

732   *Soc. Am.*, **94,** 349-356, doi:10.1785/0120030022.

733   Restrepo-Velez, L. F., and J. J. Bommer (2003). An exploration of the nature of the scatter in

734   ground-motion prediction equations and the implications for seismic hazard assessment. Journal of

735   Earthquake Engineering, **7**, 171–199. doi.org/10.1142/S1363246903001000

736   Rovelli, A., O. Bonamassa, M. Cocco, M. Di Bona, and S. Mazza (1988). Scaling laws and spectral

737   parameters of the ground motion in active extensional areas in Italy, *B. Seismol. Soc. Am.*, **78,** 530-

738   560.

739   Rovida, A., R. Camassi, P. Gasperini, and M. e. Stucchi (2011). CPTI11, the 2011 version of the

740   Parametric Catalogue of Italian Earthquakes. Istituto Nazionale di Geofisica e Vulcanologia,

741   Milano, Bologna.DOI: http://doi.org/10.6092/INGV.IT-CPTI11.

742   Ruiz-García, J. (2011). Inelastic Displacement Ratios for Seismic Assessment of Structures

743   Subjected to Forward-Directivity Near-Fault Ground Motions, *J. Earthq. Eng.*, **15,** 449-468,

744   doi:10.1080/13632469.2010.498560.

745   Selva J., Tonini R., Molinari I., Tiberti M.M., Romano F., Grezio A., Melini D., Piatanesi A., Basili

746   R., Lorito S. (2016). Quantification of source uncertainties in Seismic Probabilistic Tsunami Hazard

747   Analysis (SPTHA). Geophys. J. Int., 205, 1780-1803, doi:10.1093/gji/ggw107.

748   Spudich, P., and L. N. Frazer (1984). Use of ray theory to calculate high-frequency radiation from

749   earthquake sources having spatially variable rupture velocity and stress drop, *B. Seismol. Soc. Am.*,

750   **74,** 2061-2082.

751   Strasser, F., J. Bommer, and N. Abrahamson (2008). Estimating ground-motion variability: issues,

752   insights & challenges, in *The 14ᵗʰ World Conference on Earthquake Engineering, October 12-17,*

753   *2008, Beijing, China*.

754   Stucchi, M., C. Meletti, V. Montaldo, H. Crowley, G. M. Calvi, and E. Boschi (2011). Seismic

755   Hazard Assessment (2003–2009) for the Italian Building Code, *B. Seismol. Soc. Am.*, **101,** 1885-

756   1911, doi:10.1785/0120100130.

757   Villani, M., and N. A. Abrahamson (2015). Repeatable site and path effects on the ground-motion

758   sigma based on empirical data from southern California and simulated waveforms from the

759   CyberShake platform. *B. Seismol. Soc. Am.*, doi:10.1785/0120140359

760   Villani, M., E. Faccioli, M. Ordaz, and M. Stupazzini (2014). High-Resolution Seismic Hazard

761   Analysis in a Complex Geological Configuration: The Case of the Sulmona Basin in Central Italy,

762   *Earthquake Spectra*, **30,** 1801-1824, doi:10.1193/1112911eqs288m.

763   Yagoda-Biran, G., J. G. Anderson, H. Miyake, and K. Koketsu (2015). Between-Event Variance

764   for Large Repeating Earthquakes, *B. Seismol. Soc. Am.*, **105,** 2023-2040, doi:10.1785/0120140196.

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Tables

Table 1
Modeling parameters for the simulations at Cosenza

Parameter	Value
Strike, Dip, Rake [°]	180, 60, 270
Shear-wave velocity [km/s] (β)	3.4^1, 3.4^2, 2.5^3, 2.7^4, 3.5^5
Density [g/cm^3]	2.6^1, 2.5^2, 2.5^3, 2.5^4, 2.6^5
Rupture propagation speed [km/s] (Vr)	0.7, 0.8, 0.85 (x β)
K_0 [s]	0.02, 0.025, 0,035
Geometric spreading	1/R
Quality factor (Qs)	100

Average shear-wave velocity, crustal density and rupture velocity depend on the fault size and depth (see Table 2): [1] M7.0 (1-30 km); [2] M6.0 (1-15 km); [3] M5.0 (1-3.3 km); [4] M5.0 (5-7.3 km); [5] M5.0 (7-9.3 km). Qs is from Rovelli et al. (1988).

Table 2
Fault-rupture parameters of Child Faults and source-to-site distance range

M_w	Length [km]	Width [km]	Top Depth [km]	Bottom Depth [km]	M_0 [Nm]	Mean slip [m]	R_{JB} or R_{epi} [km]
7.0	37.0	26.0	1.0	23.5	4.0×10^{19}	1.40	0
6.0	13.0	9.0	1.0	8.8	1.4×10^{18}	0.40	0 - 7
5.0	4.0	2.7	1,5,7	3.3,7.3,9.3	4.2×10^{16}	0.13	0 – 15*

* Epicentral distance.

Table 3
Number of shaking scenarios performed for the city of Cosenza for each magnitude

M	#Nucleation Point	#rupture velocity	#k_0	#modeled faults	#simulations
7.0	27	3	3	1	243
6.0	9	3	3	5	405
5.0	3	3	3	23	621

Table 4
Crustal velocity model

Depth [km]	Vp [km/s]	Vs [km/s]	ρ [g/cm^3]
0	4.50	2.49	2.50
5	5.00	2.76	2.50
8	6.00	3.31	2.60
15	6.50	3.59	2.70
18	6.80	3.76	2.80
30	7.50	4.14	2.90
40	7.50	4.76	2.90

Data from (Barberi et al., 2004; Orecchio et al., 2011; D'Amico et al., 2011). Vs = Vp/1.81 (km/s).

Table 5
Summary of PGA and PGV values

	M	R_{JB}	BI2014	BSSA	M1	M2	M3
PGA [cm/s²]	7.0	0	2.60	2.49	2.58-2.59*	2.66-2.67*	2.68-2.56*
	6.0	0	2.41	2.44	2.34	2.47	2.53
	6.0	5	2.26	2.28	2.06	2.22	2.30
	5.0	5	1.98	1.91	2.00	1.95	2.07
	5.0	10	1.65	1.62	1.75	1.71	1.85
PGV [cm/s]	7.0	0	1.62	1.49	1.51-1.49*	1.60-1.56*	1.61-1.65*
	6.0	0	1.23	1.20	1.17	1.28	1.34
	6.0	5	1.08	1.06	0.88	1.02	1.10
	5.0	5	0.57	0.42	0.68	0.63	0.73
	5.0	10	0.24	0.15	0.41	0.38	0.59

PGA and PGV medians of empirical models are derived from BSSA (Boore et al., 2014) and BI2014 (Bindi et al., 2014) for each magnitude-distance bin considered in this work. Corresponding PGA and PGV synthetic values (log10 units) are derived from simulations at the target site (CSZ) considering the three different scenario model configurations (M1, M2, and M3 combined with the DSM local metric); * values for the quasi-unilateral site (s001).

Table 6
Summary of PGA and PGV variability

IMT	M	R_{JB}	BSSA			BI2014			M1	M2	M3
			σ	ϕ	τ	σ	ϕ	τ	σ_{DSM}	σ_{DSM}	σ_{DSM}
	7.0	0	0.27	0.22	0.15				0.17-0.18*	0.11-0.16*	0.13-0.10*
	6.0	0	0.27	0.22	0.15				0.27	0.10	0.14
PGA	6.0	5	0.27	0.22	0.15	0.33	0.28	0.18	0.35	0.09	0.16
	5.0	5	0.31	0.27	0.16				0.37	0.23	0.33
	5.0	10	0.31	0.27	0.16				0.38	0.20	0.30
	7.0	0	0.28	0.24	0.15				0.15-0.16*	0.09-0.14*	0.13-0.10*
	6.0	0	0.28	0.24	0.15				0.22	0.06	0.10
PGV	6.0	5	0.28	0.24	0.15	0.33	0.27	0.19	0.30	0.06	0.13
	5.0	5	0.31	0.26	0.16				0.35	0.24	0.32
	5.0	10	0.31	0.26	0.16				0.33	0.20	0.27

PGA and PGV variability derived from BSSA (Boore et al., 2014) and BI2014 (Bindi et al., 2014) empirical models for each magnitude-distance considered in this work (log10 units): σ) empirical total standard deviation; Φ) within-event component of the empirical total standard deviation; τ) between-event component of the total standard deviation. The corresponding standard deviation σ_{DSM} of the synthetic statistical distributions are also reported. The ground motion was simulated at the target site (CSZ) considering the three different scenario model configurations (M1, M2, and M3 combined with the DSM local metric); values denoted by * are for the quasi-unilateral site (s001).

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Table 7
Summary of the regression results for each simulation method setup and
sampled magnitude (M): first step

Setup	c_1	c_2	h_{eff}	d	σ_{reg}	M
GM-M1	1.14	-2.26	7.32	30	0.37	5.0
	1.56	-1.39	7.32	34	0.39	6.0
	1.60	-2.40	19	64	0.19	7.0
GM-M2	1.14	-2.15	7.32	30	0.14	5.0
	1.56	-1.78	7.32	34	0.16	6.0
	1.60	-2.62	19	64	0.11	7.0
GM-M3	1.14	-2.51	7.32	30	0.30	5.0
	1.56	-1.89	7.32	34	0.26	6.0
	1.60	-2.66	19	64	0.13	7.0

Legend: c_1 and c_2, regression coefficients; h_{eff}, effective depth; d, joint
distance; and σ_{reg}, standard deviation of the empirical residuals (log10 units).

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Table 8
Summary of the regression results for each sampled
magnitude (M) and for M1 model setup: second step

Setup	c_3	c_4	σ^*	M
GM-M1	-1.21	0.81	0.13	5.0
	-0.99	0.83	0.11	6.0
	-1.35	1.00	0.10	7.0

Legend: c_3 and c_4, regression coefficients; σ^*, standard
deviation of the empirical residuals (log10 units).

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831   Mw = 6.0, R_1= 5 km and R_2 = 10 km (epicentral distance) for Mw = 5.0. Each box encloses 50% of

832   the data with the median value of the parameters represented by a horizontal line; the top and the

833   bottom of the box mark the limits of ±25% of the population; the lines extending from the top and

834   the bottom of each box mark the minimum and the maximum values of the data; data with values

835   1.5 times greater/lower than the top/bottom value of the box are outliers (grey cross).

836   **Figure 5.** PGAs parametric variability of the modeling setup accounting for maximum directivity

837   effects (M1) for each simulated magnitude (M7.0, M6.0, and M5.0). a) CDFs are computed

838   grouping scenarios events that share the same rupture velocity considering the three selected values

839   for M6.0 and M7.0 and three different range of values for M5.0; scenarios at M5.0 and M6.0 are for

840   distance group R_2 =5 km and R_2 = 10 km, respectively (see caption of Figure 4). b) CDFs are

841   computed grouping scenarios that share the same k_0 values; c) CDFs are computed grouping

842   scenarios that share the same rupture nucleation area considering the three sectors of the M7.0 fault

843   (i.e. sector 1 contains nucleation points from the northern sector of the M7.0 fault). For M5.0

844   nucleation point located into the top (TOP) or the bottom (BTM) of the M7.0 fault are also

845   considered. All CDFs are compared to the overall distribution of the PGAs (black lines).

846

847   **Figure 6.** a) Comparison among PGA median values, along with their standard deviations, obtained

848   for each magnitude-distance pair by DSM simulations (circles) and empirical ground motion

849   models (triangles). The standard deviation for the empirical models are reduced by the fault-

850   variance $\tau^2/2$ instead of the between-event variance τ (Yagoda-Biran et al., 2015). b) Probability

851   Density Functions (PDFs) of the PGA (cm/s^2 log10 units) synthetic distributions computed by DSM

852   local metric at the bilateral (left) and unilateral (right) site for M7.0. The PDFs defined by three

853   different simulation setups (M1, M2 and M3) are compared with empirical PFDs predicted by

854   BI2014 (Bindi et al., 2014) and BSSA (Boore et al., 2014); black line: apparent corner frequency

855   finite-fault model (M1); grey line: point-source model (M2); light-grey line: merging between M1

856   and M2 models based on a corner frequency threshold (0.07 Hz). Empirical PDFs are plotted

857 considering the fault variance defined in Yagoda-Biran et al. (2015) as $(\tau^2/2)$ instead of the

858 between-event variance; the sigma estimated for a single seismic source (ABR) by Luzi et al.

859 (2014) is also considered.

860 **Figure 7.** Comparison between BI2014 (grey lines) and synthetic PGA (black lines) ground motion

861 models (normal faulting and EC8 soil class A), obtained by modeling a PF very close to the CSZ

862 site. The attenuation curves inferred by regression of synthetic ground motion are for three setups of

863 the simulation method (DSM, Pacor et al., 2005), which account for differently weighted directivity

864 effects: maximum level (M1 top panel), minimum level (M2 central panel), and middle level (M3

865 bottom panel). The hybrid models are obtained by adjusting BI2014 (Bindi et al., 2014) in near-

866 source ranges at different magnitudes: M5.0 (left), M6.0 (center), and M7.0 (right). White dots

867 represent the synthetic PGA; grey-shaded areas represent the ranges of hypocentral distances for

868 which the empirical model and synthetic data are merged. Grey dotted lines represent the total

869 standard deviation of the host empirical model (BI2014); light-grey lines show the sigma reduced

870 by the fault variance $\tau^2/2$ instead of the between-event variance τ (GMPE-R).

871 **Figure 8.** Hybrid model total residuals for M7.0 (M1 setup) as a function of the apparent stress

872 parameter (Δ_{app}) at the first (a) and second (b) steps of the regression. Residuals are calculated as

873 synthetic PGAs minus PGAs predicted by the hybrid attenuation model ($\log_{10}PGA_{syn}$ −

874 $\log_{10}PGA_{hyb}$). The dotted line (a) represents the fitting of the synthetic ground motion after

875 correcting the median value by the directivity term due to the modeling variability of Δ_{app}; the grey

876 rectangle marks the 16th and the 84th percentiles of the Δ_{app} distribution.

877

878 **Figure 9.** PGAs hybrid ground motion models inferred by the regression of synthetic ground

879 motion (M1 setup) and corrected for the directivity term for each magnitude (M5.0, M6.0, and

880 M7.0). Attenuation curves are for the 16th, 50th, and 84th percentiles of the apparent stress parameter

881 distributions.

882

Figure 10. a) Map of the ZS9 seismogenic zones (Meletti et al. 2008) in the Calabria region. The black triangle represents the city of Cosenza (CSZ), the zone with the black outline is the AS929 from ZS9, used for PSHA computation, and the dash-outlined rectangle is the PF simulated in this work; b) diagram showing the cumulative (open circles) and interval (solid diamonds) seismicity rates for the GR and AR branches of MPS04 for AS929 (Gruppo di Lavoro MPS, 2004). All rates are normalized to 100 years. AS929 is characterized by an FMD with the following parameters: a = 0.39 cumulative n. eqs/yr (C. Meletti, *pers. comm.*) with reference to the minimum threshold magnitude considered (Mwmin=4.76); b = 0.82; and maximum moment magnitude Mwmax = 7.29 (Stucchi et al., 2011). In the hazard calculation the a-value was appropriately reduced in order to account for a number of earthquakes coherent with the effective dimension of the modeled seismogenic source.

Figure 11. a) Annual probability of exceedance for PGA calculated at the site of interest by using empirical (black lines) or hybrid ground motion models (grey lines); b) hazard curves for a set of logic tree weights that differently combine directivity effects into M1 modeling setup. The computation of the hazard curves for empirical models was performed considering: i) the total standard deviation of the host GMPE (BI2014); ii) the sigma reduced by the fault variance $\tau^2/2$ instead of the between-event variance τ (BI2014-R); iii) the hybrid models accounting for distinct medians and variances of the synthetic ground motion (GM-M1, GM-M2, and GM-M3); iv) the three different weights for 16th, 50th and 84th percentiles of Δ_{app} are, respectively: WH1= 0.4, 0.5, 0.1; WH2 = 0.3, 0.3, 0.3 and WH3=0.1, 0.5, 0.4.

Figure 1

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911   **Figure 2**

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914   **Figure 3**

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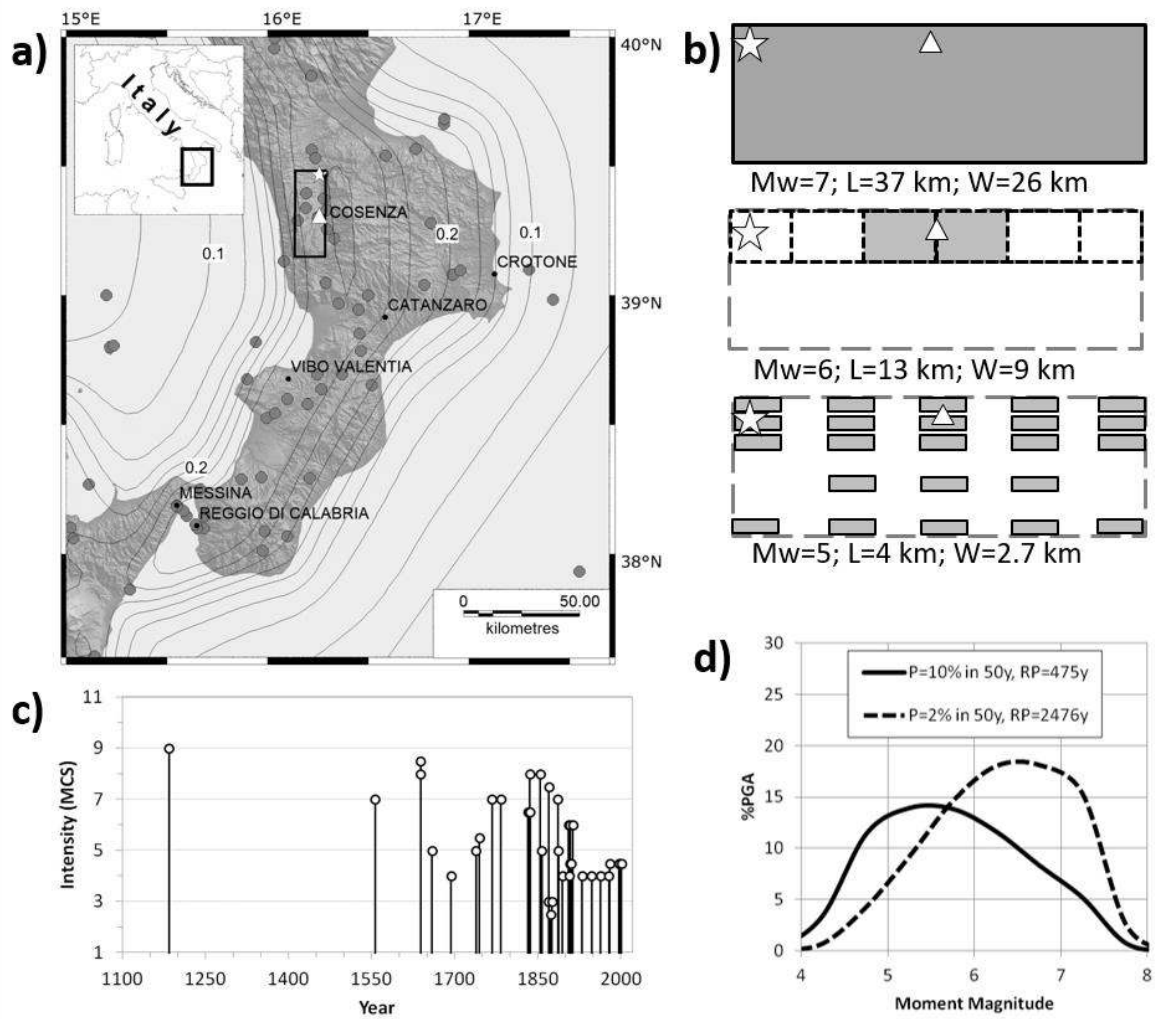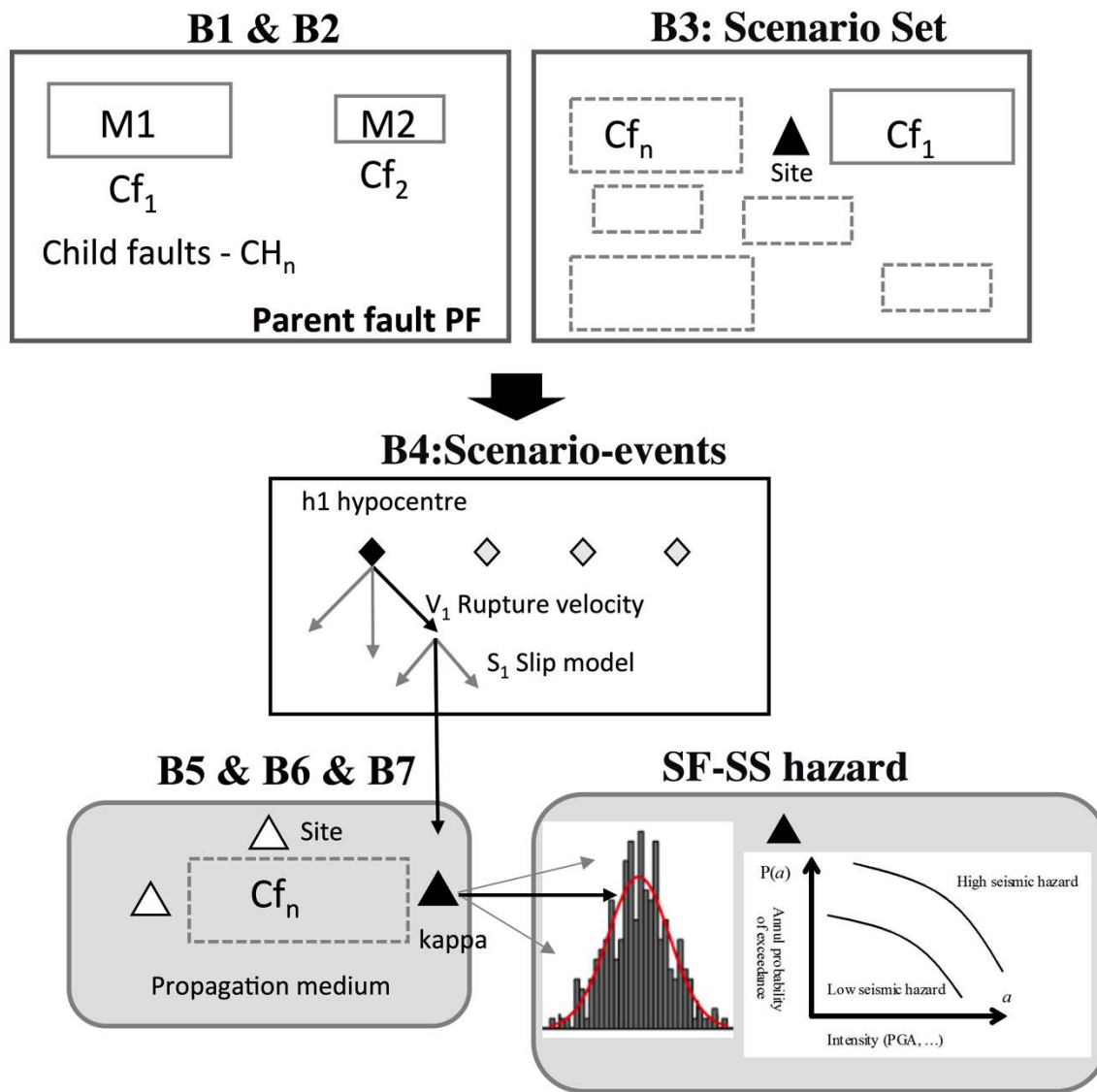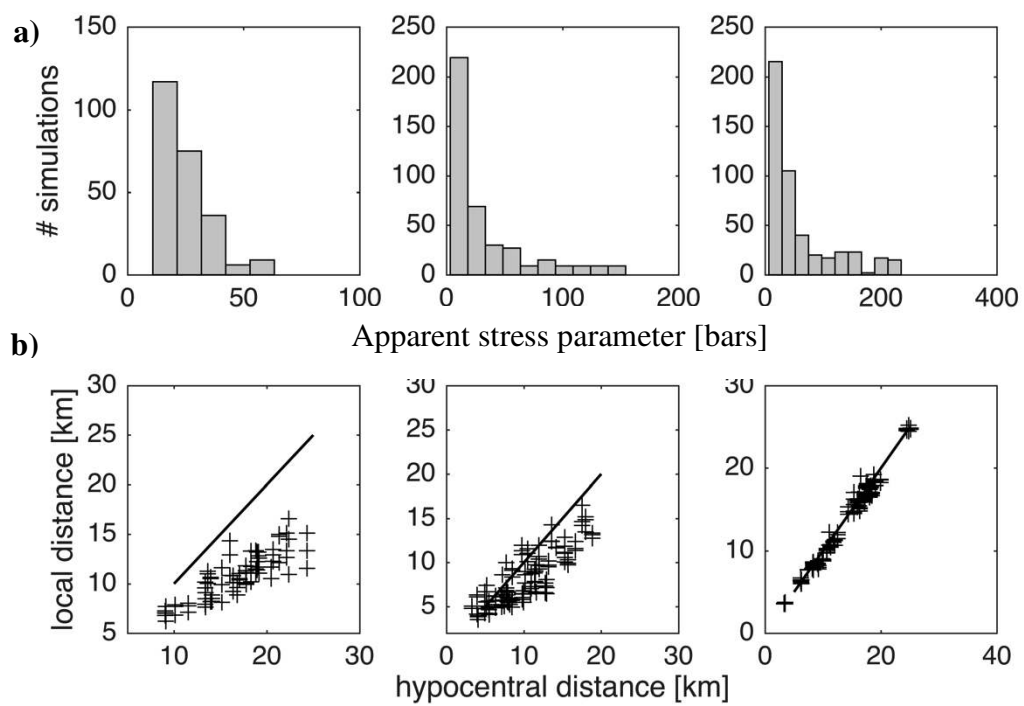
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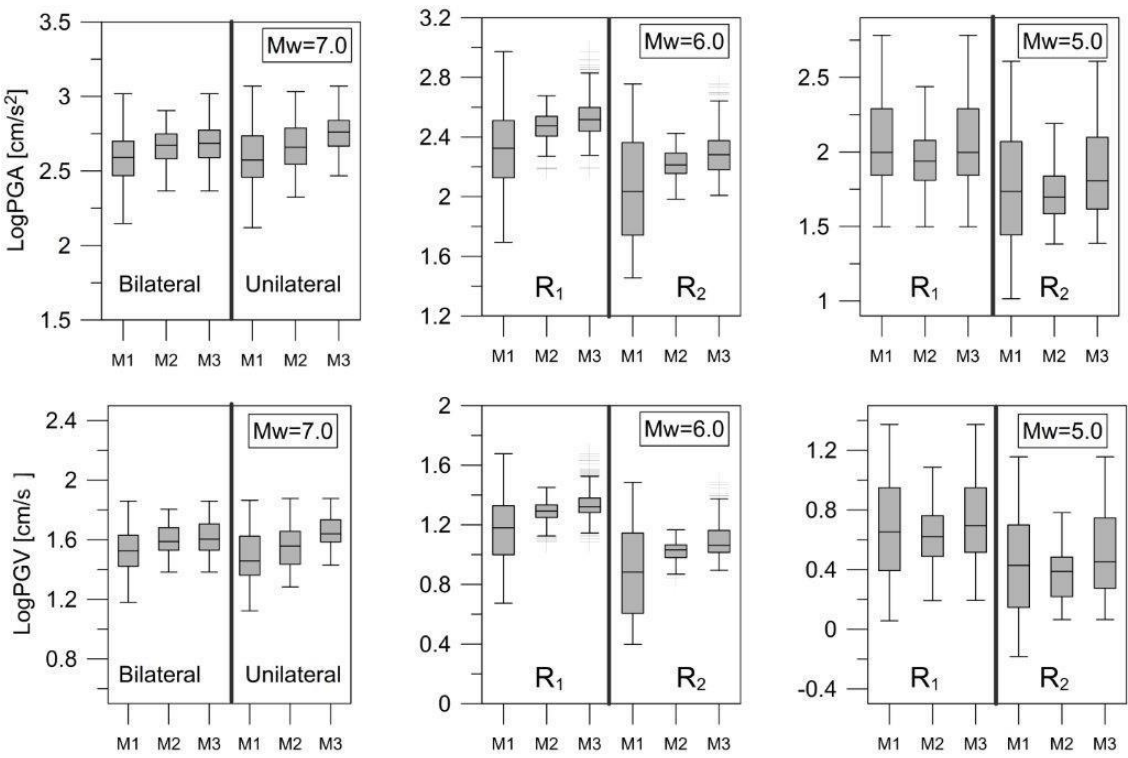
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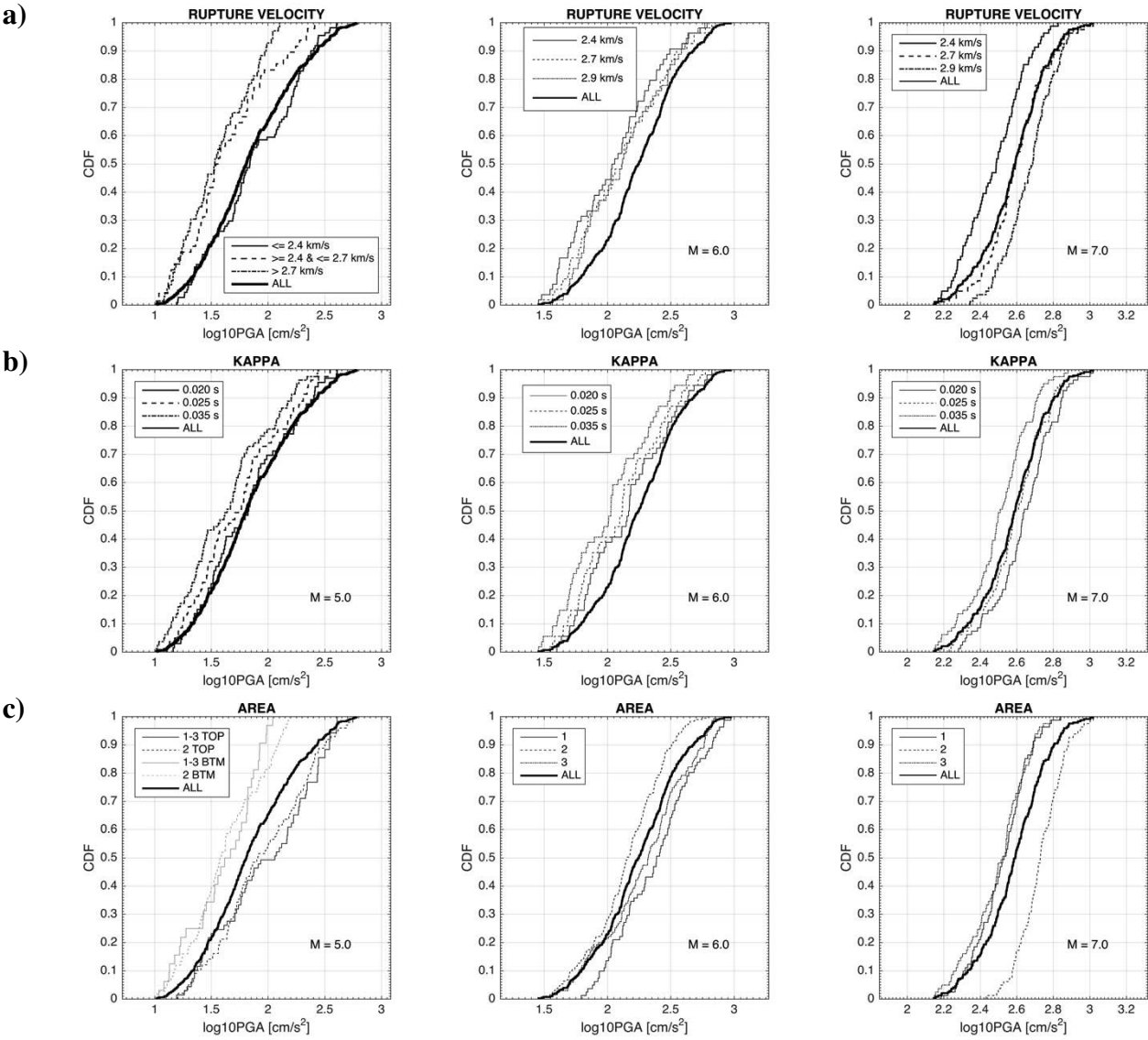
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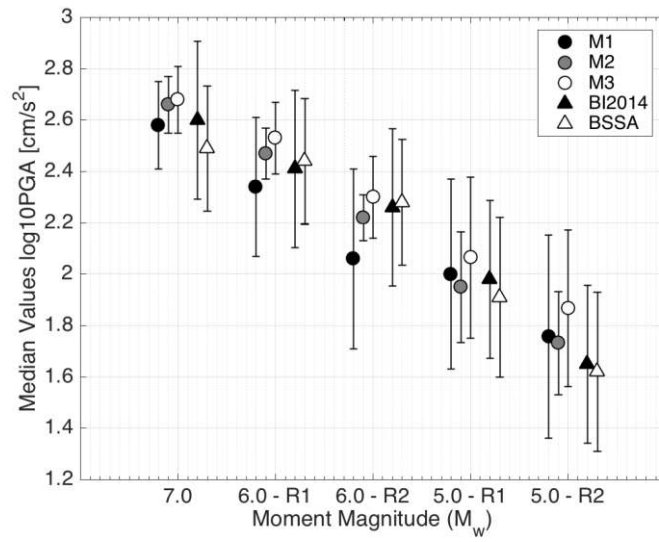
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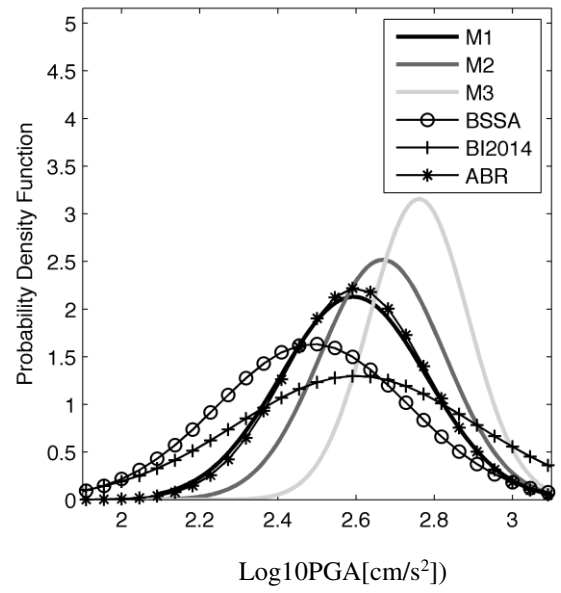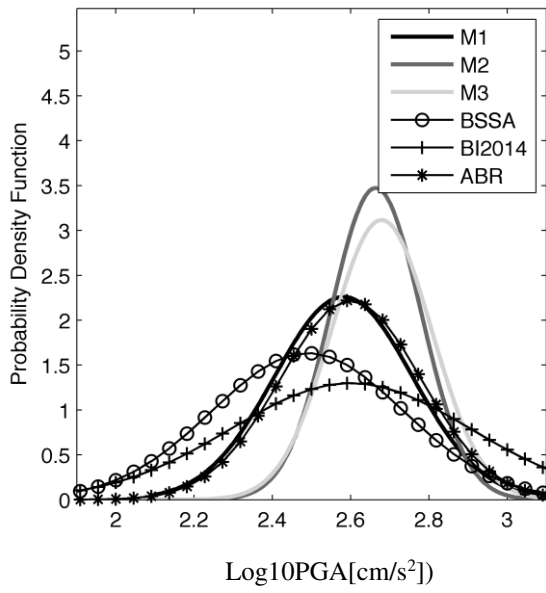
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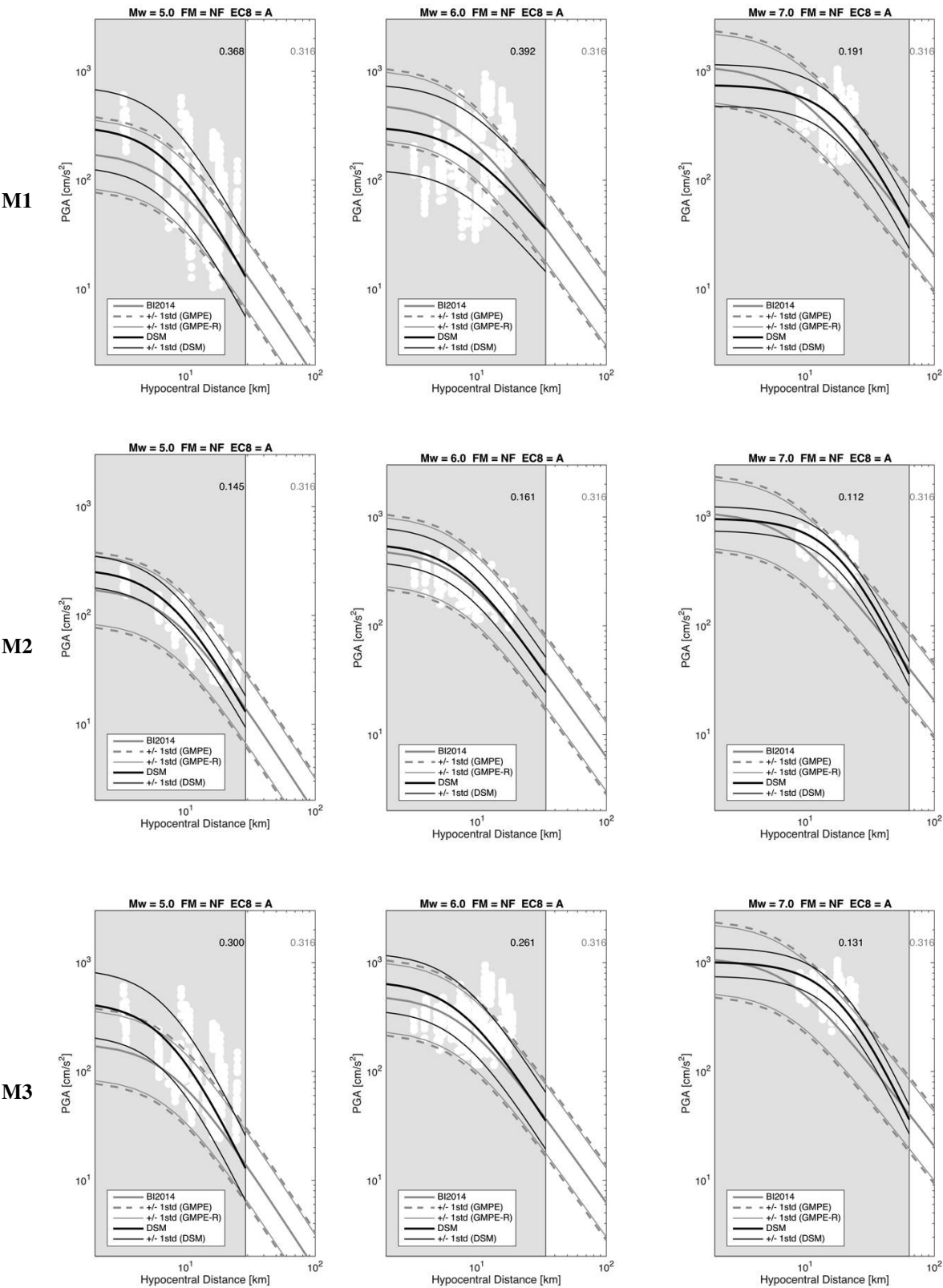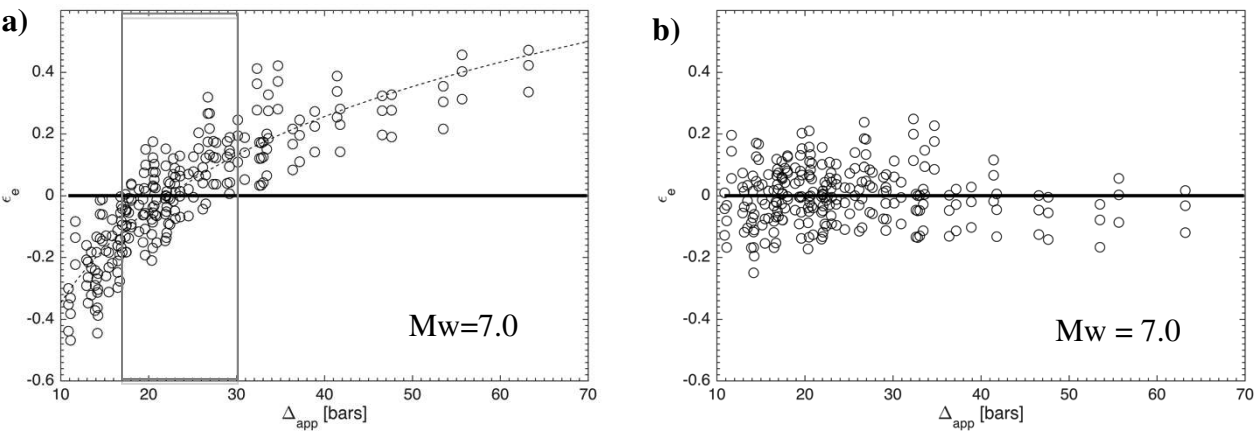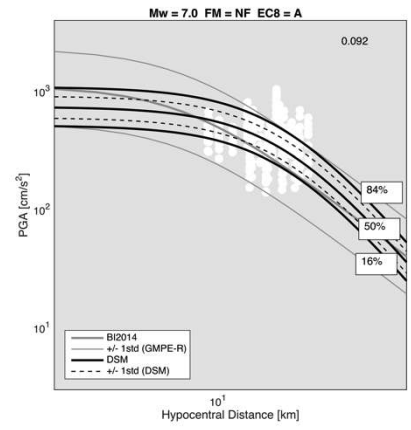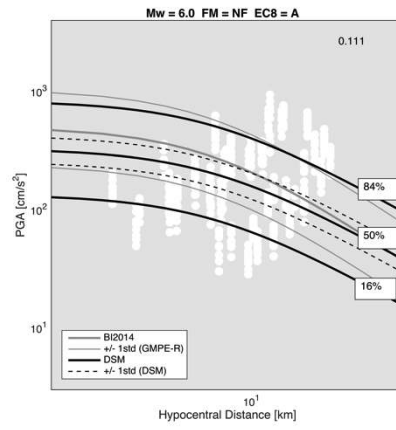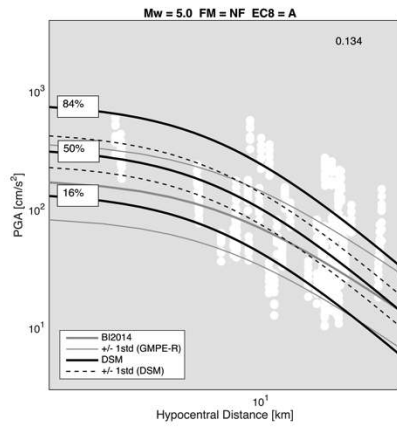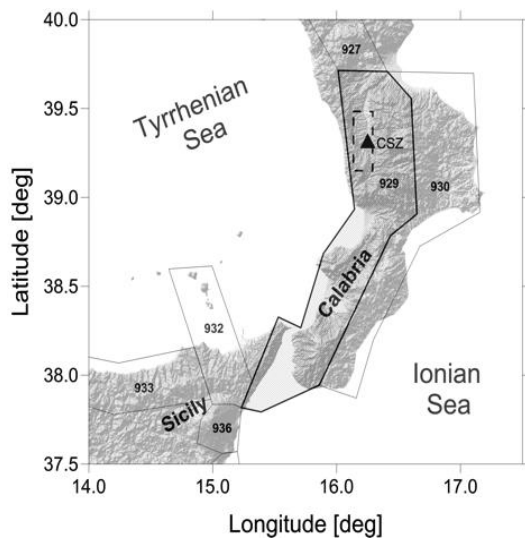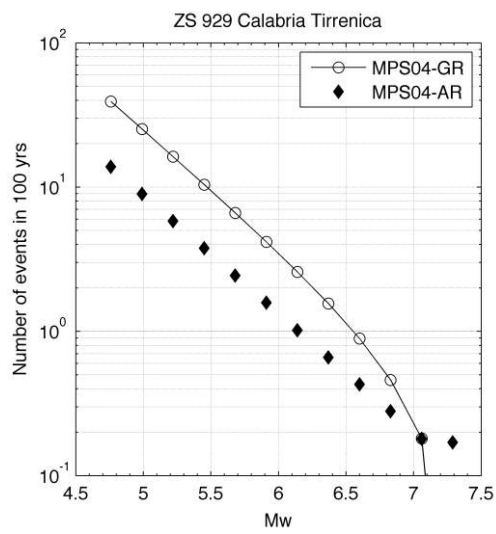
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922   **Figure 6**

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Figure 10

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Figure 11

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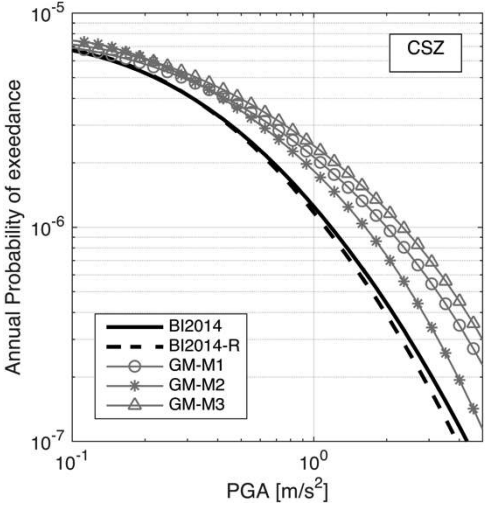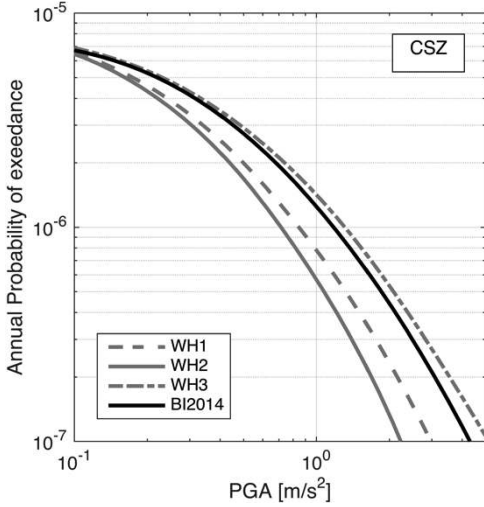
Figure 1

Figure 2

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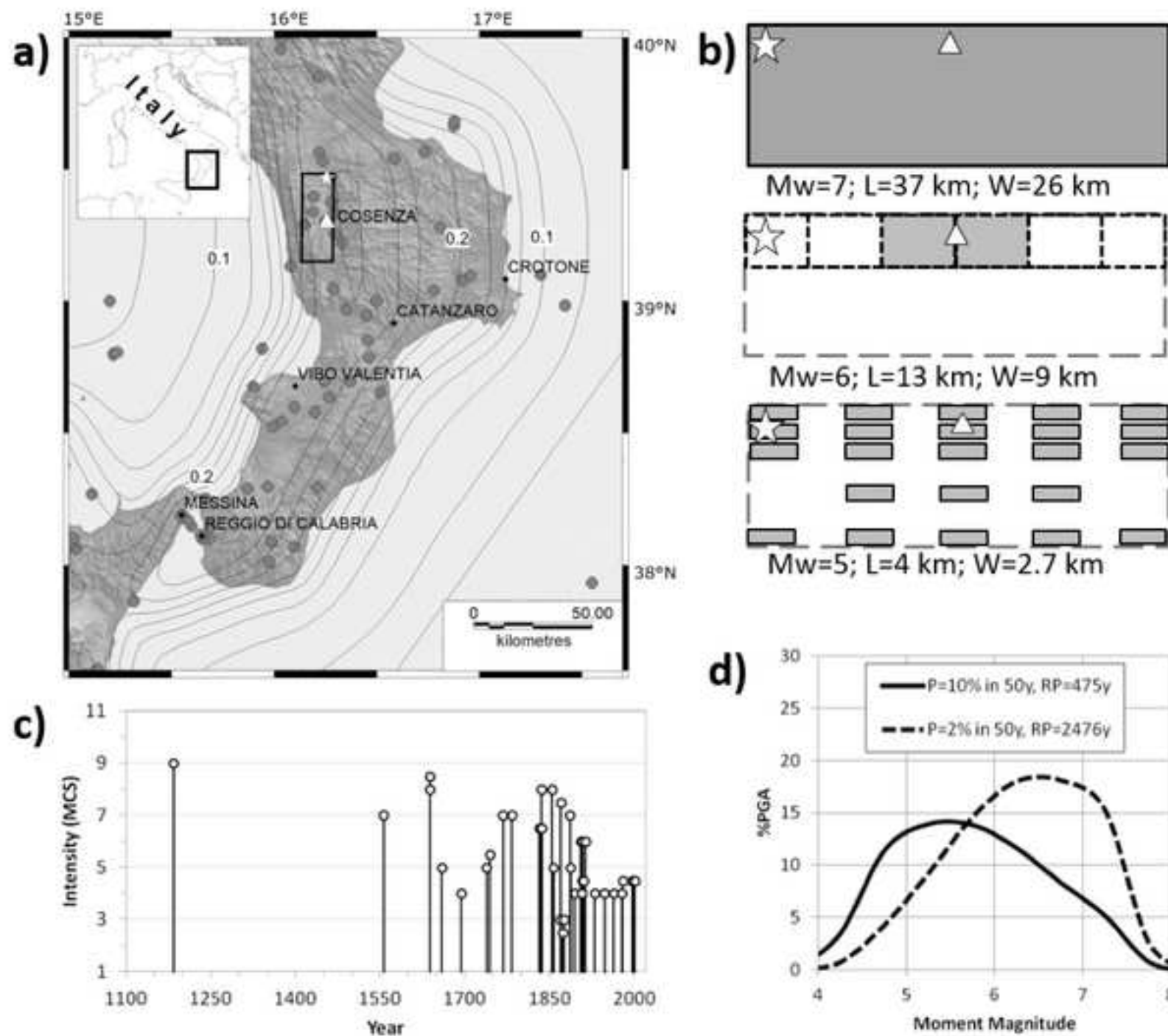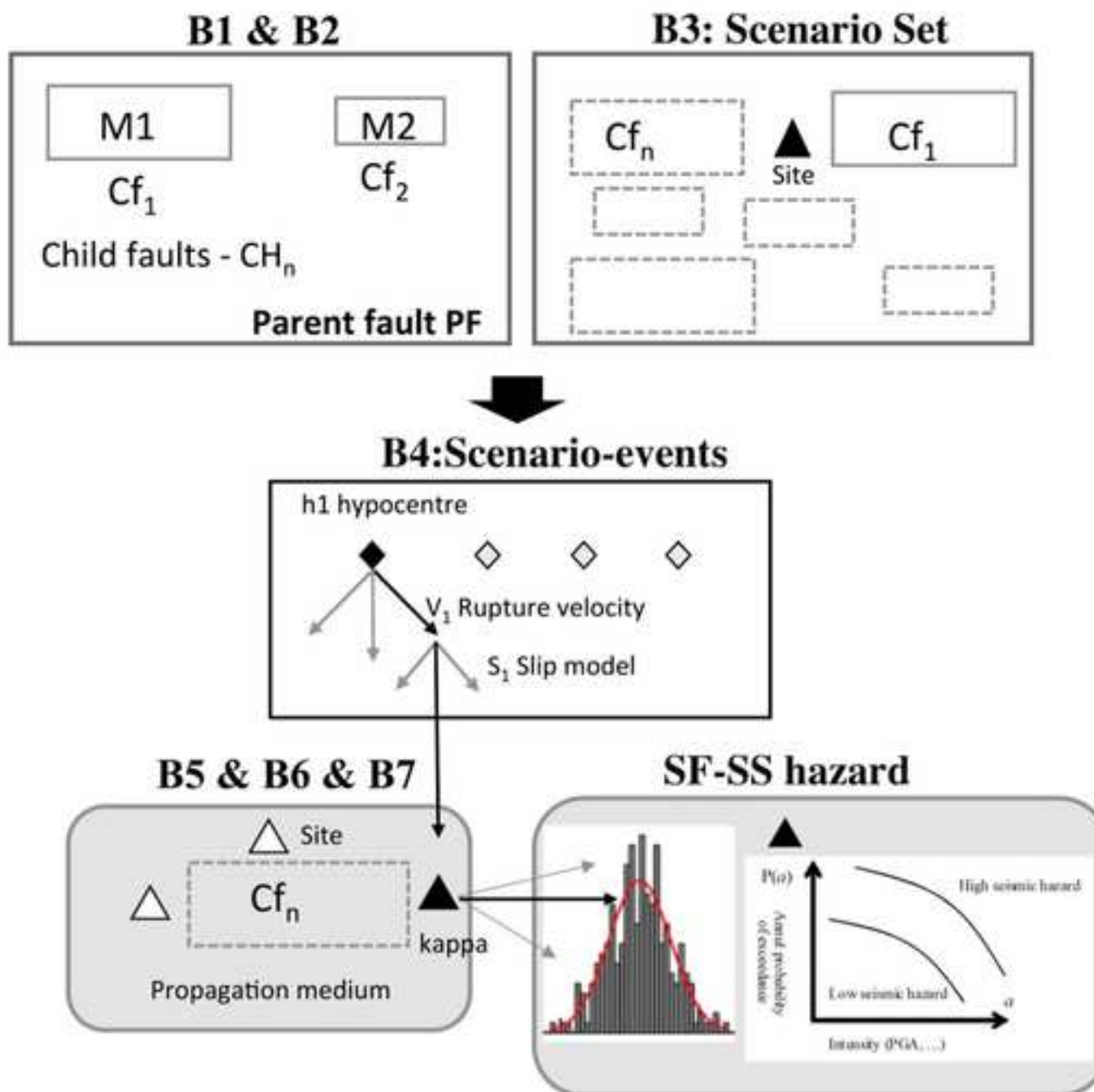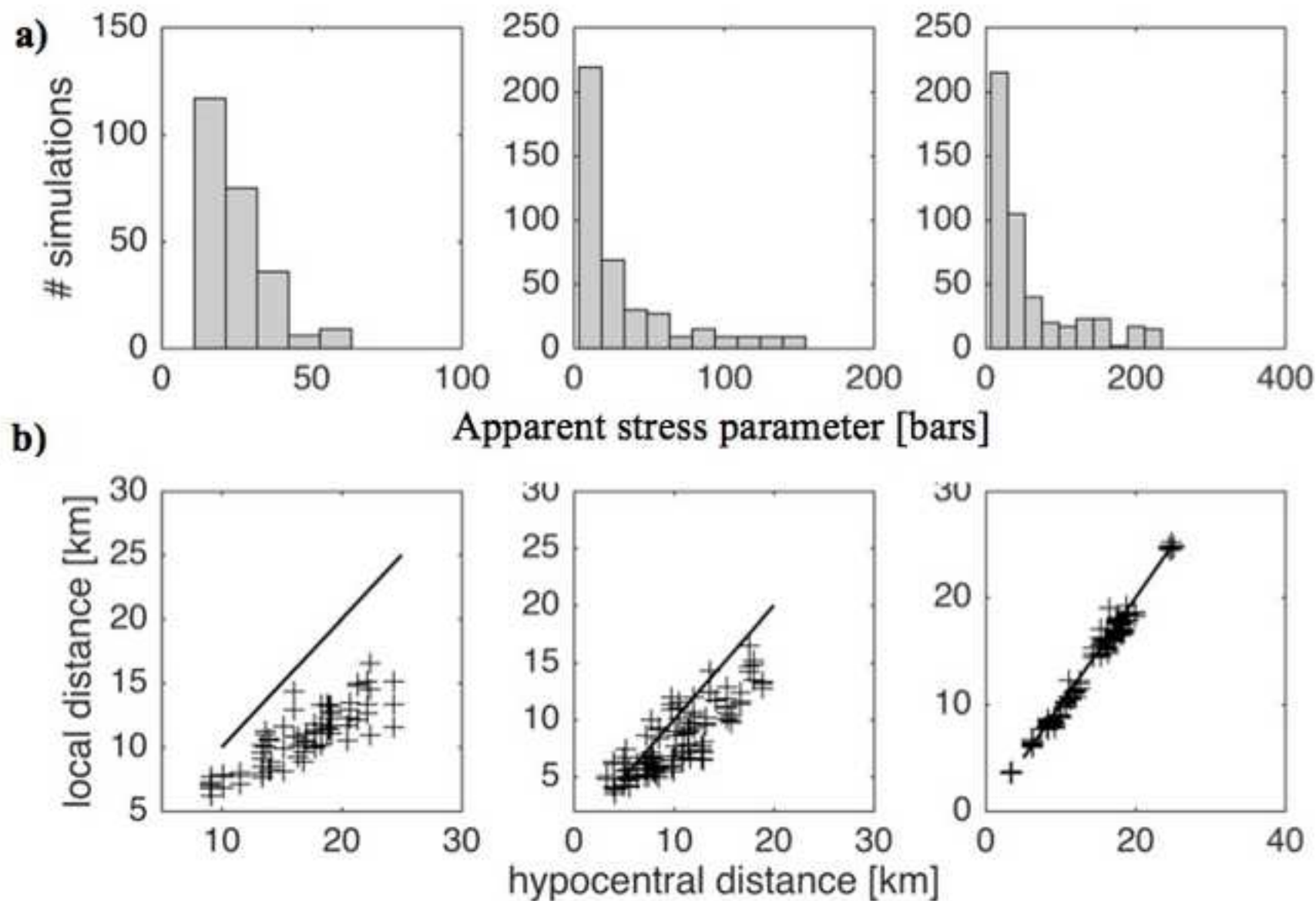
Figure 2

Figure 3

Figure 4

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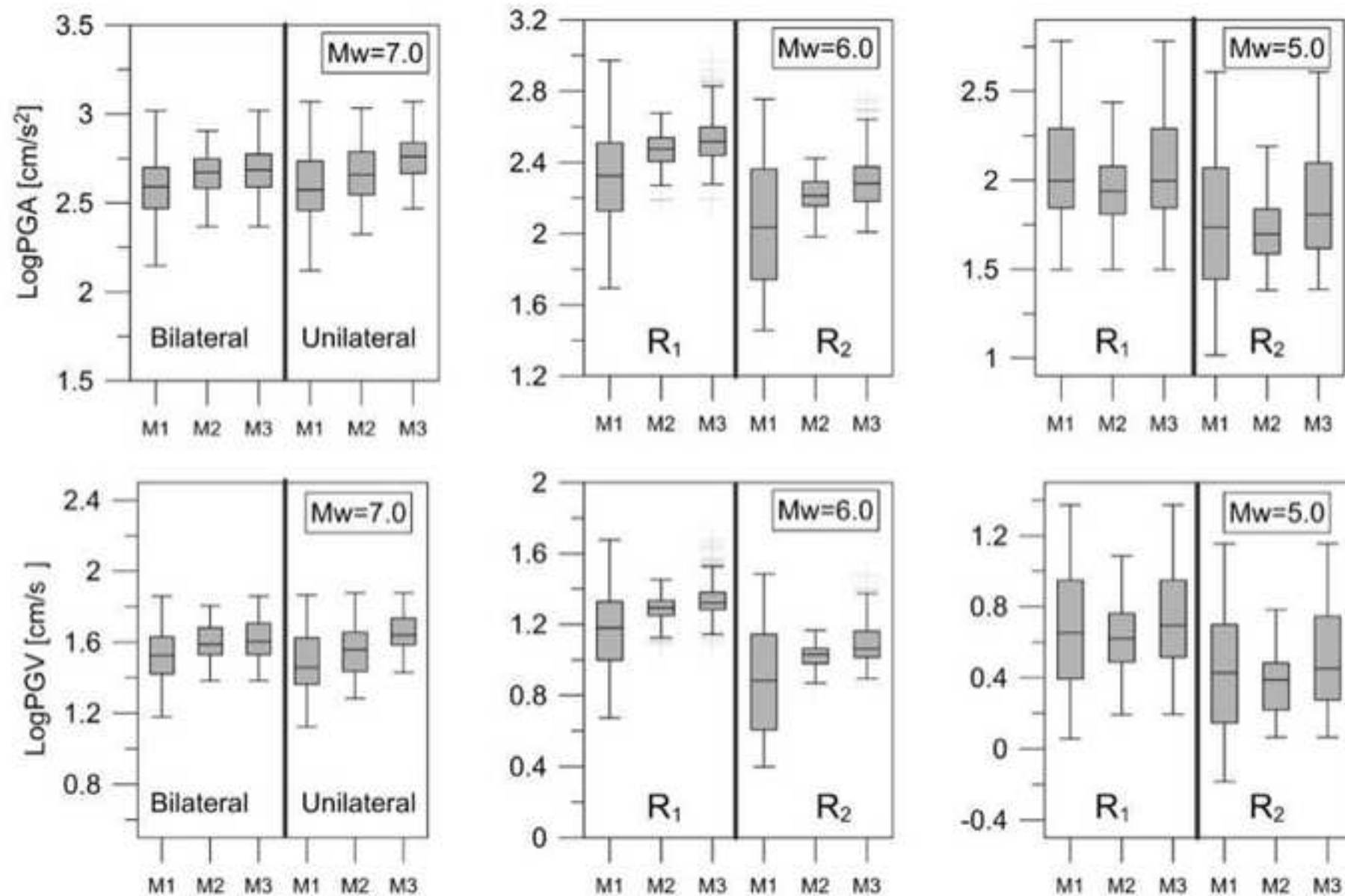
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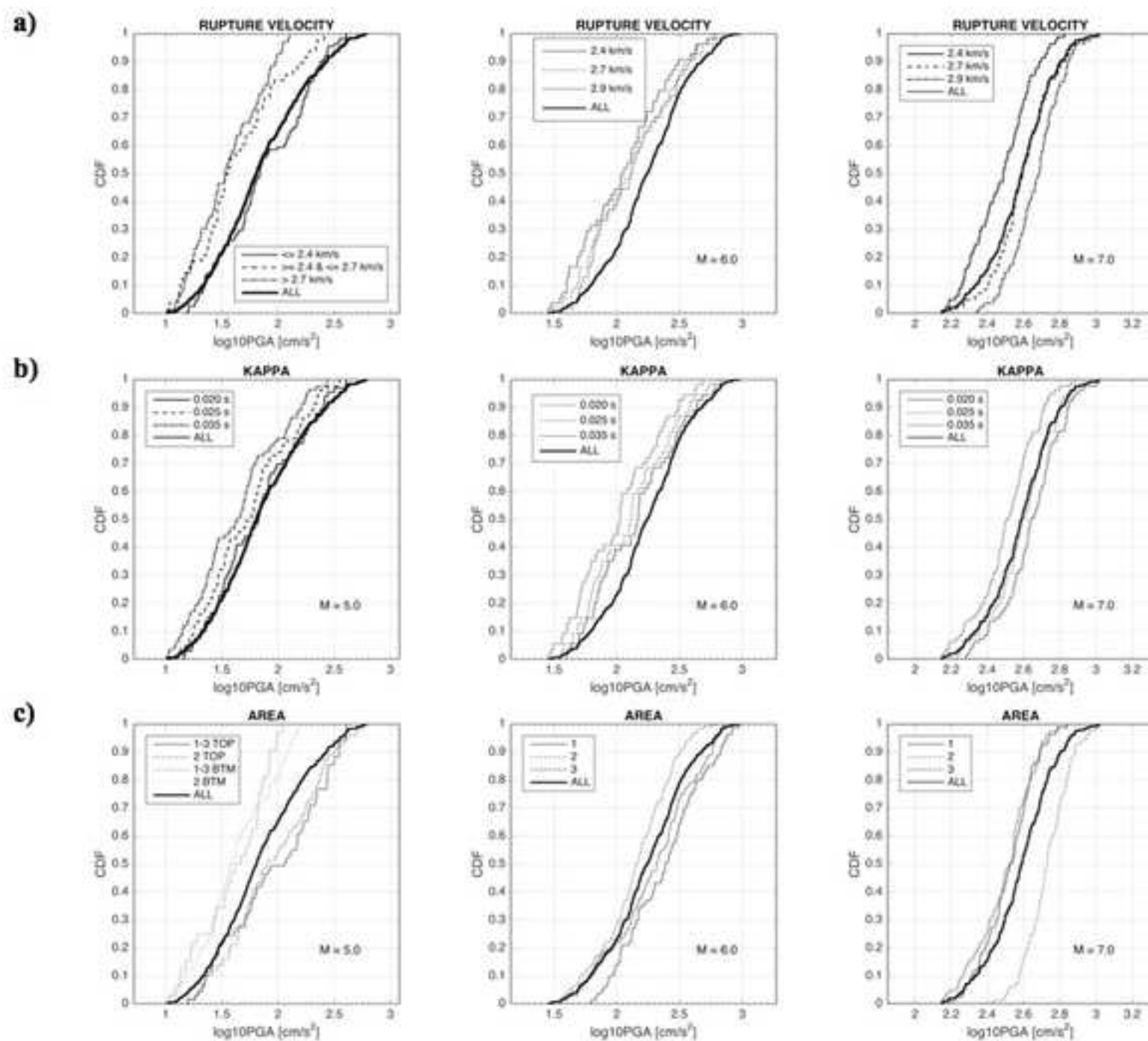
Figure 5

Figure 7   Click here to download Figure Figure7.jpg ☒

Figure 8

Figure 8

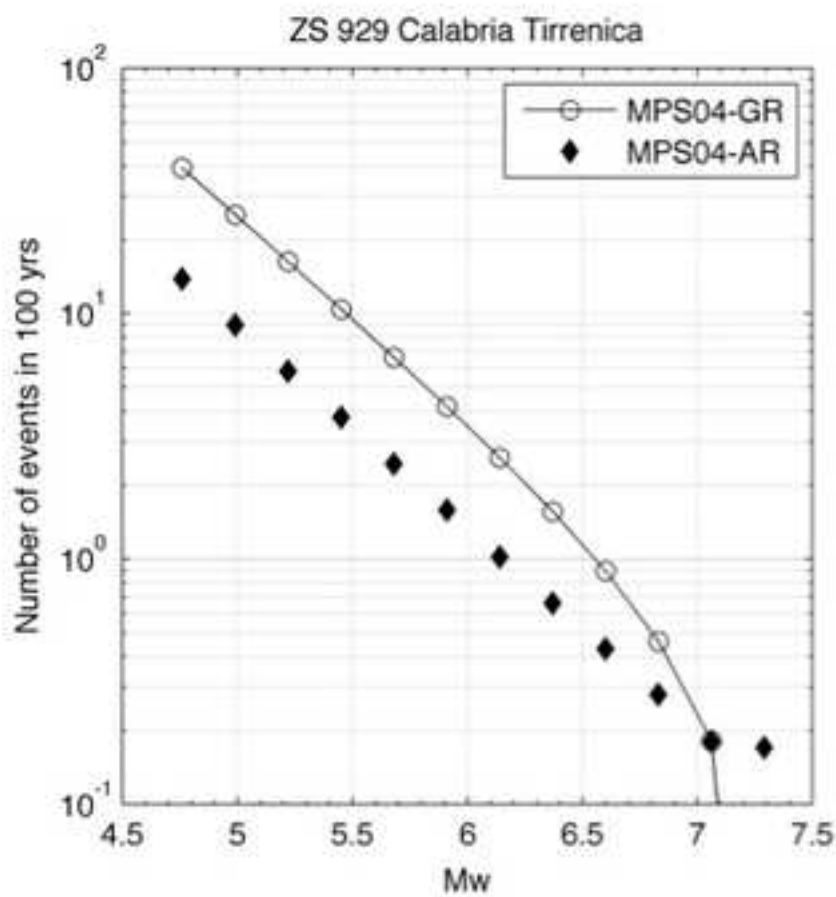Figure 9

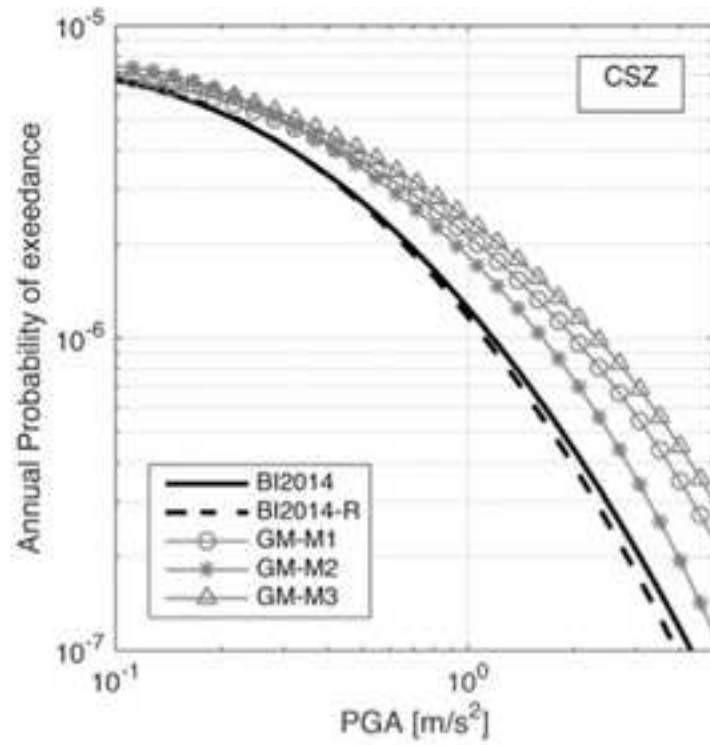Click here to download Figure Figure9.jpg ⬇

Figure 10

a)

b)
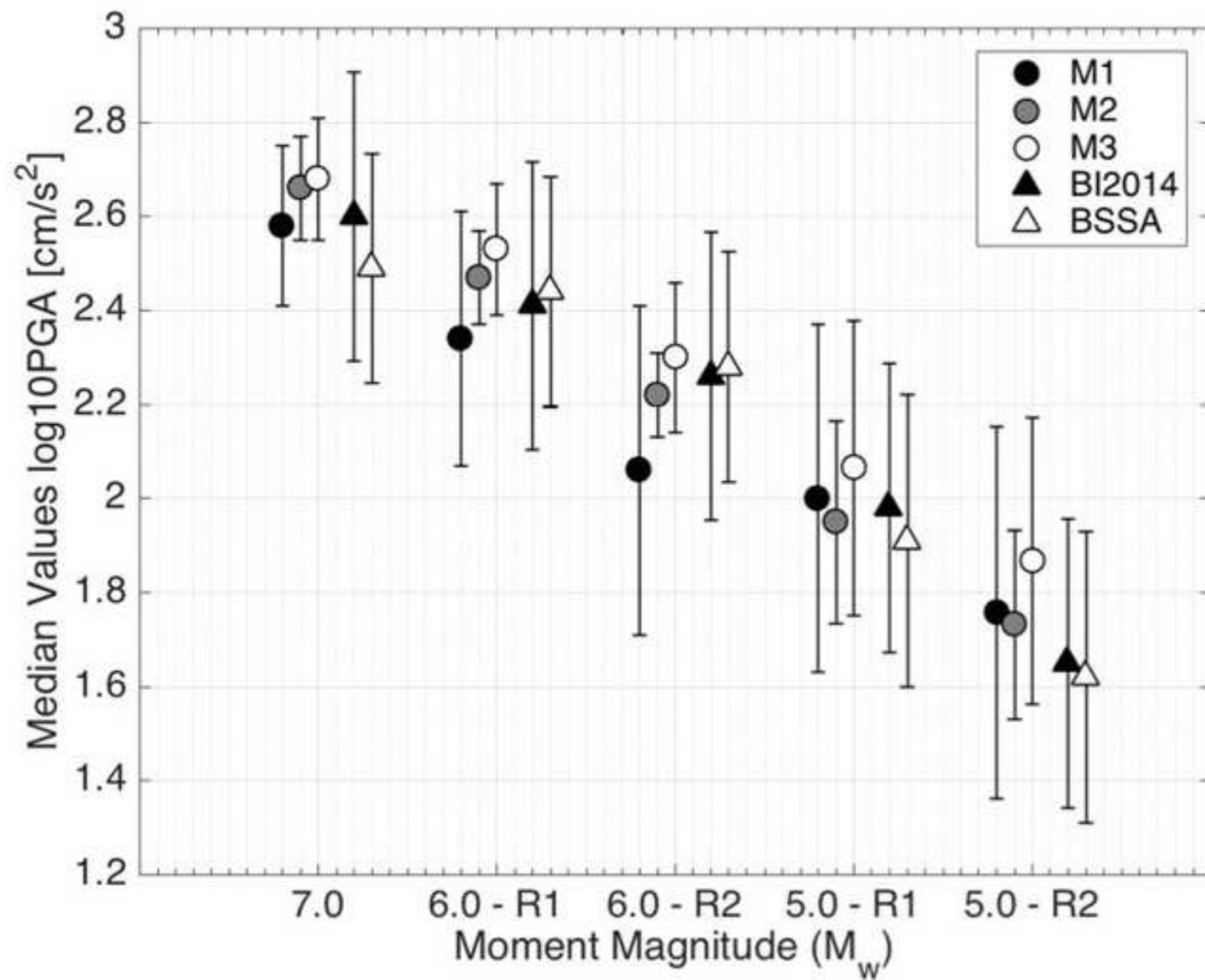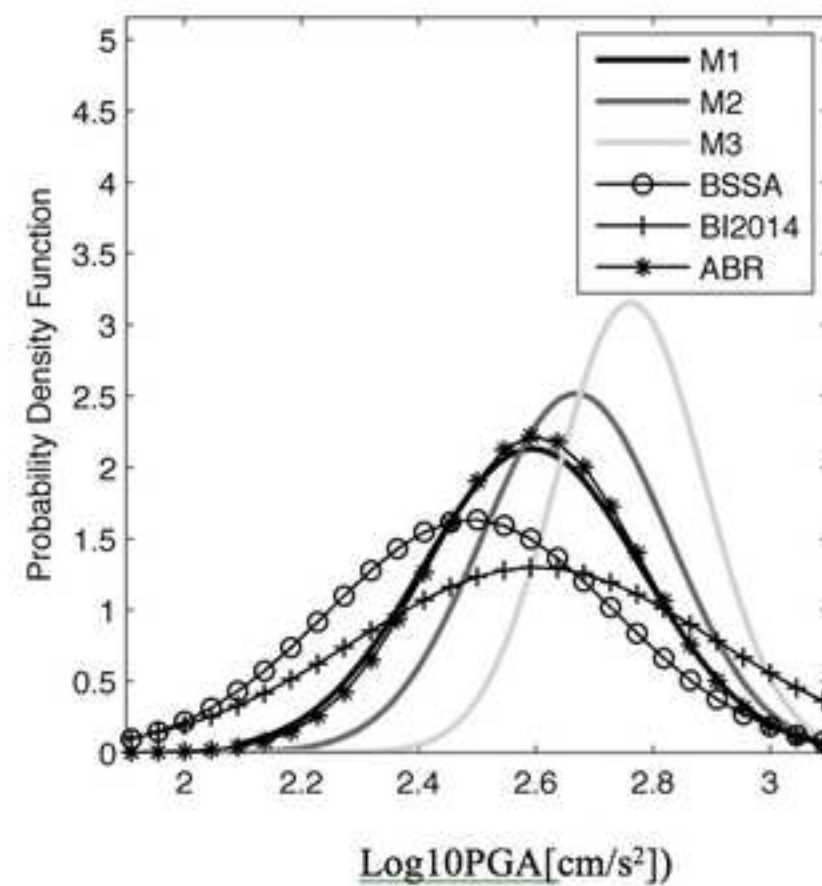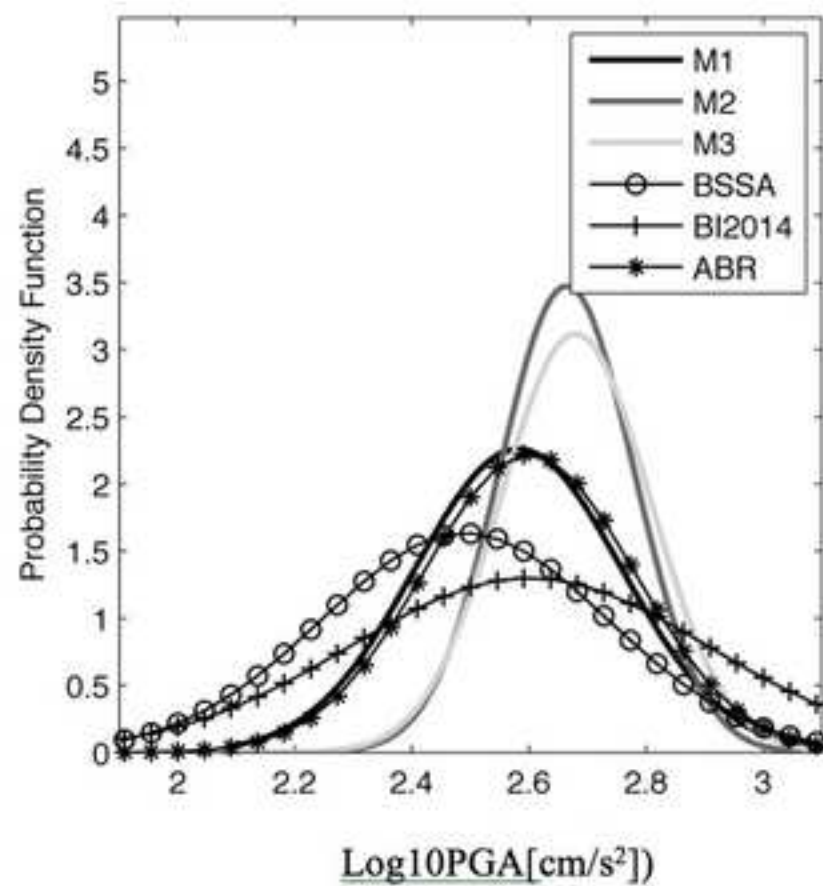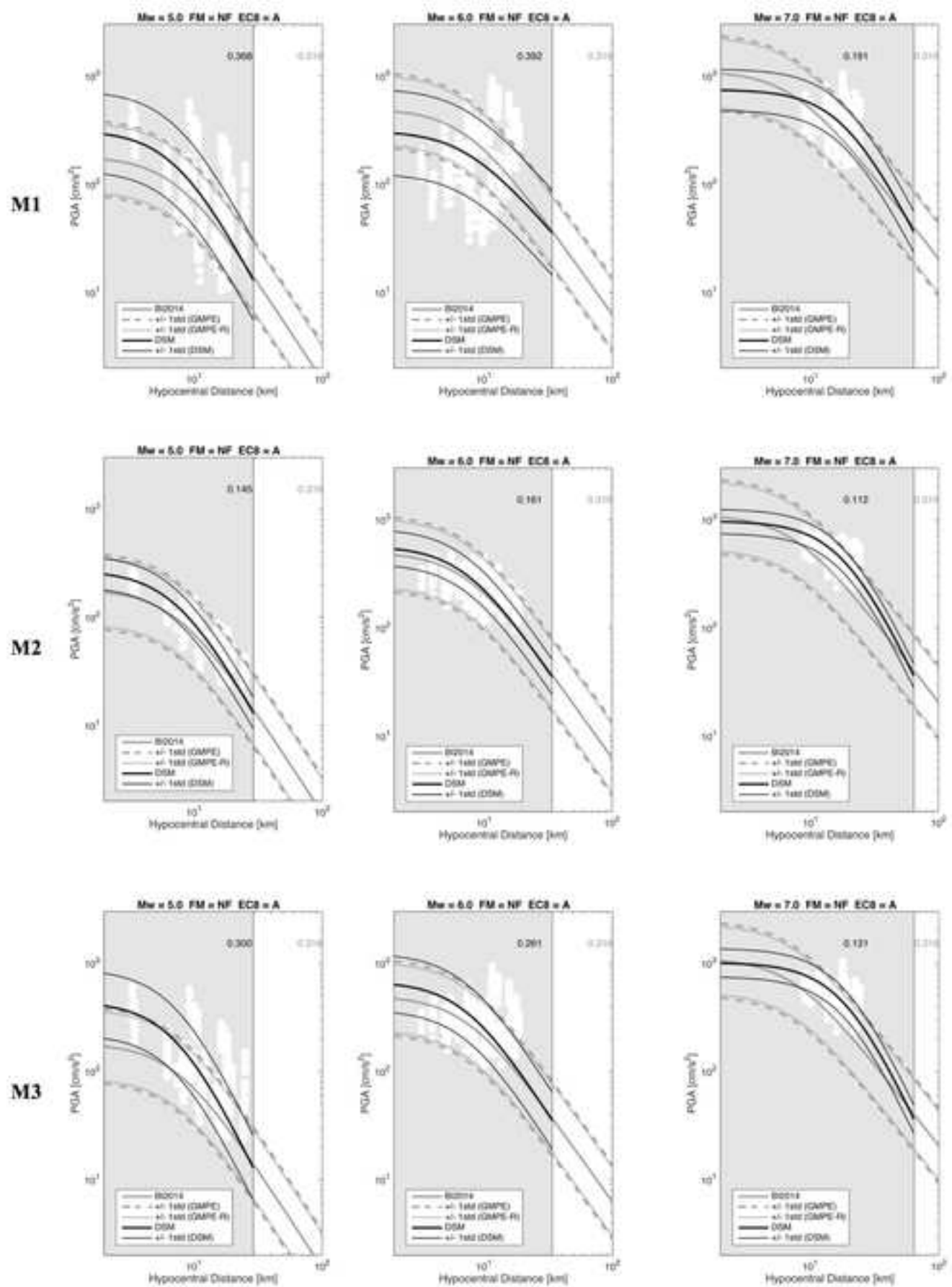
Figure 11

Figure 11
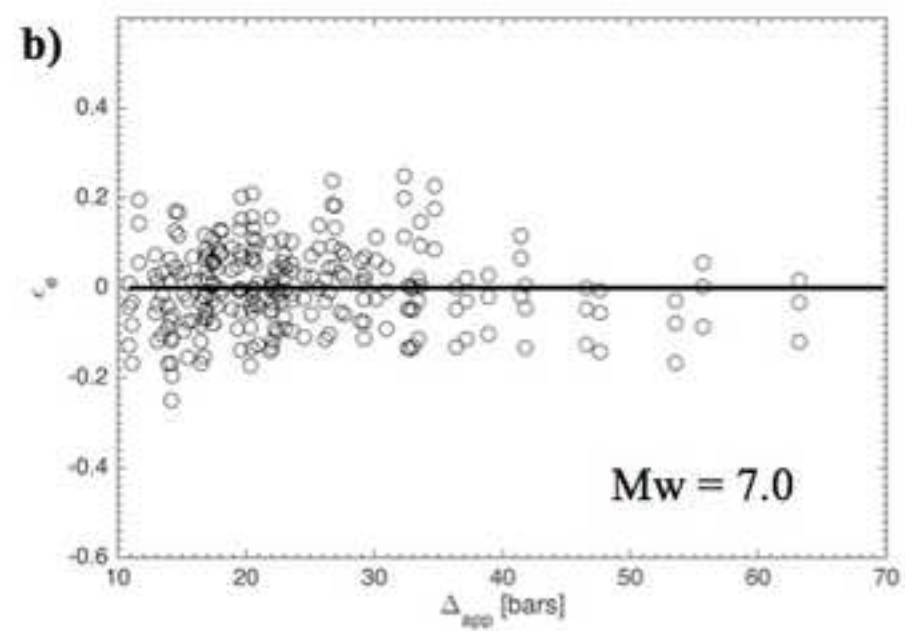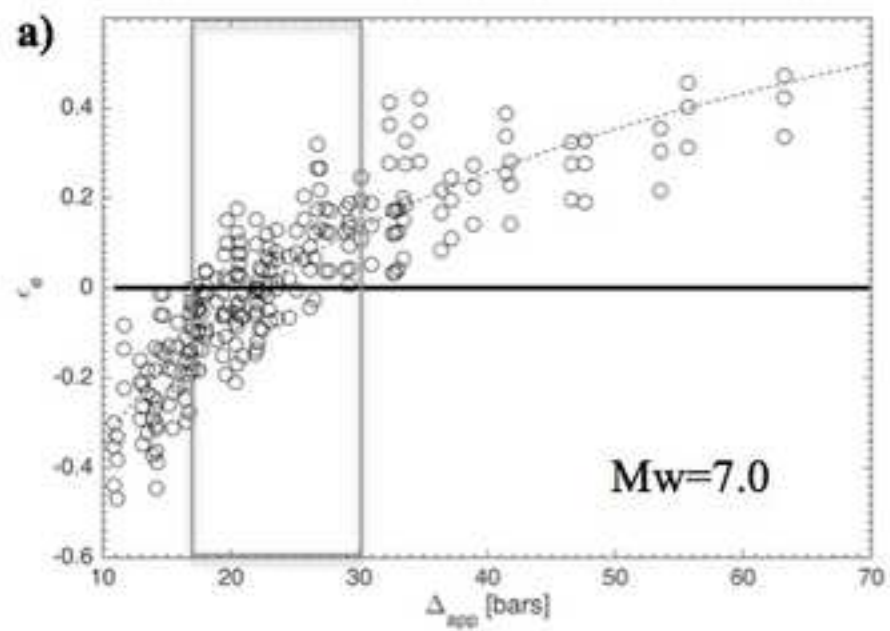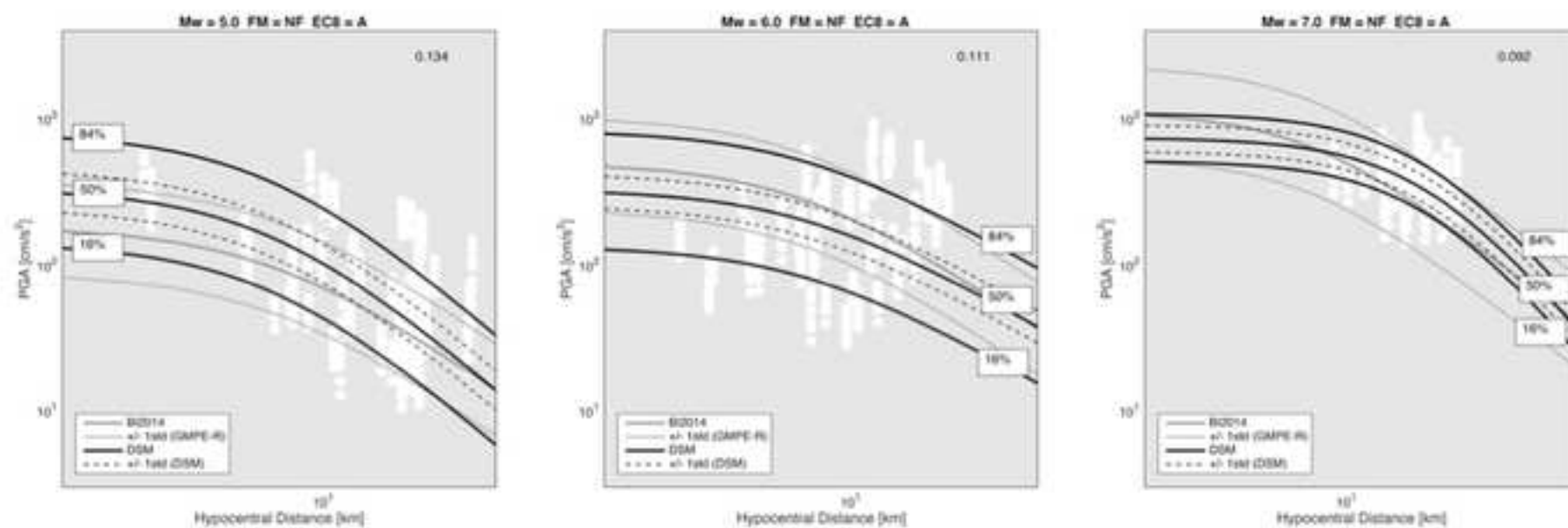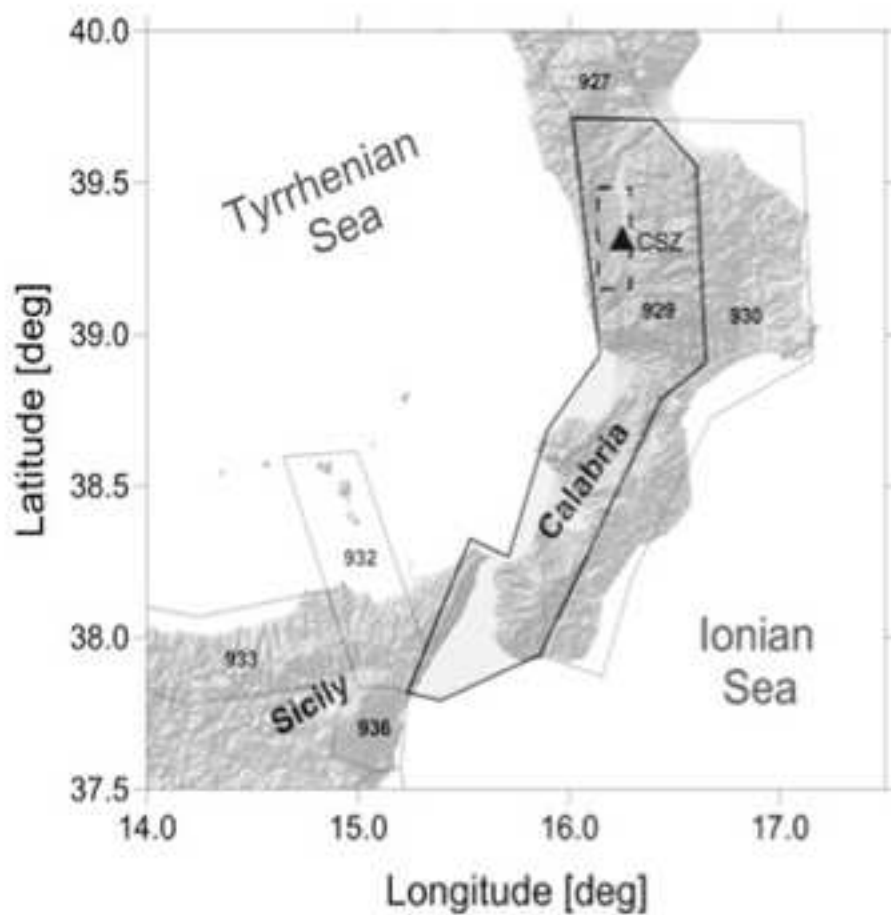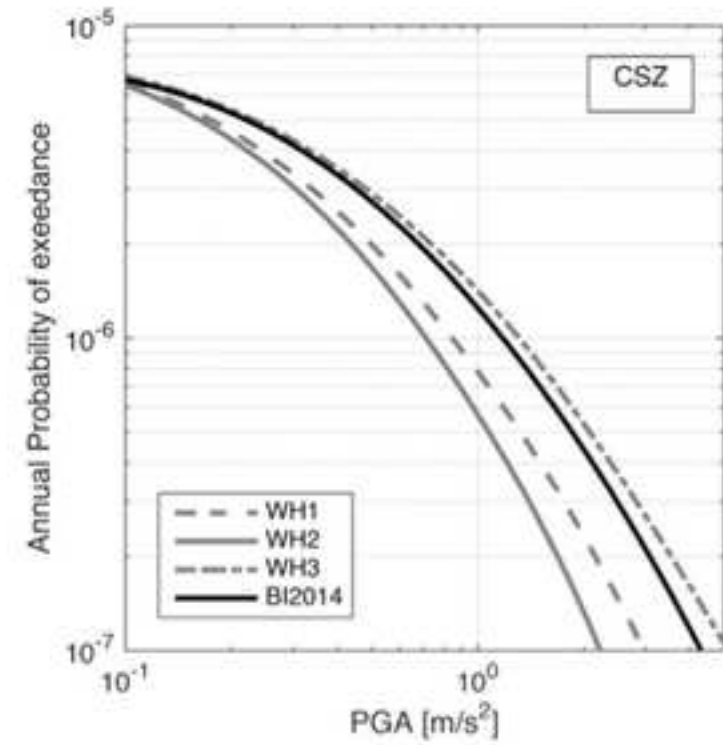
Electronic Supplement to
Ground-Motion Variability for Single Site and Single Source through Deterministic Stochastic Method Simulations: implications for PSHA
Maria D'Amico, Mara Monica Tiberti, Emiliano Russo, Francesca Pacor, Roberto Basili

We provide a detailed representation of the synthetic ground motion distributions for each magnitude and distance pairs considered in our analyses.

For M7.0 and M6.0, based on visual inspection and statistical tests (i.e. Kolmogorov test and χ-square test with 5% confidence interval), the synthetic PGA follows, on average, a lognormal distribution, independently of the modeling setup (M1, M2, and M3). However, directivity effects can generate distributions characterized by either positive or negative skew (for example the PGA distributions at s001 relative to the M7.0 case). Compared to the PGAs, the PGV values are better described by multimodal distributions. For the M5.0 case we observe that, independently from the scenario model, the ground-motion parameter distributions can be only approximated by lognormal shapes both at high and at low frequencies; a larger number of CFs should be considered to better sample the PF to generate a lognormal distribution.

Figure Captions

Figure S1. Histograms of the synthetic PGA and PGV (alternate columns) for M7.0 and RJB = 0 km, fitted by a normal distribution (grey line). Statistical distributions are for different scenario configurations: uppermost panels: finite-fault simulations with apparent corner frequency (M1); central panels: point-source simulations (M2); lowermost panels: merging between finite-fault and point-source simulations imposing a corner frequency threshold of 0.07 Hz (M3). Simulations were performed both at the bilateral site (_b = CSZ) and at the quasi-unilateral site (_u = s001).

Figure S2. Histograms of the synthetic PGA and PGV (alternate columns) for M6.0 with respect to the CSZ site fitted by a normal distribution (grey line). Leftmost two columns: R_{JB} = 0 km; Rightmost two columns: average R_{JB} = 5 km. Statistical distributions are for different scenario configurations: uppermost panels: finite-fault simulations with apparent corner frequency (M1);

central panels: point-source simulations (M2); lowermost panels: merging between finite-fault and point-source simulations imposing a corner frequency threshold of 0.23 Hz (M3).

Figure S3. Histograms of the synthetic PGA and PGV (alternate columns) for M5.0 with respect to the CSZ site fitted by a normal distribution (grey line). Leftmost two columns: average R_{epi} = 5 km; Rightmost two columns: average R_{epi} = 10 km. Statistical distributions are for different scenario configurations: uppermost panels: finite-f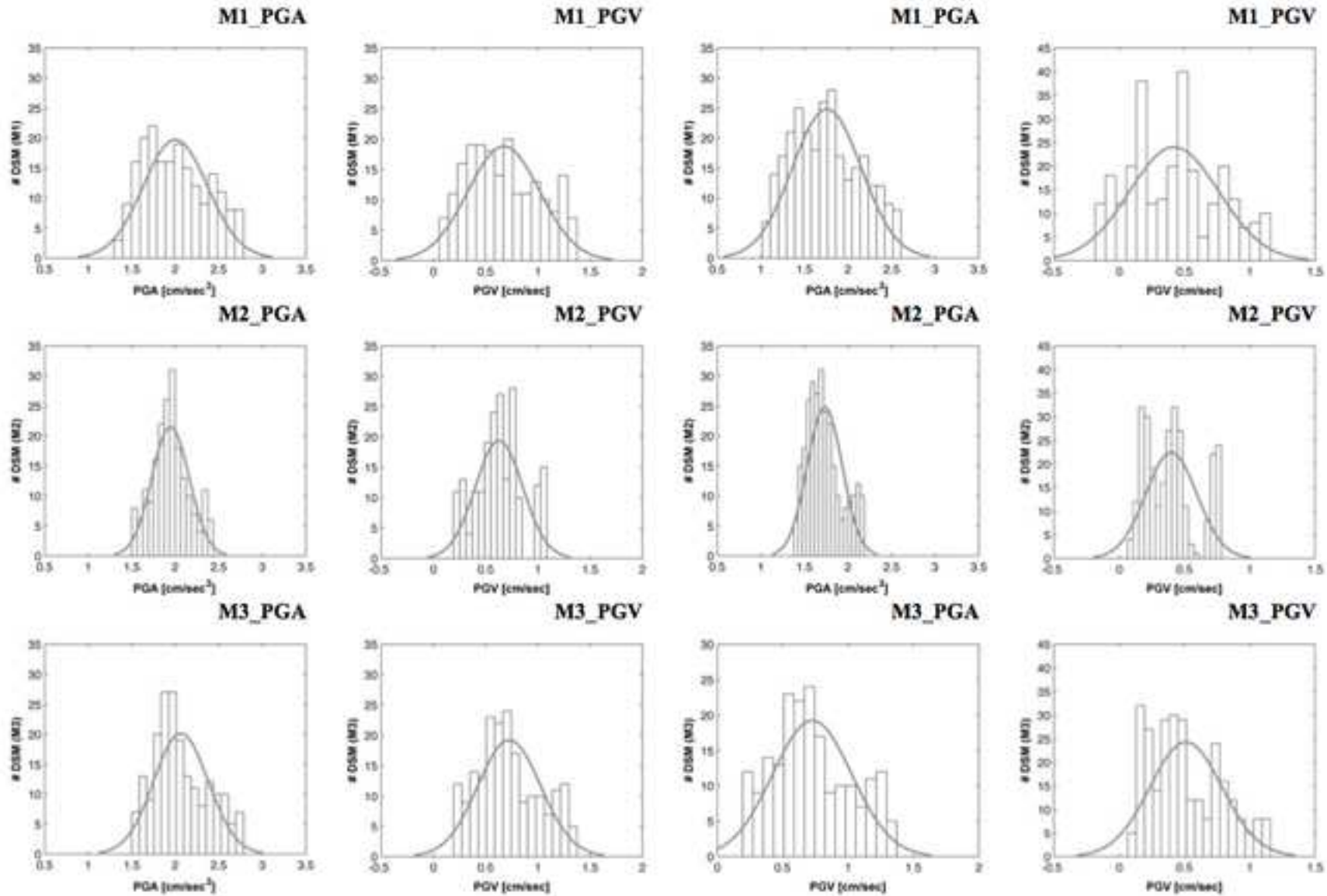ault simulations with apparent corner frequency (M1); central panels: point-source simulations (M2); lowermost panels: merging between finite-fault and point-source simulations imposing a corner frequency threshold of 0.7 Hz (M3).

M7.0
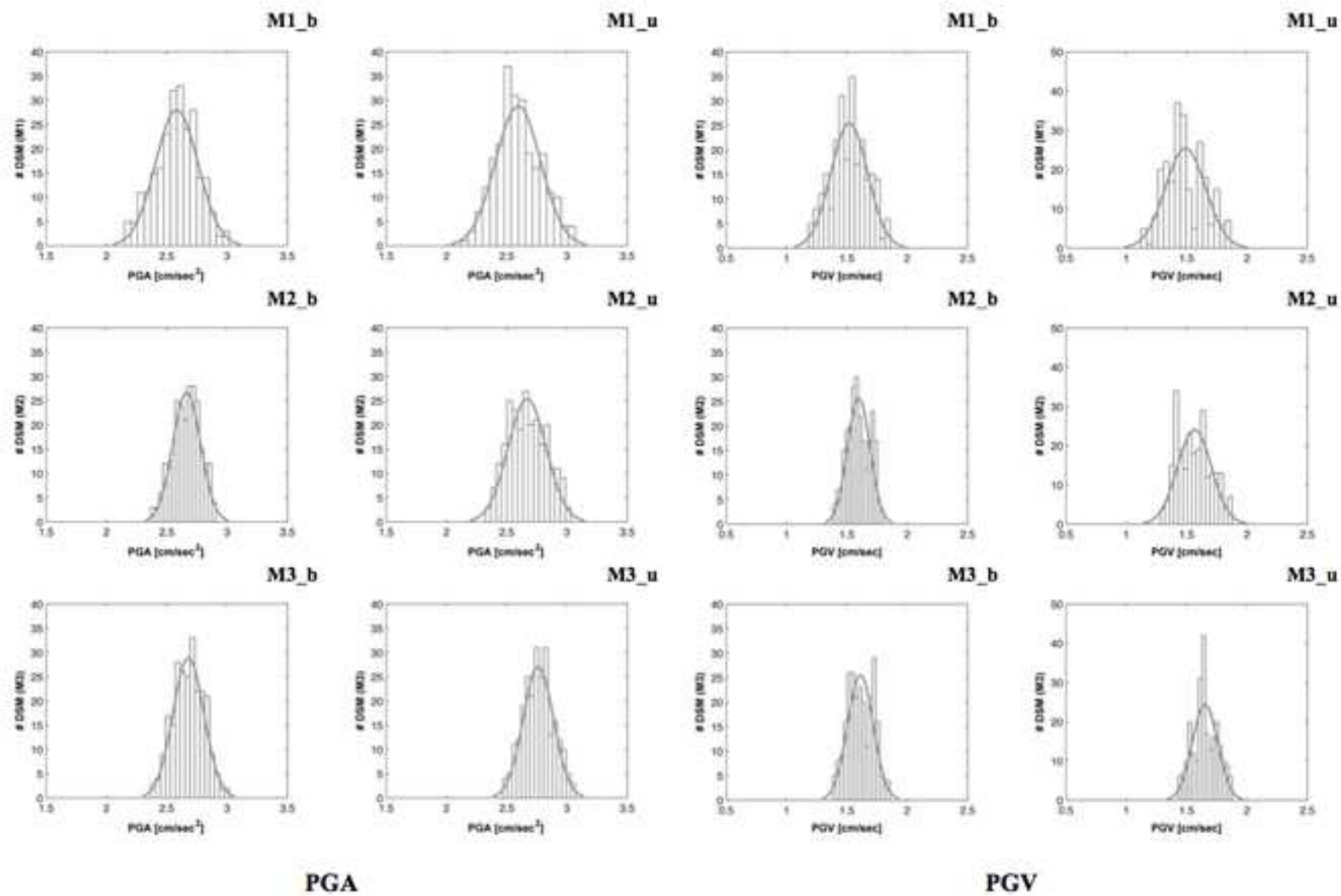
6.0

$R_{JB} = 0$ km

$R_{JB} = 5$ km

M5.0
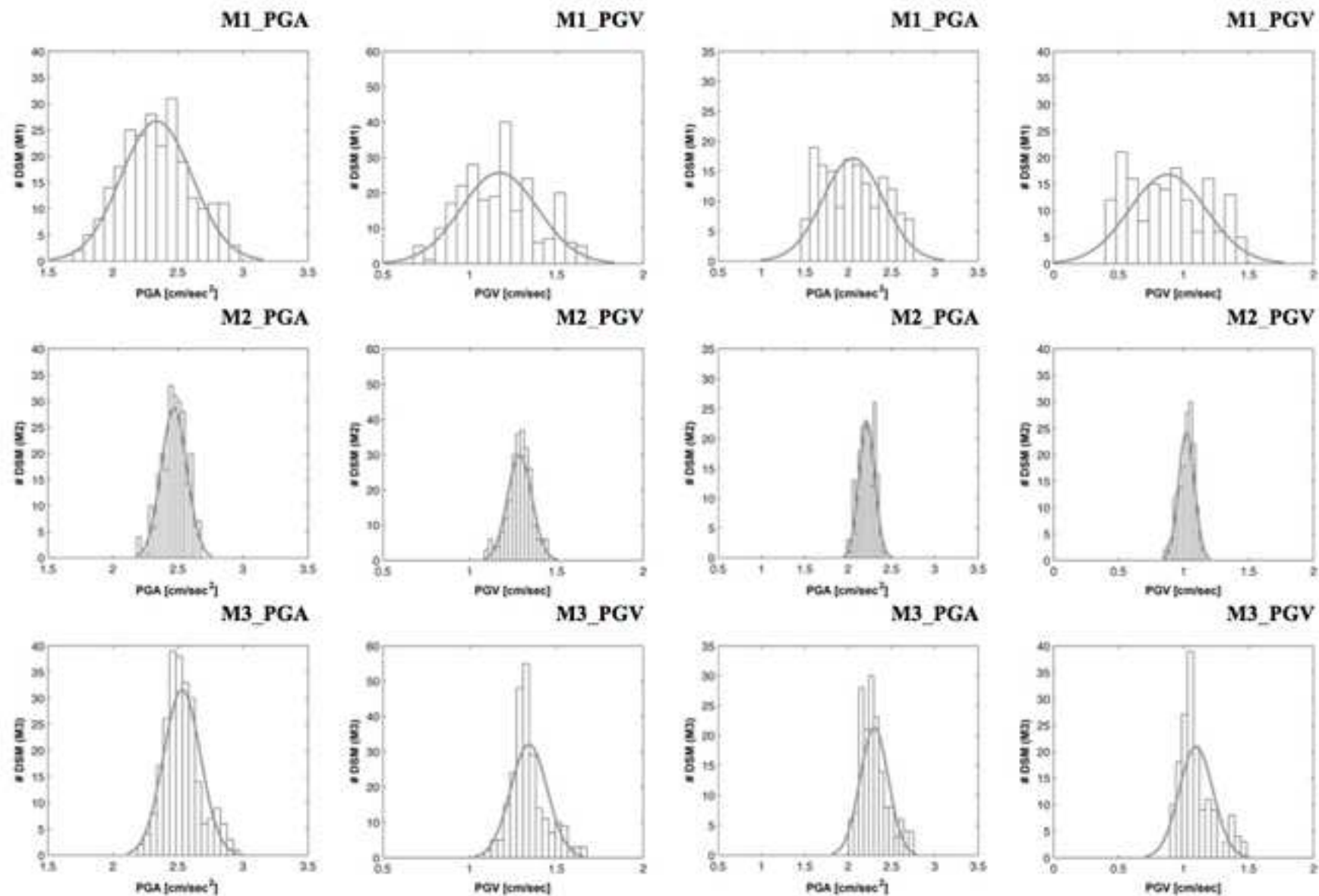
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        implications for PSHA

Authors: _Maria D'Amico, Mara Monica Tiberti, Emiliano Russo, Francesca Pacor and Robero Basili_

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