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1 **Near fault broadband ground motion simulations using**
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16

1 **Abstract**

2 Seismic hazard estimation relies classically on data based ground motion prediction equations
3 (GMPEs) giving the expected motion level as a function of several parameters characterizing
4 the source and the sites of interest. However, records of moderate to large earthquakes at short
5 distances from the faults are still rare. For this reason, it is difficult to obtain a reliable ground
6 motion prediction for such a class of events and distances where also the largest amount of
7 damage is usually observed. A possible strategy to fill this lack of information is to generate
8 synthetic accelerograms based on an accurate modeling of both extended fault rupture and wave
9 propagation process.

10 The development of such modelling strategies is essential for estimating seismic hazard close
11 to faults in moderate seismic activity zones, where data are even scarcer. For that we reason we
12 selected a target site in Upper Rhine Graben (URG), at the French-German border. URG is a
13 region where faults producing micro-seismic activity are very close to the sites of interest (e.g.
14 critical infrastructures like supply lines, nuclear power plants, etc.) needing a careful
15 investigation of seismic hazard.

16 In this work we demonstrate the feasibility of performing near-fault broadband ground motion
17 numerical simulations in a moderate seismic activity region such as Upper Rhine Graben
18 (URG) and discuss some of the challenges related to such an application. The modelling
19 strategy is to couple the multi-Empirical Green's Function technique (multi-EGFt) with a k^2
20 kinematic source model. One of the advantages of the multi-EGFt is that it does not require a
21 detailed knowledge of the propagation medium since the records of small events are used as the
22 medium transfer function, if, at the target site, records of small earthquakes located on the target
23 fault are available.

24

1 The selection of suitable events to be used as multi-EGF is detailed and discussed in our specific
2 situation where little number of events are available. We then showed the impact that each
3 source parameter characterizing the k^{-2} model has on ground motion amplitude. Finally we
4 performed ground motion simulations showing results for different probable earthquake
5 scenarios in the URG.

6 Dependency of ground motions and of their variability are analyzed at different frequencies in
7 respect of rupture velocity, roughness degree of slip distribution (stress drop), and hypocenter
8 location. In near source conditions, ground motion variability is shown to be mostly governed
9 by the uncertainty on source parameters. In our specific configuration (magnitude, distance),
10 the directivity effect is only observed in a limited frequency range. Rather, broad-band ground
11 motions are shown to be sensitive to both average rupture velocity and its possible variability,
12 and to slip roughness. Ending up with a comparison of simulation results and GMPEs, we
13 conclude that source parameters and their variability should be set up carefully in order to obtain
14 reliable broadband ground motion estimations. In particular, our study shows that slip
15 roughness should be set up in respect to the target stress drop. This entails the need for a better
16 understanding of the physics of earthquake source and its incorporation in the ground motion
17 modelling.

18

19 **Introduction**

20 To estimate the seismic hazard assessment (SHA), a proper modeling of the ground motion is
21 a fundamental step. This is commonly done through the use of ground motion prediction
22 equations (GMPEs), which are empirical relations obtained by the regression of recorded data
23 and metadata. The GMPEs estimate the ground motion level as a function of several parameters

1 concerning either the source, the wave path and the site such as distance, magnitude, fault type,
2 soil conditions, etc. The increase of the number and quality of strong motion records associated
3 to moderate to large earthquakes worldwide led to a significant improvement in the GMPEs
4 (Douglas and Edwards 2016). A variety of GMPEs has been proposed for several engineering
5 parameters (PGA, spectral ordinates, PGV, Intensity measurement) accounting for different
6 source mechanisms, tectonic environment, geographical areas and specific sites effects (e.g.
7 Campbell and Bozorgnia, 2014). A comprehensive collection of GMPEs can be found in
8 Douglas (2016). GMPEs are widely used because they are computationally inexpensive and
9 they have associated uncertainties that can be integrated in the hazard evaluation.

10 Nevertheless, GMPEs do not represent the variety of source and propagation, indeed the source
11 is mainly described by the magnitude and, for the recent GMPEs, also by the fault geometry
12 and focal mechanism, but the rupture process is not taken into account. In addition, one could
13 question of the confidence we can have in the extrapolation beyond their range of validity. This
14 is especially true in near fault conditions and for large crustal events, where the scarcity of
15 available data can lead to incorrect estimates when applied to some specific case studies (Boore,
16 2001). These specific cases include for example, interaction between the earthquake rupture
17 and basins (Koketsu and Miyake, 2008) or surface rupture for normal or thrust faults (Donahue
18 and Abrahamson, 2014) and all the cases where the time history content is dominated by the
19 source characteristics (e.g. see example of Tocopilla earthquake studied by Lancieri et al.,
20 2012). In such cases, ground motion simulations will likely be a better modelling than GMPEs,
21 provided that both source and propagation are accurately described and uncertainties properly
22 addressed. Moreover, we simulate complete waveforms having amplitudes and phases
23 information, while GMPEs only gives us information about the amplitude of the ground motion.
24 The knowledge of the seismic source is generally based on different parameters: some of them
25 can be investigated or inferred from local geology (e.g. position and geometry of the faults), or

1 geophysical studies (e.g. the depth of the faults); other parameters, related to the kinematic and
2 dynamic properties of the source, can be either assumed *a priori* making some hypothesis (e.g.
3 magnitude of the event we want to simulate) or chosen from a range of possible values. This
4 latter strategy leads to different resulting scenarios by defining an a priori probability
5 distribution for each parameter: e.g. rupture velocity, slip distribution, hypocenter position on
6 the fault plane, etc. In this paper, we will show how to produce a population of ground motion
7 records representing the possible variability of the source process for a target earthquake (e.g.
8 Causse et al. 2008; Cultrera et al. 2010).

9 When the target scenario refers to historical or paleoseismic events, and no instrumental record
10 is available, the ground motion simulations are referred to as “blind”. Performing blind
11 simulations is helpful not only to deduce an expected ground motion level, but its variability as
12 well.

13 We can separate this variability in two different parts: the aleatory and the epistemic
14 contributions. The aleatory part cannot be reduced because it comes from features that are
15 essentially or apparently random in nature. The aleatory variability comes from any parameter
16 that is intrinsically variable during the rupture process. The epistemic part though, since it is
17 related to the variable modelling strategy and parameterization can be potentially reduced
18 investigating the physics and improving our knowledge of the rupture process. For instance,
19 physics-based rupture models showed correlations between different kinematic source
20 parameters and the influence that they have on the ground motion (Song et al., 2014; Schmedes
21 et al., 2010).

22 Simulations of ground motions accounting for source variability can be performed through the
23 use of numerical codes that couple the source dynamics or kinematics with the complete
24 wavefield propagation in 3D complex media. Several techniques are commonly used to provide
25 reliable ground motion accelerograms, such as the Spectral Element Method (e.g. Komatitsh

1 et al., 2004; Cupillard et al., 2012), the Finite Differences method (e.g. Day et al., 2005; Dalguer
2 and Day, 2007; Aochi et al., 2011) and the Discontinuous Galerkin Method (e.g. Dumbser and
3 Kaeser 2007; Mazzieri et al., 2013). Accuracy in the strong motion modelling depends on the
4 knowledge of the structure, which is, in the best cases, limited at space scales larger than
5 hundreds of meters. The main problem of these approaches is that for many sites crustal models
6 are barely known. In addition, for broadband ground motion estimations (above 10Hz) those
7 numerical schemes need to be completed by stochastic high frequency methods.

8 For these reasons, the use of Empirical Green's Functions (EGF) may help in correctly model
9 the wave propagation up to short wavelengths (Hartzell, 1978; Irikura, 1983), providing an
10 elastic response of the medium and a compatibility of the small earthquakes with the target
11 event to simulate in terms of location on the fault, focal mechanism and stress drop (Irikura,
12 1984). Although this approach was developed and validated for far-field broadband
13 simulations, it has been recently extended by Del Gaudio et al. (2015) to the near fault case
14 through the introduction of the multi-EGF concept. In this concept, different EGFs are
15 attributed to different part of the target fault in order to cover the whole range of different
16 orientations between the source and a receiver that is close to it, so that the approximation of
17 EGF remains valid locally. Regarding the source process, the multi-EGF technique is coupled
18 with a k^{-2} kinematic model (Herrero and Bernard, 1996) that will be described in the
19 methodology section of the paper. This methodology allows for rapid estimations of broadband
20 ground motions in the near fault area together with a detailed extended source description,
21 without needing either a detailed knowledge of propagation medium nor additional
22 methodologies for modeling different frequency bands. This methodology of broadband ground
23 motion simulations is thus adapted to the need for challenging GMPEs on their limited range
24 of validity close to faults, especially due to their lack of precision regarding source description.

1 Finally, we face an additional challenge regarding SHA and GMPEs in moderate to low seismic
2 activity context. In such areas, small earthquakes are recorded and estimation of seismic hazard
3 is needed. However, GMPEs are criticizable in such places because of the possible
4 inconsistency between the local context and the data used in the GMPE. Therefore, simulations,
5 and in particular EGFt, can improve the ground motion prediction. Thanks to the presence of
6 multiple small earthquakes, EGFt can be applied directly to moderate seismicity areas. For that
7 reason, we applied our methodology to the Upper Rhine Graben (URG) area, where minimal
8 experimental conditions are found: active faults, recorded moderate seismicity, and need for a
9 near-fault SHA. As a first step toward near-fault SHA, we perform broadband blind simulations
10 for two scenarios (M_w 6 and M_w 6.5) on an active fault in the URG. Along the text we point out
11 the difficulty in doing such an exercise in an area scarcely instrumented where information on
12 small recorded events are imprecise.

13 After a description of the URG, we describe the implemented strategy to select and characterize
14 the EGFs, to explore the source parameters variability and its influence on the resulting ground
15 motion simulations.

16 We selected a target site which is located in very near fault conditions, but also close to seismic
17 activity in the center of the Graben, where most of the infrastructures (e.g. buildings, roads,
18 industries, etc.) and also some critical facilities (e.g. supply lines, nuclear power plants, etc.)
19 are located.

20

21 **1. Simulations method**

22 **1.1. Simulations method: EGF technique**

23 Using the representation integral (Aki and Richards, 2002), the ground displacement recorded
24 at a position \bar{x} on the Earth's surface at a time t can be expressed as:

$$1 \quad \mathbf{u}(\bar{x}, t) = \int_{\Sigma} s_i(\bar{\xi}, \tau) * [c_{ijkl}(\bar{\xi}) \mathbf{v}_j(\bar{\xi}) \mathbf{G}_{k,l}(\bar{x}, \bar{\xi}; t, \tau)] d\Sigma(\bar{\xi}) \quad (1)$$

2 where s is the slip vector, c is the elastic coefficient matrix, \mathbf{v} is the normal to the fault, \mathbf{G} is the
3 Green's function and Σ is the fault surface. Summation over repeated indices is assumed and
4 the symbol $*$ denotes time convolution. The Green's function represents the crustal medium
5 response to an impulsive wave and it can be computed knowing the crustal structure (i.e.
6 geometrical and rheological properties). In this work we adopted a simulation method based on
7 the empirical Green's functions (EGF) approach. Many applications have made use of the EGFs
8 for ground motion simulation (Hutchings 1994; Irikura & Kamae 1994; Hartzell et al. 1999;
9 Causse et al. 2009; Del Gaudio et al. 2015) since the pioneering works of Hartzell (1978) and
10 Irikura (1986). This technique consists in replacing the contribution
11 $c_{ijkl}(\bar{\xi}) \mathbf{v}_j(\bar{\xi}) \mathbf{G}_{k,l}(\bar{x}, \bar{\xi}; t, \tau)$ with the displacement record of a small earthquake $\mathbf{G}_e(\bar{x}, \bar{\xi})$ having
12 the same location as the Green function, sharing the same focal mechanism and stress drop as
13 the target event. After multiplication by the shear modulus μ and normalization by the seismic
14 moment of the small event $M_{\bar{G}}$, we obtain:

$$15 \quad \mathbf{u}(\bar{x}, t) = \int_{\Sigma} \frac{\mu}{M_{\bar{G}}} S(\bar{\xi}; \tau) * \mathbf{G}_e(\bar{x}, \bar{\xi}; \tau) d\Sigma(\bar{\xi}) \quad (2)$$

16 The record of small earthquake used to describe the medium response is generally referred to
17 as an EGF. The index i of the slip function has been removed because we assumed a constant
18 rake direction, so S now only represents the amplitude of the slip.

19 For broadband simulations, the main advantage of using EGFs is that we do not need a detailed
20 knowledge of the crustal velocity structure; we indeed need a good quality location catalog of
21 small events and some reliable indication of the fault geometry, moreover the earthquakes used
22 as EGF should satisfy specific criteria: first of all, the signal-to-noise ratio has to be sufficiently
23 large in all the frequency range of interest, its location and focal mechanism has to be

1 compatible with the fault plane considered for the target event and its magnitude must be at
2 least 2 point smaller than the one of the target event.

3 Under this latter condition an EGF can be considered as the medium response to a Dirac delta
4 function because it is a good approximation of a point source with respect to the large event to
5 be simulated.

6 The space discretization on the fault plane is controlled by the size of the event used as EGF,
7 according to earthquake scaling laws. Assuming self-similarity between the rupture of small
8 and large events (Brune 1970), the number of subfaults associated to small events to be
9 considered is

$$10 \quad N = \frac{L}{l} = \frac{W}{w} = \left(\frac{M_0}{M_{\bar{c}}} \right)^{1/3} \quad (3)$$

11 N is the spatial scale factor between the mainshock and the associated EGF. In this equation L ,
12 W and M_0 are the length, width, and seismic moment of the target event, respectively, while l ,
13 w and $M_{\bar{c}}$ represent the same quantities for the small event. In this study we used squared
14 subfaults with size $\Delta x=w$ to discretely solve equation (2).

15 **1.2. Simulations method: the Multi-EGF approach**

16 The classic EGF approach uses a single event as EGF translated along the fault plane. This is
17 equivalent to assume that the propagation term (path, radiation) is the same for all the points of
18 the crustal volume surrounding the fault plane. This is a strong approximation, especially for
19 large faults and in near source conditions, where the wave path from fault to site varies strongly.

20 To overcome this limit, Del Gaudio et al. (2015) proposed to use several EGFs, each EGF
21 sampling the closest portion of the fault plane, allowing to better take into account the wave
22 path and source radiation variability. This technique is called multi-EGF. Del Gaudio et al.

1 (2015) demonstrated the validity of the methodology on the 2009 L'Aquila earthquake using
2 several aftershocks as multi-EGF to reproduce the main event accurately.

3 In practical, the difference with the single EGF technique is that the Green's function is variable
4 along the fault plane. Each portion of the fault plane gets its own EGF as being the closest one,
5 such as illustrated on Figure 1. In addition, a correction in time and amplitude is also applied to
6 each EGF to take into account the difference between original hypocentral position of the event
7 and applied subfault (see Causse et al. 2009). After a discretization of equation (2), the
8 simulated displacement can be written as a summation of EGF

$$9 \quad \mathbf{u}(\bar{x}, t) = \sum_{ij} \frac{\mu^{(ij)} \Delta x^2}{M_G^{(ij)}} S^{(ij)} * \mathbf{G}^{(ij)}(\bar{x}, t) \quad (4)$$

10 The indices i and j are related to subfault (i,j) and run over strike and dip directions respectively.

11 **1.3. Simulations method: source model**

12 To describe the source process we adopted the k^{-2} kinematic source model (Herrero and
13 Bernard, 1996; Gallovič and Brokešová, 2004). In the wavenumber domain \mathbf{k} , this model is
14 characterized by an asymptotic k^{-2} decay of the slip amplitude beyond the corner wavenumber
15 $k_c = \mathfrak{K}/L$, where L is the characteristic fault dimension and \mathfrak{K} is a non-dimensional parameter
16 which represents the roughness degree of the slip distribution (in Figure S1 of the electronic
17 supplement are shown two example of slip distributions for two different values of \mathfrak{K}). This
18 particular asymptotic behavior is able to reproduce the high frequency f^{-2} decay observed in
19 far-field displacement spectra. While the slip amplitude spectrum in the wavenumber domain
20 follows this model, the phase distribution φ is randomly chosen and it represents a source of
21 variability for k^{-2} models. The slip distribution in the wavenumber domain can be summarized
22 as

$$S_k(k_x, k_y) = \frac{\bar{S}LW}{\sqrt{1 + \left[\left(\frac{k_x L}{\mathfrak{K}} \right)^2 + \left(\frac{k_y W}{\mathfrak{K}} \right)^2 \right]^2}} e^{i\varphi(k_x, k_y)} \quad (5)$$

where \bar{S} is the average slip value, L , W , k_x and k_y are the fault dimensions and wavenumbers respectively along strike and dip directions.

Rise time is assumed to be k -dependent. In particular it is constant for $k < k_c$ and it linearly decreases with k for larger wavenumbers. Rupture velocity is assumed to be constant over the fault plane.

All the source parameters such as the roughness degree of the slip \mathfrak{K} , the rupture velocity v_r , the rise time τ and the position of the hypocenter on the fault plane, can be deterministically defined (i.e. from a kinematic source model obtained from low frequency inversion) or randomly chosen from *a priori* distribution (Causse et al., 2009; Del Gaudio et al., 2015).

11

12 **2. Upper Rhine Graben case study**

13 To better investigate the advantages and limitation of the technique, and to test the influence
14 that each considered source parameter has on the simulated ground motion and its variability,
15 we set up an application to the Upper Rhine Graben (URG). The URG is a region located along
16 the border line between French and Germany, characterized by a moderate level of seismicity.

17 Historically, one of the major West-European earthquakes happened in 1356, near Basel
18 (Switzerland) at the Southern termination of the Graben. MKS maximum intensity of this event
19 was estimated between VIII and IX (Mayer-Rosa and Cadiot, 1979), but the fault source has
20 been not clearly identified (Mayer et al., 1994; Lambert et al., 2005; Meghraoui et al., 2001;
21 Ferry et al., 2005).

1 The Rhine Graben is characterized by the presence of several fault systems. In Figure 2 all the
2 segments that have shown evidence of activity are represented. Specifically we can recognize
3 the Western Rhine Fault, at the western border of the Graben; the Black Forest Fault, at the
4 eastern border of the Graben and the Rhine River Fault (Bertrand et al., 2006; Nivière et al.,
5 2008; Palumbo et al., 2013), following the river path.

6 Considering historical seismicity and the large number of active faults in the area, people and
7 infrastructures (e.g. buildings, roads, industries, etc.) and also some critical facilities (e.g.
8 supply lines, nuclear power plants, etc.) are potentially exposed to the risk that comes from
9 earthquakes generated along the URG. The size of the fault segments in the URG suggests that
10 earthquakes with magnitude larger than 6 are likely to happen. Their return periods are
11 estimated as a function of the magnitude (Nivière et al., 2008) and, for instance, a return interval
12 of about 8000 years was estimated for the Rhine River Fault for an event of magnitude of 6.5.

13 In addition, such faults were also considered in long return period probabilistic seismic hazard
14 assessment (PSHA) by Chartier (2015). Such studies use GMPEs to evaluate the ground
15 motions close to the fault, where they are likely to be biased. As a consequence, ground motion
16 simulations can provide a useful comparison with GMPEs and eventually an alternative choice
17 for PSHA. For these reasons the URG is an interesting test case for applying our technique and
18 performing blind ground motion simulations.

19 For the simulations, we decided to focus on the Rhine River fault. We considered this fault as
20 divided in two segments. From surface evidence, we set their strikes equal to 172° for the
21 northern segment, and 203° for the southern segment. From geological and geophysical
22 investigations (Nivière et al., 2008) the faults are west dipping with an angle of approximately
23 60° - 70° . We decided to adopt a dip angle of 70° but, for future applications, an exploration of
24 different values should be performed in order to investigate the influence that it could have on

1 simulation results. Regarding the depth of the faults, we prolonged the surface trace up to a
2 maximum depth of 15 km. In Figure 3 the two selected segments of the Rhine River Fault are
3 schematically represented.

4 To perform ground motion simulation in the URG we faced several problems. Due to the fact
5 that we are in “blind” conditions, kinematic parameters (e.g. rupture velocity, slip distribution)
6 and dynamic parameters (e.g. stress drop, interaction between different fault segments) are
7 unknown, as well as details regarding the fault geometry (e.g. hypocenter location, depth of the
8 fault). Sensitivity studies for all the different parameters are, hence, required to characterize the
9 aleatory and epistemic variability of the simulated ground motion. Moreover, the low rate of
10 seismicity and the consequent small amount of records requires a careful investigation of the
11 different events to be used as EGF, whose selection depends on the hypothesis for the target
12 event (fault geometry, magnitude, etc.).

13

14 **3. EGF Selection and Analysis**

15 After selecting the fault geometry, we started screening data of small earthquakes to be used as
16 an empirical approximation of the propagation medium response function. As described in the
17 methodology section, to be used as an EGF, an event must satisfy specific criteria.

18 We screened out the French instrumental catalog Si-Hex (Sismicité instrumentale de
19 l’Hexagone), the Renass (Réseau National de Surveillance Sismique) catalog, and the seismic
20 catalog of the LGRB (Landesamt für Geologie, Rohstoffe und Bergbau) Institute of Freiburg in
21 a time period ranging between January 2000 and December 2014. The seismological institutes
22 responsible for the location of earthquakes indeed share the data across the border. Twenty-
23 seven events were identified with a local magnitude ranging between 1.5 and 3.2 (Figure 3).

1 We decided to adopt the locations proposed by the LGRB catalog, because they are done
2 without fixing the hypocentral depth. This choice will reduce possible biases in the correction
3 for the geometrical spreading.

4 As target site we chose the BREM station (see Figure 3) which is close to both the considered
5 faults (it's located exactly on the surface projection of both the faults planes and at about 5 km
6 of geometrical distance from them).

7 We selected five events, three having the largest magnitude in the catalog, to have a large signal
8 to noise ratio in a wide frequency range, and the two whose location is the closest to the selected
9 fault system. In Figure 3, we plot all the considered events (black dots) and the selected EGF
10 (red dots). From the figure results clear that two of the five selected EGF can be associated to
11 the northern fault segment and three to the southern segment. Therefore our selection covers
12 spatially the target faults, which is needed in the multi-EGF approach for near field
13 computation. On the map the seismic stations located in the area belonging to both the French
14 and the German national networks are also showed.

15 To verify the hypothesis of self-similarity of the EGF, we computed seismic moment and corner
16 frequency and we inferred the apparent stress drop by inverting the S phase Fourier amplitude
17 spectrum. The S wave has been manually picked on the records at the available stations. A time
18 window of 5s (0.5s before and 4.5s after the S wave arrival time) containing the whole direct
19 S-wave train has been isolated. We removed baseline from signals and computed displacement
20 from acceleration by double integration. After computing Fourier spectra of the three
21 components we combined them by vector summation. For the spectral inversion, we assumed
22 in the angular frequency domain ω a ω^{-2} decay of the displacement spectrum beyond its corner
23 frequency f_c (Brune, 1970). We also estimated the focal mechanisms for eligible EGF
24 computing long-period spectral level ratios at each station (De Matteis et al., 2016). Because of
25 the sparse network geometry, azimuthal gap ($>300^\circ$), paucity of records and low signal to noise

1 ratio for P wave, we fixed the strike and the dip angle according to the geometry of the faults
2 to which the event is related by proximity, and we computed the rake angle using single station
3 spectral ratios between S and P displacement levels at low frequency. Assuming a Brune's
4 source model, the ratio between the low frequency plateaus, can be expressed as:

$$5 \quad \frac{\Omega_{0,s}}{\Omega_{0,p}} = \frac{R_{\lambda\phi}^P}{R_{\lambda\phi}^S} \left(\frac{v_s}{v_p} \right)^3 \quad (6)$$

6 where v_s and v_p are the mean values of P and S wave velocities and $R_{\lambda\phi}^{P,S}$ are the radiation
7 pattern coefficients which depend on the rake angle (a detailed formulation of this coefficients
8 is given in Aki and Richards, 2002). After measuring the ratio, a grid search was performed to
9 determine the value of the rake angle which at best approximates the equation (5). Two
10 symmetric solutions are always available for the rake angle and, to remove this ambiguity, we
11 have to measure P-wave polarities for each station. Obtained results show mainly a normal fault
12 behavior with a strike slip component in the northern part, as showed also in previous studies
13 performed for the same region (Homuth et al., 2014). For this reason, we did not apply any
14 correction for the focal mechanism differences of the EGF.

15 Location and computed parameters of the selected EGFs are reported in TABLE 1. Figure 4
16 shows the retrieved corner frequency as a function of the seismic moment in a logarithmic scale
17 respectively, for all the selected EGFs. In Figure S2 of supplementary material are also shown
18 the spectral inversions for all the EGFs. As shown in Figure S2, not all the signals are
19 characterized by a good signal to noise ratio in all the considered frequency range (from 1 to
20 20 Hz). In particular this ratio becomes lower than 1 at low frequencies for stations END, LIBD
21 and STAU and EGF1, EGF3 and EGF4. We decided to keep these data and source parameters
22 were obtained by making a weighted average of values computed for each station, with weights
23 proportional to signal-to-noise ratios.

1 For the selected events, we found that the average stress drop ranges between $3MPa$ and 35
2 MPa . Nevertheless uncertainties are very large owing to the difficulty in well constraining the
3 corner frequencies with a small number of records. Different values in the stress drop may lead
4 to differences in simulated ground motion amplitude, increasing the epistemic variability
5 associated with the EGFs. According to Del Gaudio et al. (2015), we applied a correction to
6 each EGF. The EGF amplitude spectrums were first divided by their corresponding Brune
7 spectrums, considering the seismic moment and stress drop values of TABLE 1. The spectra
8 were next multiplied by a Brune spectrum associated to a reference seismic moment of a M_w 3
9 event with a stress drop $\Delta\sigma=8 MPa$, this latter value being the geometric mean of the EGF stress
10 drops.

11

12 **4. Ground motion simulations**

13 **4.1. Sensitivity analysis**

14 We recall that, in blind conditions, we do not have a benchmark time history, so our aim is not
15 to simulate an observed motion, but all the possible ground motions produced by all the possible
16 source configurations. In fact, while the knowledge on fault geometry can be improved through
17 geophysical investigations), dynamic and kinematic source parameters are unknown until the
18 occurrence of a big earthquake. Moreover, they can be unique for each event and then, for this
19 reason, it is necessary to make several simulations with variable source parameters to
20 investigate all the possible scenarios and the variability associated to them.

21 The k^2 model is characterized by three parameters that mainly affect the ground motion: the
22 roughness parameter \mathfrak{K} (eq. 4), the rupture velocity v_r and the nucleation position on the fault
23 plane. We did sensitivity analysis for all of them. Figure 5, Figure 6 and Figure 8 show
24 simulation results for a magnitude 6 event occurring on the southern segment of the Rhine River

1 Fault in terms of PGA and spectral acceleration (Sa) at 0.5 Hz, 1Hz, 2Hz, 5 Hz and 10 Hz as a
2 function of the roughness parameter, rupture velocity and nucleation position respectively. On
3 each of these figures, an example of simulated waveforms (East-West component of
4 acceleration) is also shown to see clearly the effect of each considered source parameters. PGA
5 and Sa are obtained as the geometrical mean of two quantities measured on the horizontal
6 components. This choice is consistent with what is generally done for GMPEs and give us the
7 possibility of a comparison with them.

8 We considered a large range of variation for each parameter to explore the effect on the ground
9 motion. Several authors (e.g. Gallovic and Brokesova, 2004; Causse et al., 2009 and 2010) have
10 given different probable values of roughness for the slip distribution ranging it between 0.7 and
11 1.6, we then let \mathcal{K} vary uniformly between 0.3 and 2 to explore a wider range.

12 For v_r , as well we selected a wide range letting it vary between 2100 *m/s* and 3400 *m/s*. For this
13 latter parameter we assumed subshear rupture propagation on average with the maximum
14 rupture velocity smaller than the average crustal shear wave speed of about 3500 *m/s*.

15 For the nucleation position, any location on the fault plane has been considered.

16 Simulations were first performed looking at the influence of one parameter at a time. In Figure
17 5, the influence of \mathcal{K} on ground motion was investigated performing 100 simulations with a
18 fixed $v_r = 2800m/s$ and the hypocenter location at the center of the fault. In Figure 6, we
19 performed 100 simulations fixing $\mathcal{K}=1$ and the hypocenter location again at the center of the
20 fault to check the impact of v_r . We observe a linear trend at low frequency and an exponential
21 trend at high frequencies. Variability for specific values of the source parameters is inherited
22 by the aleatory variability of the slip phases, which are randomly chosen in the k^{-2} model as
23 discussed in the first section. We can also observe that, for high frequencies (above 5Hz),
24 ground motion is not influenced by rupture velocity (the trend is linear with a slope close to

1 zero) up to a threshold above that we observe an exponential increase. This threshold is between
2 $3000m/s$ and $3200m/s$.

3 To simultaneously investigate the influence that these two parameters have on ground motion,
4 in Figure 7 results of simulations obtained combining the variability of \mathfrak{K} and v_r are shown,
5 while the nucleation position is always fixed at the center of the fault. The six subplots refer to
6 six frequencies and, for each frequency, a clear trend of the ground motion parameters as a
7 function of both the roughness and rupture velocity is observed. Specifically the dependency
8 on the roughness looks quite linear at all the considered frequencies. From Figure 7 we observe
9 how roughness and rupture velocity jointly affect the ground motion. We can see how amplitude
10 variation for low frequencies (up to $2Hz$) is of about two order of magnitude: we identified three
11 different color areas (each color area corresponds to half order of magnitude), separated by
12 black lines, for which the logarithm of the spectral acceleration and PGA is almost constant. If
13 we move to higher frequencies, we observe a wider range of variation (with five different areas
14 highlighted for the $10Hz$ plot). From this figure we can also conclude that for small value of \mathfrak{K}
15 (below 0.5 for spectral acceleration and between 0.4 and 0.9 for PGA) ground motion
16 amplitudes is less sensitive to rupture velocity. For larger values of \mathfrak{K} , variations of v_r become
17 really important to control the simulated ground motion values.

18 Concerning the variability associated with the nucleation position on the fault plane, we
19 separated its variation along the strike and the dip directions, here represented by the variables
20 x_n and y_n respectively. Figure 8 shows the ground motion parameters as extracted from the
21 simulations as functions of the nucleation position on the fault plane. In this subset of
22 simulations we fixed $v_r = 2800m/s$ and $\mathfrak{K}=1$. A correlation at very low frequencies (0.5 Hz)
23 can be observed. Specifically we computed the corner frequency for the simulated events. Since
24 they range between 0.1 and 0.5 Hz, we expect that the directivity effect is more important
25 around this interval while it starts to disappear at higher frequencies (≥ 1 Hz). To investigate

1 this aspect we performed another set of simulations for a magnitude M_w 5.0 event. To be
2 consistent with the new magnitude, also the size of the fault was reduced while the corner
3 frequency of the synthetics increased at around 1.5 Hz. It is well known that the directivity
4 effect is mainly observed in a range below the corner frequency (e.g. Causse et al., 2009). For
5 this reason, in Figure S3 of the supplementary material, the results of the test for a M_w 5 event
6 clearly show the rupture directivity effect up to 2 Hz.

7 This sensitivity analysis shows that both the rupture velocity and the roughness degree of the
8 slip have a strong impact on the high frequency strong motion parameters while they generally
9 control the amplitude of the ground motion. For this reason, constraining their range of variation
10 could significantly reduce the epistemic variability of the simulated ground motion. We should
11 take into account these results to build up a proper strategy of selection of realistic values for
12 these parameters to not introduce strong biases in the calculation.

13

14 **4.2. Fault geometry and Stress Drop**

15 Another important aspect consists in evaluating the static stress drop associated to our
16 simulations. This stress drop is related to the slip distributions and hence to the roughness
17 parameter. It is independent from seismological data (but depends on geological information)
18 and we can compare it with the estimates from the EGF reported in TABLE 1. According to
19 Kanamori and Anderson (1975), for an extended fault, the static stress drop associated to a
20 particular slip distribution can be defined as:

$$21 \quad \Delta\sigma = C\mu \frac{\bar{S}}{\tilde{L}} \quad (7)$$

22 where C is a non-dimensional shape factor (≈ 1 in many cases), μ is the rigidity, \bar{S} is the mean
23 slip value over the fault plane and \tilde{L} represents the length of the rupture area defined as the
24 square root of the surface where the slip is over 20% of the maximum slip. The size of the

1 rupture area is correlated to the value of the roughness degree of the slip: for large values of \mathcal{K}
2 the slip is concentrated in small areas characterized by large amplitudes, inversely, for small
3 values of \mathcal{K} , we will have large rupture area with lower amplitude.

4 The stress drop depends on selection for the fault geometry and different fault surfaces can lead
5 to different stress drop values. Moreover, for the same fault surface, different rupture areas
6 (different values of \mathcal{K}) corresponds to different stress drops. To better understand this aspect,
7 in Figure 9 we show $\Delta\sigma$ as a function of \mathcal{K} for three different fault geometries. For each case
8 we performed 450 simulations linearly varying \mathcal{K} and v_r with the same procedure as for the tests
9 showed in Figure 7. The first test corresponds to the entire extension of the segment identified
10 for the southern part of the Rhine River Fault, (27 km along strike and 16 km along the dip)
11 (Figure 9a). For the other two cases, we reduced the fault area to 1/3 of the original one keeping
12 the same shape ratio between L and W and considered two different fault position with respect
13 to the surface: one is placed in depth while the other reaches the surface. As discussed by Causse
14 et al. (2013), stress drop should increase with \mathcal{K} for a fixed fault area. We observe in all the
15 cases an almost linear increase of mean $\Delta\sigma$ value with the roughness. Also stress drop
16 variability at fixed \mathcal{K} comes from randomness of slip phases. Another intuitive result is that
17 reducing the fault area the mean slip value increases producing larger stress drops (Figure 9b
18 and c).

19 Strong motion peak parameters (PGA and PGV) are also shown in Figure 9 as functions of the
20 mean stress drop value (computed for each \mathcal{K}) and rupture velocity. They are well correlated
21 with the position of the fault with respect to the target site. Larger values of peak parameters
22 are observed when reducing the fault size and increasing the stress drop, with a significant
23 increase when the small fault is placed at shallow depth (Figure 9c).

24 Even if these analyses shown that stress drop variability associated to \mathcal{K} is not large enough to
25 better constrain roughness values (one order of magnitude of variation for \mathcal{K} corresponds in

1 just one order of magnitude of variation for $\Delta\sigma$), it is important to note that stress drop values
2 obtained using the entire fault surface inferred from geological knowledge are really small
3 compared to the average stress drop computed from the EGF ($\sim 8MPa$). Since the EGF
4 technique is based on the self-similarity assumption, we concluded that using a smaller fault
5 surface could be more appropriate for our simulations. Geological faults are generally big
6 structures, while rupture surface should be related to the characteristics of the event we want to
7 simulate and can be just a portion of the geological fault plane. For the rest of the paper, all the
8 simulations relative to a $M_w 6$ event will be performed for a smaller fault plane (the red rectangle
9 in Figure 9b).

10 Finally, we can also observe that high values of rupture velocity result in very large peak
11 amplitudes on the simulations.

12

13 **4.3. Blind simulations**

14 To perform blind simulations a useful strategy consists in defining the probability distribution
15 of the source parameters to control their variability. An example is given in Figure 10 for the
16 rupture velocity. For a uniformly distributed probability (between 2200 m/s and 3400 m/s),
17 resulting values of PGA are between 10% and 60% of g . For a normal distribution centered in
18 $v_r = 0.8v_s$ and truncated in the same interval as above, the resulting PGA variability is
19 significantly reduced (from 10% to 38% of g). From this simple example we can easily deduce
20 that constraining the variability in the source parameters with a proper probability distribution
21 will reduce ground motion variability of our simulations.

22 For the roughness parameter, Causse et al. (2010) showed a correlation between its logarithm
23 and the logarithm of the PGA. Under the far-field approximation, they show that
24 $PGA \propto (\mathcal{K}/L)^{3/2}$ proposing a lognormal distribution for this parameter with a magnitude
25 dependent mean value and a standard deviation $\sigma = 0.12$. Our results show an almost linear

1 increase of the PGA with \mathfrak{K} (Figure 5) probably due to the very near fault conditions. In any
2 case, the dependence of the PGA from the roughness of the slip is confirmed and it is still
3 reasonable to adopt a lognormal distribution. Nevertheless, mean value of this distribution is
4 not clearly identified in literature. According to Gallovic & Brokesova (2004), a reasonable
5 value of \mathfrak{K} must be chosen around 1, while using the hypothesis of self-similarity between the
6 target event and the EGFs, Causse et al. (2009) found $\bar{\mathfrak{K}} = 0.74$. The empirical relation derived
7 by Causse et al. (2010) shows, for a M_w 6 event, $\bar{\mathfrak{K}} = 1.6$. For this reason, we decided to perform
8 three different sets of simulations changing the mean value for the distribution of the roughness
9 parameter.

10 For the rupture velocity we selected a range of variation according to observations from source
11 studies where v_r is generally found between 60% and 90% of v_s (e.g. Heaton, 1990). So we
12 decided to assume a normal distribution with a mean value $\bar{v}_r = 0.8v_s = 2800m/s$ and $\sigma =$
13 $400m/s$, truncated between $2100m/s$ and $3400m/s$ to avoid super shear propagation.

14 According with results obtained by Mai et al. (2005), nucleation position should be chosen close
15 to zones with significant slip values. Since our explored slip distributions mostly have large slip
16 patches far from the fault edges, we chose normal distributions centered in the middle of the
17 fault plane for x_n and y_n .

18 In Figure 11 are summarized all the chosen source parameters probability density functions
19 (Figure 11a) and the choices we made for the roughness mean value, the fault size and its
20 position with respect to the main fault plane (Figure 11b).

21 Finally we let vary all the source parameters together, according to the probability distributions
22 described above, and performed three sets of 500 blind simulations for a magnitude 6 event
23 located on the southern fault segment and we compared results with prediction of different

1 GMPEs. Each set has a different mean roughness value: 0.74 (from self-similarity assumption),
2 1.0 (from Gallovic & Brokesova 2004) and 1.6 (from empirical relations).

3 We chose four different prediction equations that were compatible with the considered case
4 study: Boore and Atkinson (2008), Chiou and Youngs (2008), Cauzzi et al. (2014) and Akkar
5 and Bommer (2010). Some details about the considered GMPEs are shown in TABLE 2. All
6 these GMPEs take into account the soil site condition through the V_{S30} parameter (mean shear
7 wave velocity in the first 30 m from the surface). For the selected site we assumed $V_{S30} = 580$
8 m/s (Chartier 2015).

9 As an example, in Figure 12 PGA and S_a (computed at 0.5, 1, 2, 5 and 10 Hz) values from
10 simulations are compared with GMPEs predictions for a M_w 6 event recorded at BREM station.
11 As observed also by other authors (e.g. Baumann and Dalguer, 2014; Dalguer and Mai, 2012),
12 empirical models predictions generally produce higher values than simulation results in near
13 source conditions (distances lower than 10 km). Here we observe the same discrepancy at all
14 frequencies, except for the simulations obtained with a mean roughness value of $\bar{\mathfrak{K}} = 1.6$. This
15 is clearly visible between 5 and 10 Hz, where we can observe a strong increase of the simulated
16 ground motion values.

17 Figure 12 also shows simulation results for different ranges of rupture velocities: $v_r \leq$
18 $2400m/s$, $2400 < v_r < 3000m/s$ and $v_r \geq 3000m/s$. As expected, due to the choice of a
19 normal distribution for rupture velocity centered on $2800m/s$, most of the data are concentrated
20 in the range between 2400 and $3000m/s$.

21 Finally, we decided to adopt the roughness mean value that comes from the self-similarity
22 assumption (0.74) in order to fix the stress drop of the target event as the average of the values
23 computed for the EGFs. Under this assumption, the Figure 13 shows the results of three sets of
24 500 blind simulations obtained for three different scenarios: the first one considering only the

1 southern segment of the Rhine River Fault; the second one considering only the northern
2 segment; the third one considering the two segments together.

3 In Figure 13 the spectral accelerations are shown as functions of the period T (obtained as the
4 geometrical mean of the two horizontal components) in terms of mean and standard deviation
5 for each scenario. Each single fault has been associated to a magnitude 6 event, such that a
6 rupture scenario propagating through both the segments generates a M_w 6.5 event.

7 As we can see, if we consider the two faults separately, results are very similar with the northern
8 segment producing larger amplitudes especially for periods between 0.05 and 0.1 s (10 to 20
9 Hz). Results obtained involving both the two fault segments are giving, as expected, larger
10 amplitudes with values of response spectra over 1 g for periods between 0.1 s and 0.2 s (5 to 10
11 Hz).

12 The possibility to investigate different scenarios results extremely important in the case of a
13 probabilistic hazard analysis. Including faulting models in PSHA let us to identify which could
14 be the source contributing the most to the hazard (Chartier 2015).

15

16 **Discussion and conclusions**

17 In the framework of the BestPSHANI workshop (Best Practices in Physics-Based Fault Rupture
18 Models for Seismic Hazard Assessment of Nuclear Installations, Vienna, Austria, 18–20
19 November 2015), whose purpose was to discuss the applicability of different ground motion
20 simulation techniques for hazard assessment of nuclear installations, we propose a near fault
21 application to the Upper Rhine Graben based on the multi empirical Green's function approach
22 coupled to a k^{-2} kinematic source description. The importance of performing simulations relies
23 on the fact that GMPEs are often not robust in near fault conditions. The lack in near fault
24 records makes them not able to cover all the possible earthquake scenarios likely leading to
25 incorrect ground motion estimation.

1 Numerical simulations can be a way to overcome this problem, although they need to be
2 properly calibrated with the weight of each parameter investigated. One of the advantages of
3 the approach we use for modeling the seismic wave propagation is that a very detailed
4 description of the crustal medium is not required because it is replaced by a significant number
5 of records of small earthquakes. In the case of the application shown here, the Upper Rhine
6 Graben, a region located at the border between France and Germany which is characterized by
7 a low to moderate seismic activity, finding enough records was part of the challenge. From a
8 database of about 30 events recorded in the last 15 years, we were able to extract 5 events which
9 satisfy strict quality criteria to be used as EGFs. Even if it worked out in this case, this is one
10 limitation of our application. Indeed improvement of seismic networks for regions demanding
11 seismic hazard assessment is required to increase the robustness of ground motion prediction.

12 After choosing the BREM station as the target site, we tested the influence of source parameters
13 on the simulations. In particular we showed the correlations of the ground motion parameters
14 with the roughness of the slip, the rupture velocity and the nucleation position. The roughness
15 parameter mostly shows a linear correlation with ground motion amplitudes, while for the
16 rupture velocity we observe a faster growth at high frequency (mimicking an exponential
17 behavior). Nucleation position is related to rupture directivity effect and it has a strong influence
18 only at low frequencies below the corner frequency of the simulated event. To better understand
19 the physical meaning of the roughness parameter and try to reduce its range of variability, we
20 studied its correlation with the static stress drop. All these parameters have shown to play a key
21 role and we studied in details this effect to better constrain the variability of the ground motion
22 and properly calibrate simulations.

23 While for rupture velocity and the hypocentral position we can make some assumptions on the
24 most probable values and the associated variability, the roughness parameter has no *a priori*
25 constraints because it is directly related to the slip distribution, which can be quite different

1 from earthquake to earthquake. So we decided to adopt a lognormal probability distribution for
2 it according to Causse et al. (2010) and to explore three (very) different mean values as proposed
3 in several previous studies (e.g. Causse et al., 2009; Gallovic and Brokesova, 2004). Without
4 any *a priori* assumption, as discussed also by Del Gaudio et al. (2015), using the EGF approach,
5 $\bar{\mathcal{K}} = 0.74$ should be preferred according to the self-similarity hypothesis.

6 We then performed blind simulations for a magnitude 6 event occurring on the southern
7 segment of the Rhine River Fault system assuming *a priori* probability distributions of source
8 parameters and comparing them with four different GMPEs. We found that generally our
9 simulations lead to lower ground motion estimations (and variability) than the ones obtained
10 from GMPEs, with a strong dependence on the input source parameters. This comparison is not
11 straightforward though, because in both cases we are not comparing the same ground motions
12 estimators. Regarding simulations, the level and the variability of the results are reflecting the
13 large uncertainties on the controlling source parameters, exhibiting the lack of physical
14 constrains on them. In the future, physics-based rupture models should help to reduce those
15 uncertainties. Regarding the GMPEs, the results are reflecting the lack of near fault data and
16 the summation of uncertainties due to both extrapolation and ergodicity. Large epistemic
17 uncertainties remain in both methodologies, although they are essentially different for each.
18 The relative consistency between GMPEs with respect to simulations may just be symptomatic
19 of the common methodology of GMPEs which are essentially lacking of data in near source
20 conditions, while the biases of simulations are essentially different and independent ones
21 originating from the lack of physics.

22 With this work we confirm that, for a defined earthquake scenario, distance is not sufficient to
23 explain the variability of the ground motion. In this synthetic case, it is dominated by the
24 uncertainty on sources parameters (roughness degree, average rupture velocity, etc.) rather than
25 on aleatory parameters such as slip distribution or hypocenter location. Our work clearly

1 identifies parameters controlling the ground motion, and subsequently point out which
2 uncertainties should future studies aim at reducing. Meanwhile, those uncertainties should be
3 taken into account in ground motion computations. This is an important point if the simulations
4 carried out have to be included into a probabilistic seismic hazard model to complete
5 information that comes from GMPEs at short distances from the fault. For a PSHA, it is
6 necessary not only to retrieve the average ground motion produced by a given earthquake, but
7 the distribution of all the possible scenarios that can be generated.

8 Finally, for the specific case study we also showed results for three different sets of scenarios
9 considering the two selected segments of the Rhine River Fault. For each of them we showed
10 average simulated ground motion and its variability in terms of acceleration response spectra
11 as functions of the period of the oscillation. For these simulations we fixed the magnitude to
12 M_w 6 for the case of a single fault involved in the rupture process, and M_w 6.5 when considering
13 both the fault segments. Our results show that the northern segment produces on average larger
14 amplitudes than the southern one, and that the worst case of a bigger earthquake producing over
15 the two fault segments can reach high ground motion level for a target site located in very near
16 fault conditions (more than 1 g for response spectra \sim 5 Hz with a PGA of 0.4 g). Again, this
17 result is strongly dependent on the uncertainties we have on source parameters. In blind
18 conditions, where no benchmark are available, source parameters should be accurately
19 investigated and their natural variability properly reproduced. A strategy which combines
20 physics-based simulation methods with the knowledge that comes from real observations could
21 be in future the right choice to correctly calibrate source parameters and hence to obtain realistic
22 strong ground motion predictions.

23

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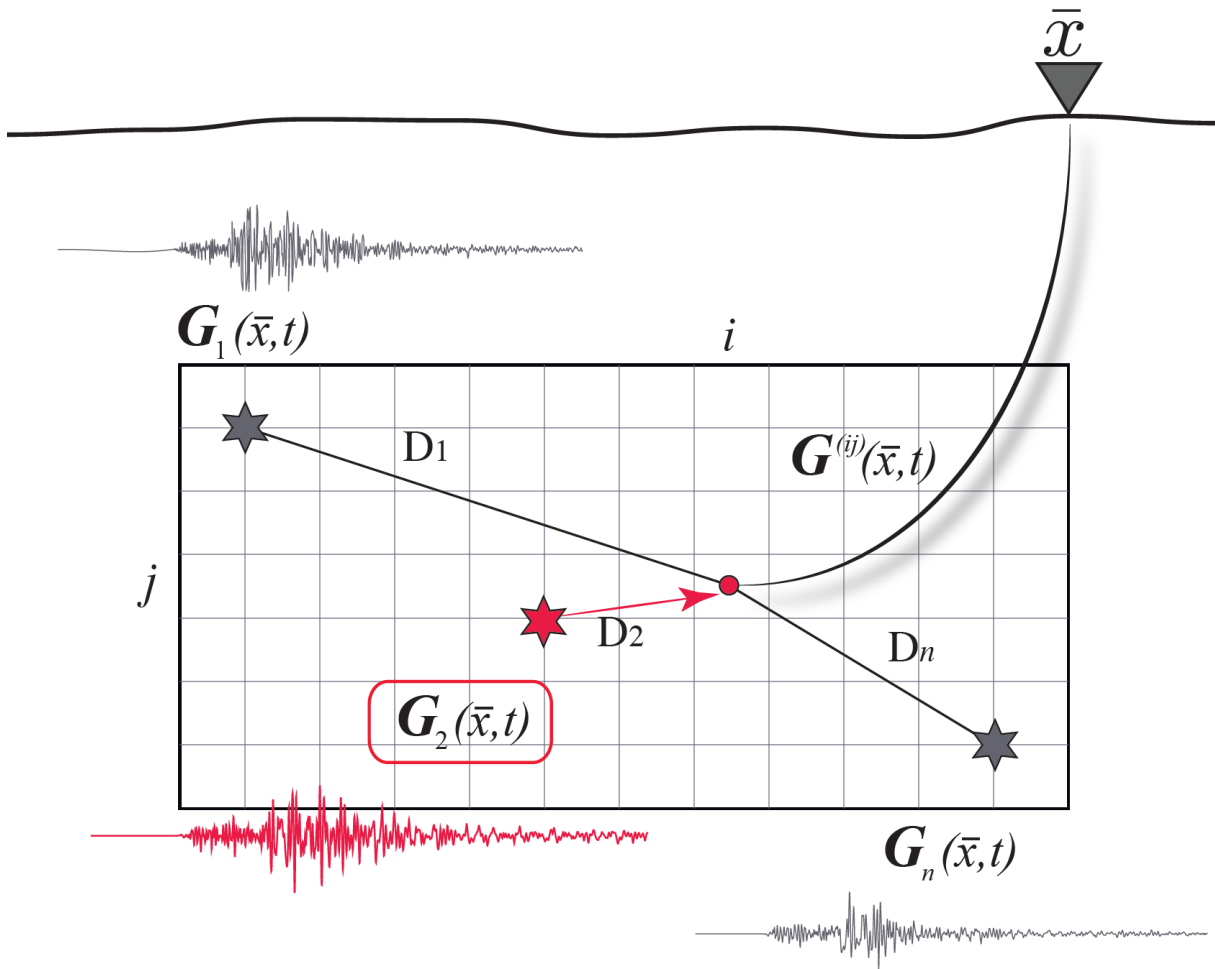
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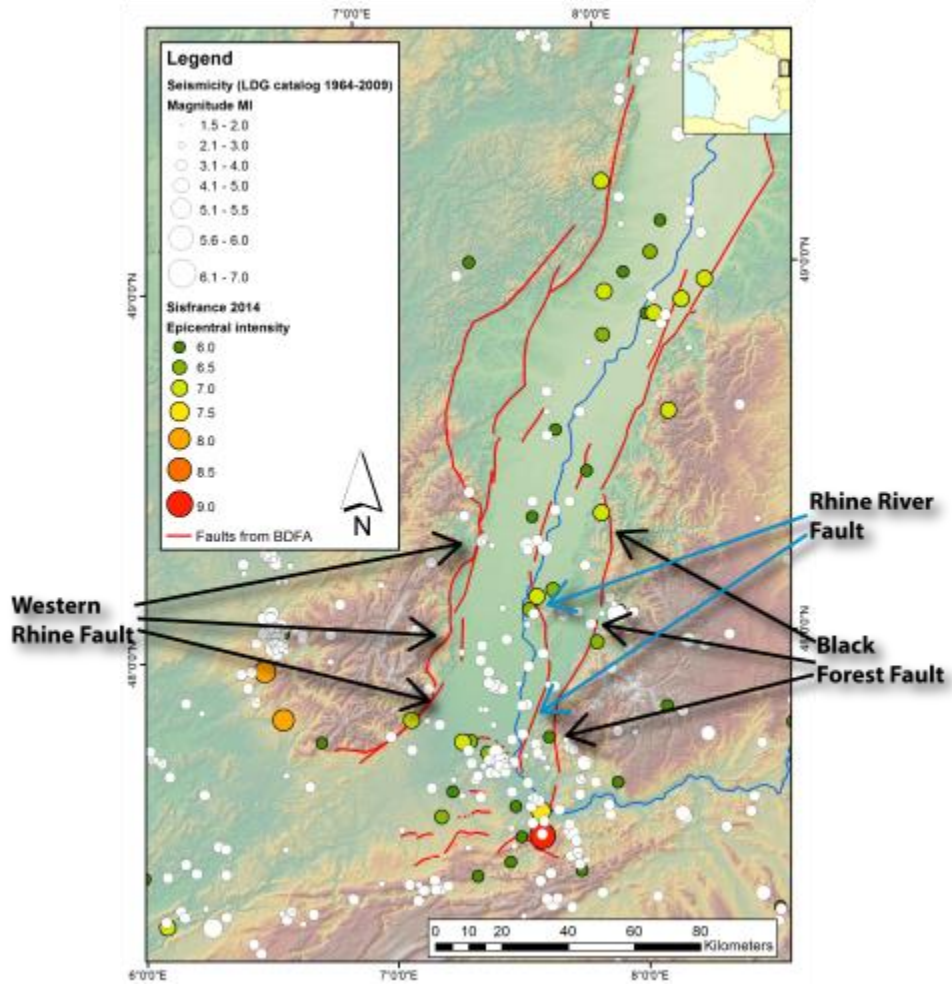
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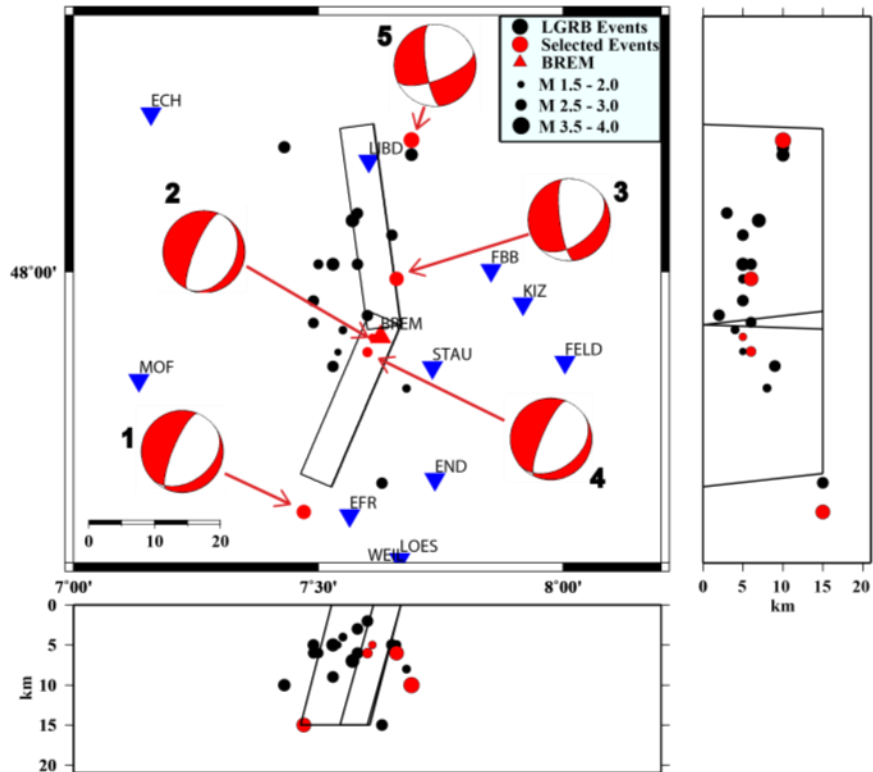
Figure 1 Schematic view of multi-EGF technique. Stars locate n different small earthquakes recorded at station x , that are candidate for being the EGF used at each point of the gridded fault. To determine which of the n different EGF is applied at each grid point, distance D_1, D_2, \dots, D_n are calculated. At the red spot, D_2 is found to be the shortest distance. The EGF for this point is $G_2(\bar{x}, t)$.



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2 **Figure 2** Seismicity and faults map of the Upper Rhine Graben; in particular the Western Rhine Fault and the
 3 Black Forest Fault systems are highlighted, which follow the borders of the Graben, and the Rhine River Fault,
 4 which follows the river path. As indicated in the upper legend, white circles represents recorded earthquakes in
 5 the area (from 1964 to 2009), while colored circles represents historical earthquakes in the area (different colors
 6 refers to different estimated intensities).

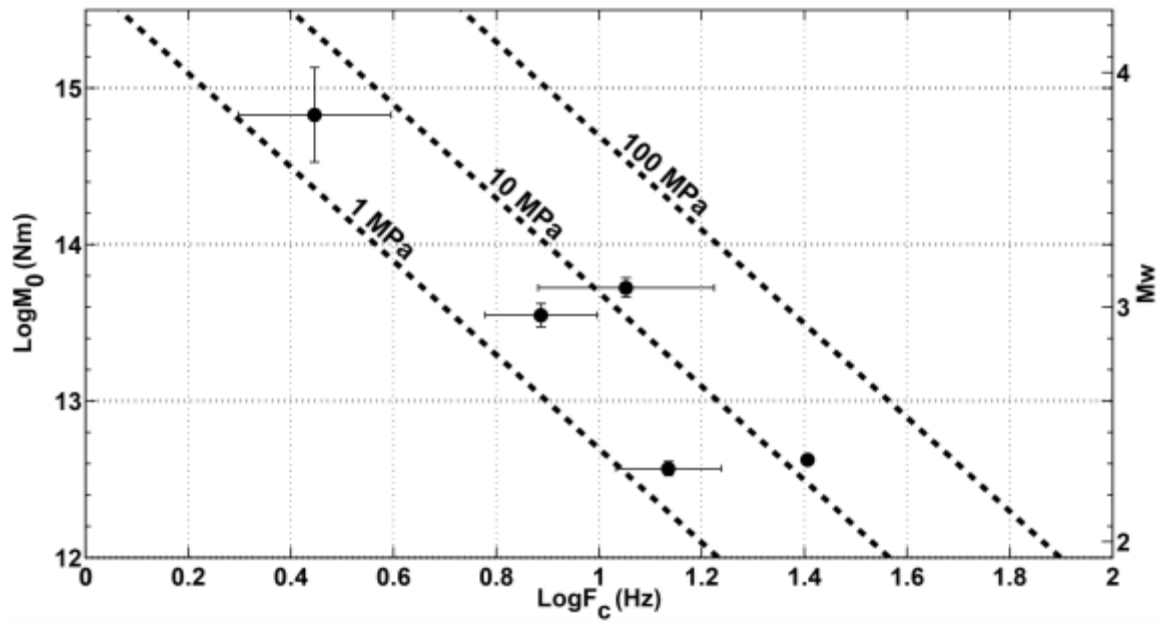
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2 **Figure 3** Simplified map of the area, showing the location of the considered events (black dots with a magnitude
 3 dependent size) and the surface projection of the modelled faults. Red dots represent the selected EGFs
 4 (identification numbers are the same as Table 1) for which focal mechanism solutions (computed fixing the strike
 5 and the dip angle, according to the hypothesis made for the considered fault geometry, and retrieving the rake
 6 angle from eq. 5) are also plotted on the map. The French and German stations located in the area are represented
 7 with blue triangles. Bottom and right panels are vertical sections in the EW and NS directions respectively.

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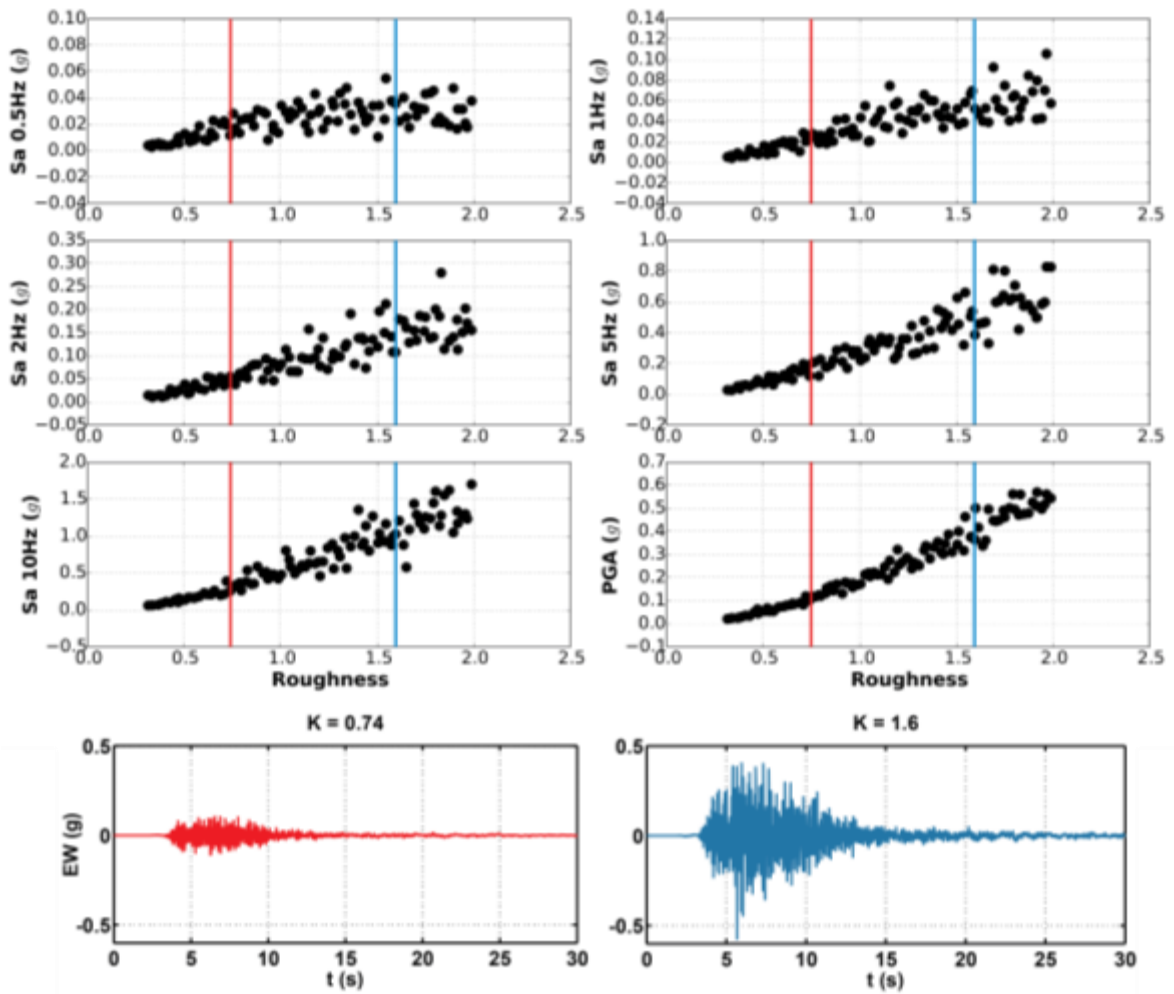
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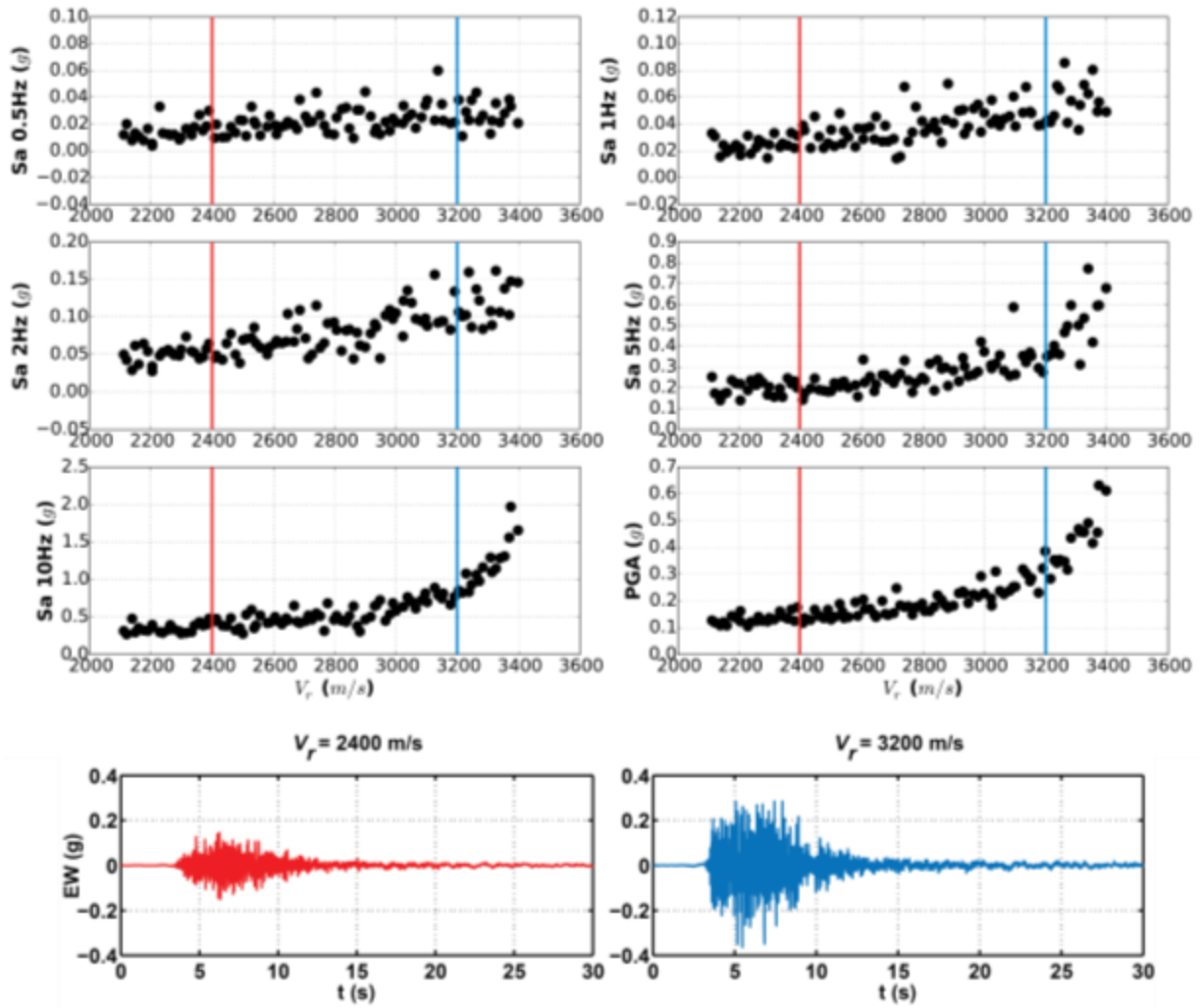
Figure 2 Logarithm of the corner frequency as a function of the logarithm of the seismic moment. Dashed lines represent constant stress drop values of 1, 10 and 100 MPa. Error bars represent the standard deviation associated to the different estimates of corner frequency and seismic moment from different stations.



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2 **Figure 3** Spectral acceleration at 0.5 Hz, 1 Hz, 2 Hz, 5 Hz, 10 Hz and PGA as functions of the roughness parameter
 3 for a M_w 6 event occurring on the southern segment of the Rhine River fault. The nucleation position is fixed at
 4 the center of the fault and the rupture velocity is fixed to 2800 m/s. Red and blue lines on the plots corresponds to
 5 two values of the roughness parameter, 0.74 and 1.6, for which an example of simulated waveforms is shown.

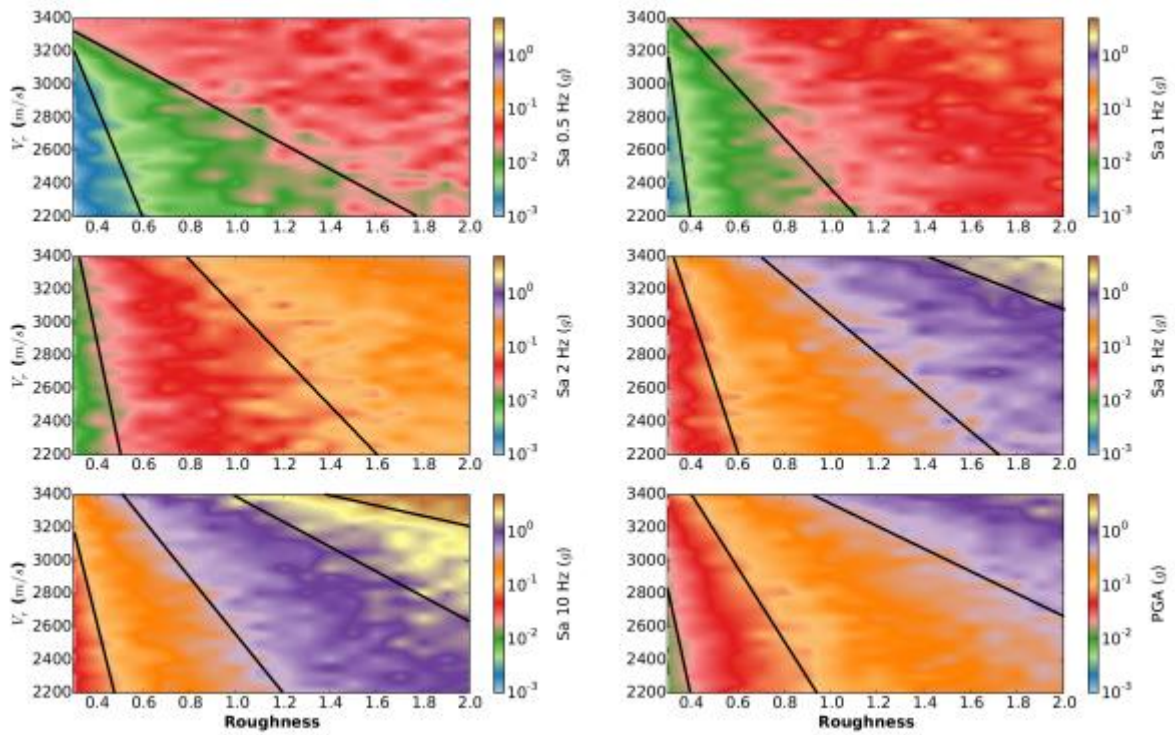
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2 **Figure 4** Spectral acceleration at the same frequencies as in Figure 5 and PGA as functions of the rupture velocity
 3 for a M_w 6 event occurring on the southern segment of the Rhine River fault. The roughness parameter is fixed to
 4 1 and the nucleation position is fixed at the center of the fault. Red and blue lines on the plots corresponds to two
 5 values of rupture velocity, 2400 and 3200 m/s, for which an example of simulated waveforms is shown.

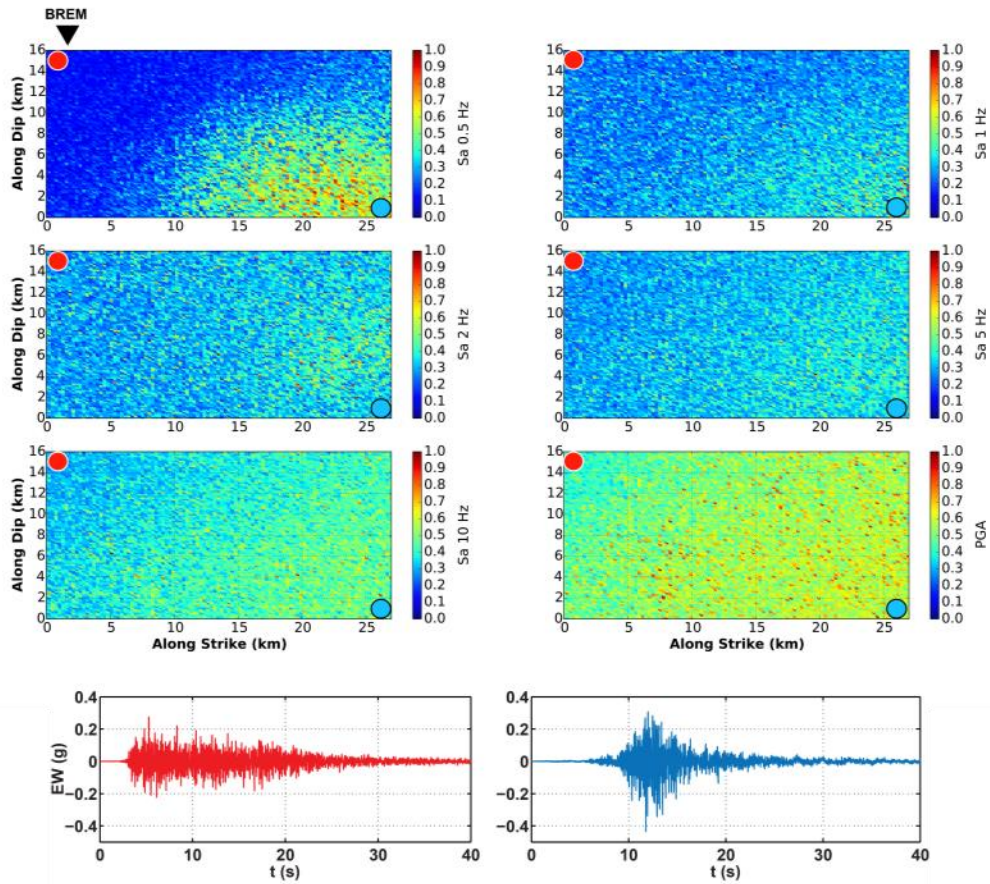
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2 **Figure 5** Spectral acceleration in logarithmic scale at same frequency as in Figure 5 and PGA as functions of the
 3 rupture velocity and the roughness parameter for a M_w 6 event occurring on the southern segment of the Rhine
 4 River fault. Only the nucleation position is fixed at the center of the fault. Paired color scale is used to highlight
 5 ground motion variations. Black lines separate qualitatively zones in which amplitudes are almost constant.

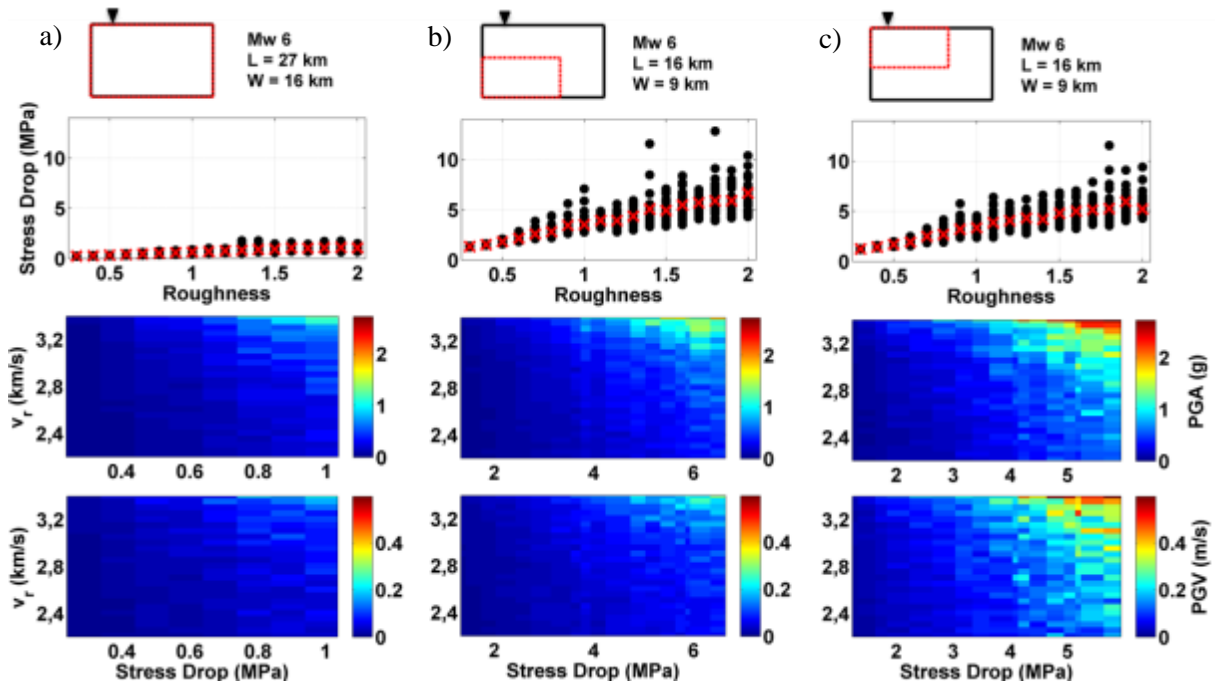
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2 **Figure 6** Normalized spectral acceleration and PGA as functions of the nucleation position for a M_w 6 event
 3 occurring on the southern segment of the Rhine River fault. Each point in a plot corresponds to a specific location
 4 for the rupture initiation points. The roughness parameter is fixed to 1 and the rupture velocity to 2800 m/s. The
 5 location of the target station with respect to the fault surface trace is also indicated. Red and blue spots on the plots
 6 corresponds respectively to an anti-directive and directive positions for which an example of simulated waveforms
 7 is shown.

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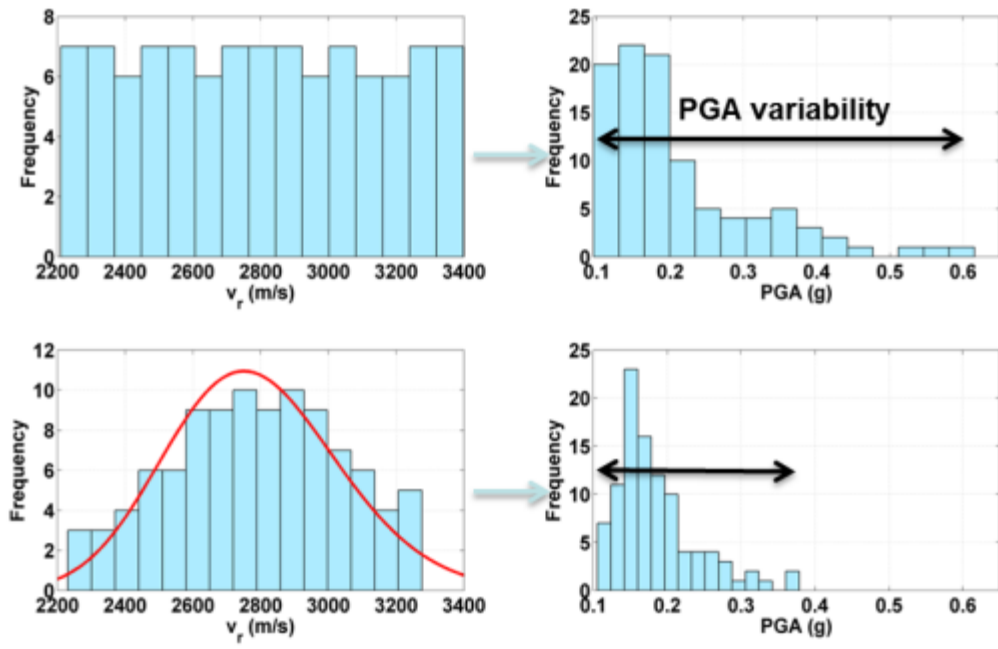
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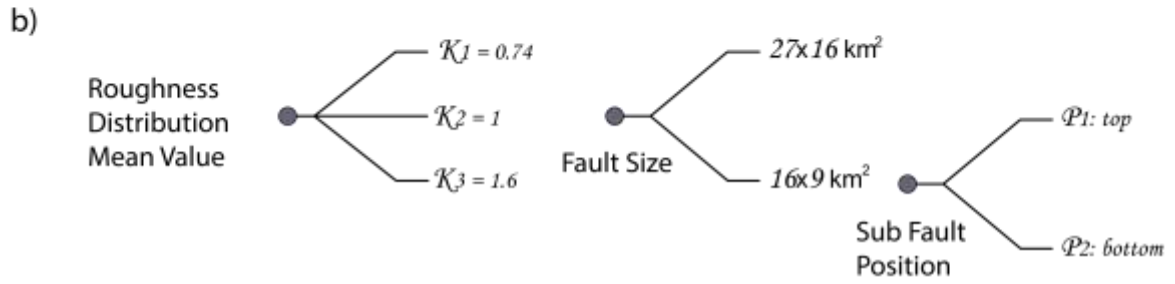
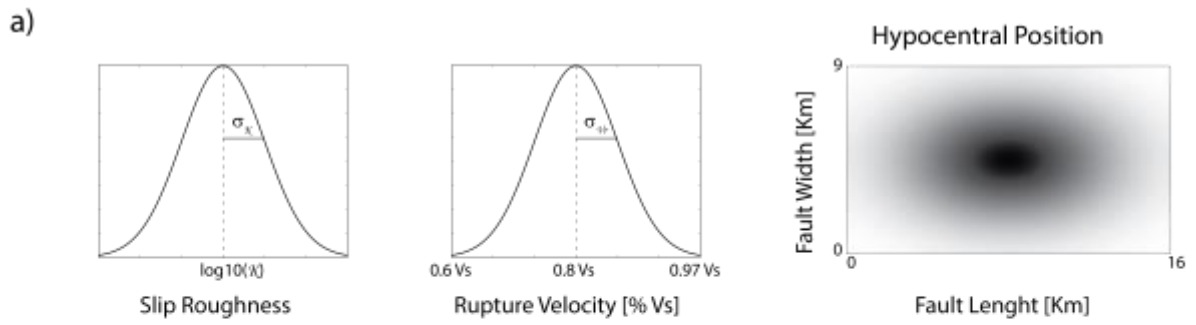
Figure 9 Top panels : Stress drop as a function of the roughness parameter (red crosses represent average values for fixed K) for the three different fault geometries a) Southern segment of the Rhine River fault; b) smaller fault surface with the same shape ratio of a); c) same fault of b) but placed at a shallow depth. In the bottom panels PGA and PGV distributions are shown as functions of mean $\Delta\sigma$ and v_r values for the same cases.



1

2 **Figure 10** Influence of source parameters variability on the resulting ground motion. On the top: A uniform
 3 distribution of rupture velocity with resulting PGA distribution; on the bottom, normal distribution of v_r
 4 centered in $v_r = 0.8v_s$ and truncated between 2200 m/s and 3400 m/s with resulting PGA distribution.

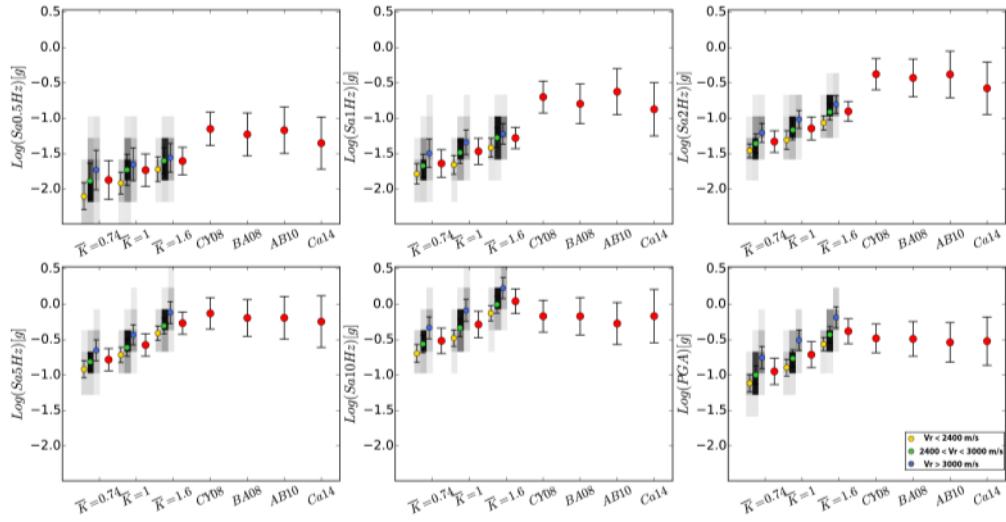
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2 **Figure 11** Considered probability density functions for the roughness parameter, the rupture velocity and the
 3 hypocentral position on the fault (a). Hypothesis made for blind simulations are also shown (b): mean values for
 4 the roughness parameter, considered fault size and its relative position with respect to the main fault plane.

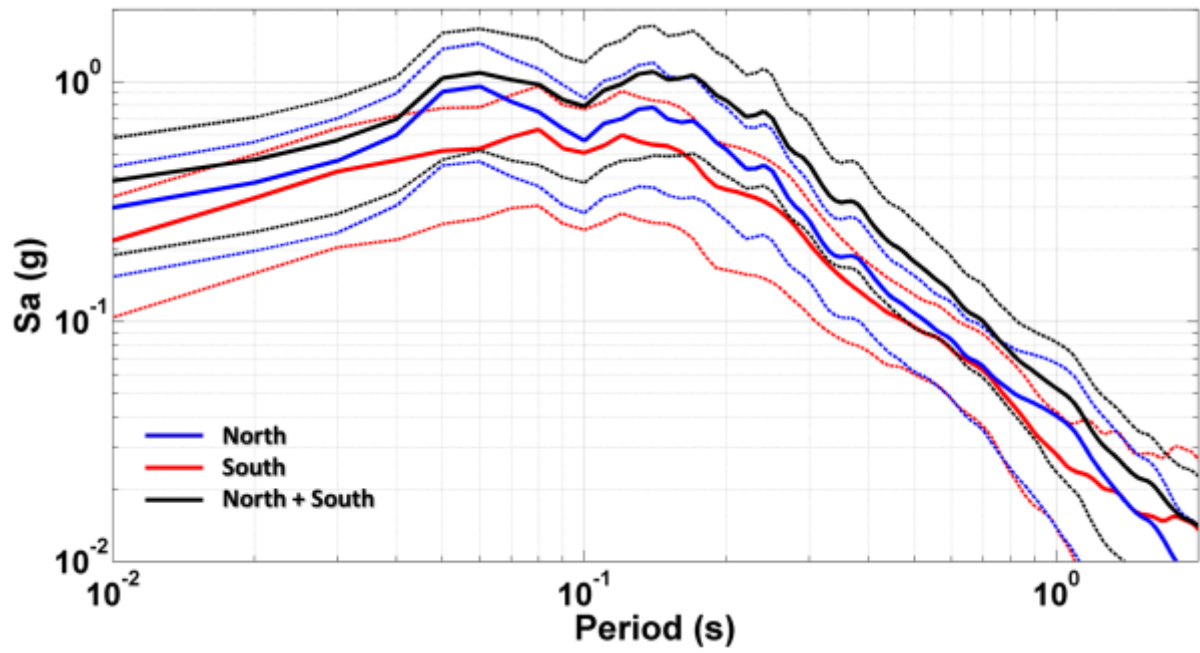
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2 **Figure 12** Comparison between simulations and GMPEs in terms of PGA and Sa (0.5, 1, 2, 5 and 10 Hz) for
 3 a M_w 6 event recorded at BREM station. Red dots represent the mean values for simulations (with different
 4 mean values of roughness parameter distribution) and GMPEs; error bars represent one σ interval. For
 5 simulations we also show density of values (in grey scale), mean and standard deviation for different ranges
 6 of rupture velocity.

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2 **Figure 13** Spectral acceleration versus period of an equivalent harmonic oscillator with 5% damping for three
 3 different earthquake scenarios (only southern segment in red, only northern segment in blue and both the
 4 segment together in black). Solid lines represent the average of 500 simulations, while dashed lines represent
 5 the $\pm 1 \sigma$ interval.

6

1 **TABLE 1** Source parameters for the selected EGFs: location from LGRB; moment magnitude, corner frequency
2 and stress drop calculated as the average of the estimations at each station. Standard deviations for magnitude,
3 corner frequency and stress drop are also indicated. For EGF 2 standard deviations are not indicated because only
4 one record is available.

EGF #	Date	Time	M_w	σ_{M_w}	Lat (°)	Lon (°)	Depth (km)	f_c (Hz)	σ_{f_c}	$\Delta\sigma$ (MPa)	$\sigma_{\Delta\sigma}$
1	26/09/2002	21:01:40.30	3.0	0.2	47.67	7.47	15	8	2	3	1
2	18/05/2005	15:34:10.10	2.3	-	47.91	7.61	5	25	-	15	-
3	25/07/2005	01:36:32.00	3.1	0.2	47.99	7.66	6	11	4	35	40
4	15/12/2009	21:12:35.00	2.3	0.1	47.89	7.60	6	14	3	3	2
5	01/11/2011	19:22:16.00	3.8	0.7	48.18	7.69	10	3	1	7	7

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6

1 **TABLE 2** GMPEs used for the comparison.

Reference Paper	Validity range of distance	Validity range of magnitude	Used metric	Origin of used data
Boore and Atkinson (2008)	1 – 200 km	5 – 8	R_{JB}	California and Taiwan.
Chiou and Youngs (2008)	1 – 200 km	4 – 8.5	R_{JB} , R_{RUP}	Tectonic region all over the world (subduction earthquakes are excluded).
Cauzzi et al. (2014)	1 – 150 km	4.5 – 7.9	R_{RUP}	Europe, Japan, California, China, New Zealand and Taiwan (subduction earthquakes are excluded).
Akkar and Bommer (2010)	5 – 100 km	5 – 7.6	R_{JB}	Europe and Middle East.

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