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Future magnitude 7.5 earthquake offshore Martinique: Spotlight on major source-related factors of ground motion variability

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SUMMARY

The eastern offshore of Martinique is one of the active areas of the Lesser Antilles Subduction Zone (LASZ). Although its seismicity is moderate compared to other subduction zones, LASZ is capable of generating a M 7+ interplate earthquake and recent studies and historical events, such as the M8 1839 and M 7-7.5 1946 earthquakes, confirm this possibility. Given the high risk that Martinique can face in case of unpreparedness for such a M 7+ earthquake, and the lack of a regional seismic hazard study, we investigated through numerical modelling the ground motion variability for a hypothetical M_w 7.5 interplate earthquake. Our main objective is to highlight the major factors related to earthquake source that can bring the highest variability of ground motion at four broadband seismic stations across Martinique. For this purpose, we generated 320 rupture scenarios through a fractal kinematic source model, by varying rupture directivity, source dimension, slip distribution. We computed the broadband ground motion (0.5-25 Hz) by convolution of source-time functions with Empirical Green's Functions (EGFs), that we selected from the analysis of moderate events (M 4-4.5) recorded in the area of interest since 2016 by the West Indies network. We found that the fault geometry and the spatial extension of the largest slip patch are the most determinant source-related factors of ground motion variability. The significance of such ground motion variability with respect to ground motion prediction equations (GM-

PEs) depends on the evaluated frequency of ground motion and on the station. Moreover, we concluded that the EGF selection can be another significant factor of the variability of the modelled ground motion depending on station. Our results provide a new insight on the source-related ground-motion variability across Martinique and can guide future blind seismic hazard assessment studies in different regions.

Key words: Strong ground motion, Fault slip, Rupture propagation, Source time functions, Synthetic seismograms

1 INTRODUCTION

Martinique is located on the Lesser Antilles Subduction Zone (LASZ, Fig. 1), that is moderately active but capable of generating a M 7+ interplate earthquake (e.g., Feuillet et al. 2011). LASZ is formed by the subduction of the Atlantic oceanic lithosphere under the Caribbean plate at a relatively slow convergence rate of 18 mm per year (DeMets et al. 2010). Martinique island is part of the north-south trending magmatic arc of LASZ. The seismicity of LASZ can be divided into: 1) flat-thrust interplate events above approximately 50 km in the fore-arc; 2) deep intraslab events in the back-arc; 3) intraplate events within the Carribean Plate (Russo et al. 1992; Laigle et al. 2013; Ruiz et al. 2013). The scarcity of large (M > 7) interplate thrust earthquakes in LASZ implies an unusual strain release compared to other subduction zones (Russo et al. 1992). Nonetheless, past studies (Ruiz et al. 2013; Laigle et al. 2013; Weil-Accardo et al. 2016) proposed that LASZ has high potential to generate a mega-thrust earthquake: the seismogenic zone might extend to the mantle wedge, below the forearc, and moderate seismic activity at the base of the seismogenic zone can load shallower segments and initiate a larger mega-thrust event. An example of this phenomenon was observed during the 2011 M_w 9 Tohoku, Japan earthquake; Laigle et al. (2013) and Satriano et al. (2014) point to the similarities between the North-Eastern Japan mega-thrust and LASZ—such as the lack of tremors and very-slow-low-frequency earthquakes, and the sustained activity in the mantle wedge—to better understand the long-term seismic activity of LASZ. Indeed, the recent study of Paulatto et al. (2017), linking heterogeneity of V_p/V_s ratio to earthquake activity in LASZ, supports the proposed tectonic explanation and the analogy between the North-Eastern Japan mega-thrust and LASZ.

Historical events in the region confirm the possibility of a mega-thrust earthquake generation in LASZ. Feuillet et al. (2011) compiled the data from several reports and papers for all significant historical earthquakes in the Lesser Antilles. They concluded that the magnitudes of the 1839 and the 1946 earthquakes offshore Martinique (Fig. 1) should be in the range of 7-8, based on regional intensity reports. Moreover, Weil-Accardo et al. (2016) studied the sea level changes over the last two centuries by analysing morphological changes of microatolls in eastern offshore Martinique. They underlined the strong possibility of magnitude 7 or more for both historical earthquakes. They also interpreted the long-term subsidence, that was likely due to the 1839 earthquake, as an indicator of the locking of the mantle wedge during the interseismic period.

Great population density in Martinique leaves it vulnerable to high risk in case of unpreparedness for a M > 7 earthquake (Audru et al. 2013). In the absence of a regional seismic hazard study, the assessment of ground motion variability by numerical modelling can guide future mitigation studies. The conventional approach in seismic hazard assessment is the use of ground motion prediction equations (GMPE) that provide estimation of peak ground motion at a distance (Douglas 2003). A GMPE is developed based on statistical data, and the paucity of large events in LASZ renders a regional GMPE development difficult in Lesser Antilles. Indeed, the only available GMPE, the 'B3' model of Beauducel et al. (2011), is limited to events of magnitude less than 6.3. As an alternative to GMPE, numerical modelling offers the possibility of better understanding the physical aspect of the phenomenon (i.e., earthquake source and wave propagation). It allows for testing the outcomes of different configurations, which is particularly important for moderately seismic areas such as LASZ.

The challenge in numerical modelling is the uncertainty associated with model or input parameters, in particular when working with limited knowledge on earthquake process. The uncertainty related to earthquake source parameters can bring significant variations in the modelled ground motion (e.g., Ripperger et al. 2008; Imperatori & Mai 2012; Spudich et al. 2019). This impact is also valid in backward modelling. For example, as shown in Ragon et al. (2019) by their analyses on the 2016 Amatrice, Italy earthquake, accounting for uncertainties of only fault geometry can drastically control the estimated fault slip.

Our main objective is to identify the major factors related to earthquake source that can cause ground-motion variability in Martinique during a future M_w 7.5 interplate thrust earthquake. Within this objective, we prepared 320 rupture scenarios by varying kinematic features of the target hypothetical earthquake. For each scenario, we coupled fault rupture with Empirical Green's Functions (EGF) for seismic wave propagation, and predicted broadband ground motion (0.5-25 Hz) at four stations of Martinique. Past studies (e.g., Ameri et al. 2009; Hartzell et al. 2002; Pacor et al. 2017; Sørensen et al. 2007; Wang et al. 2009; Withers et al. 2019) underlined the significant effect of source parameters on ground motion —for example, spatial variations of ground motion amplitudes due to rupture directivity or the location of slip asperities—, and the necessity of accounting for the variability of source parameters to decrease the variability of the modelled ground motion with respect to GMPEs. Here, we take forward these studies by considering a comprehensive set of source parameters and performing analyses in a broader frequency range.

A second objective is to test the role of EGF selection on ground-motion variability. The EGF approach emerges as a powerful method to model broadband ground motion, especially when no detailed knowledge on propagation path is available, as revealed by many applications in the literature (e.g., Kamae & Irikura 1998; Pulido et al. 2004; Causse et al. 2009; Courboulex et al. 2010; Del Gaudio et al. 2018). It also takes into account possible site effects (except for soil non-linearity) and provides full time histories of ground motion, differently than GMPEs. On the other hand, among the applications in actively seismic areas, EGFs can be selected from foreshocks or aftershocks of a specific earthquake (e.g., Del Gaudio et al. 2015; Dujardin et al. 2016). Here, we study a moderately-active zone with no successive recordings of such smaller events. In this case, selected events can differ more by several aspects such as seismic moment, stress drop, hypocentre location, etc. As Pavic et al. (2000) denoted, due to such differences between selected EGFs, further variability of ground motion can arise from the EGF method itself. Therefore, we also questioned the influence of EGF selection on ground-motion variability.

Scoping these two objectives, the paper is structured as follows: 1) we detail the methods that we used for modelling source kinematics and wave propagation; 2) we explain how we constructed the set of earthquake scenarios and selected moderate earthquakes to employ as

EGF; 3) we address the following three questions, respectively: ‘Which aspect of the source controls the ground motion variability, and why?’; ‘How important is the source-related ground motion variability with respect to the GMPE?’; ‘Is the EGF selection another factor of ground motion variability?’; 4) we discuss the limitations of our study and present the main conclusions.

2 METHODS

We model the target interplate M_w 7.5 earthquake by using the kinematic source model of Ruiz’s Integral Kinematics (RIK, Ruiz et al. 2011). RIK model generates, for an earthquake with a prescribed seismic moment, a stochastic slip distribution along with the full slip history —the source-time functions (STF)— at each node of a discretised fault plane. We convolve the output STFs with empirical Green’s functions (EGFs) to compute ground motion at four stations of Martinique. In the following are given the main features of the RIK and EGF methods, respectively.

2.1 Ruiz’s Integral Kinematics (RIK) model

We performed kinematic rupture modelling by using the RIK model implementation of Gallovič (2016). Slight modifications of the original RIK method issued by this implementation are also present here. The numerical tool that we used is an open source code (see Data and resources).

RIK is a composite model that defines an earthquake as a cascade of sub-sources. The number of sub-sources depends on their size, which follows a fractal distribution, i.e. the number of sub-sources with radius greater than a given size is:

$$N = \sum_{i=SUB_{min}}^{SUB_{max}} (2i-1)\frac{L}{W} \tag{1}$$

where L is fault length; W is fault width; SUB_{min} and SUB_{max} are lower and upper limits of the ratio of fault width to sub-source diameter, respectively.

Each sub-source is a circular fault, or crack—by definition of Eshelby (1957)—that is associated with a slip function of Δu, as follows:

$$\Delta u(r) = \frac{24}{7\pi}\frac{\Delta\sigma}{\mu}\sqrt{R^2 - r^2} \tag{2}$$

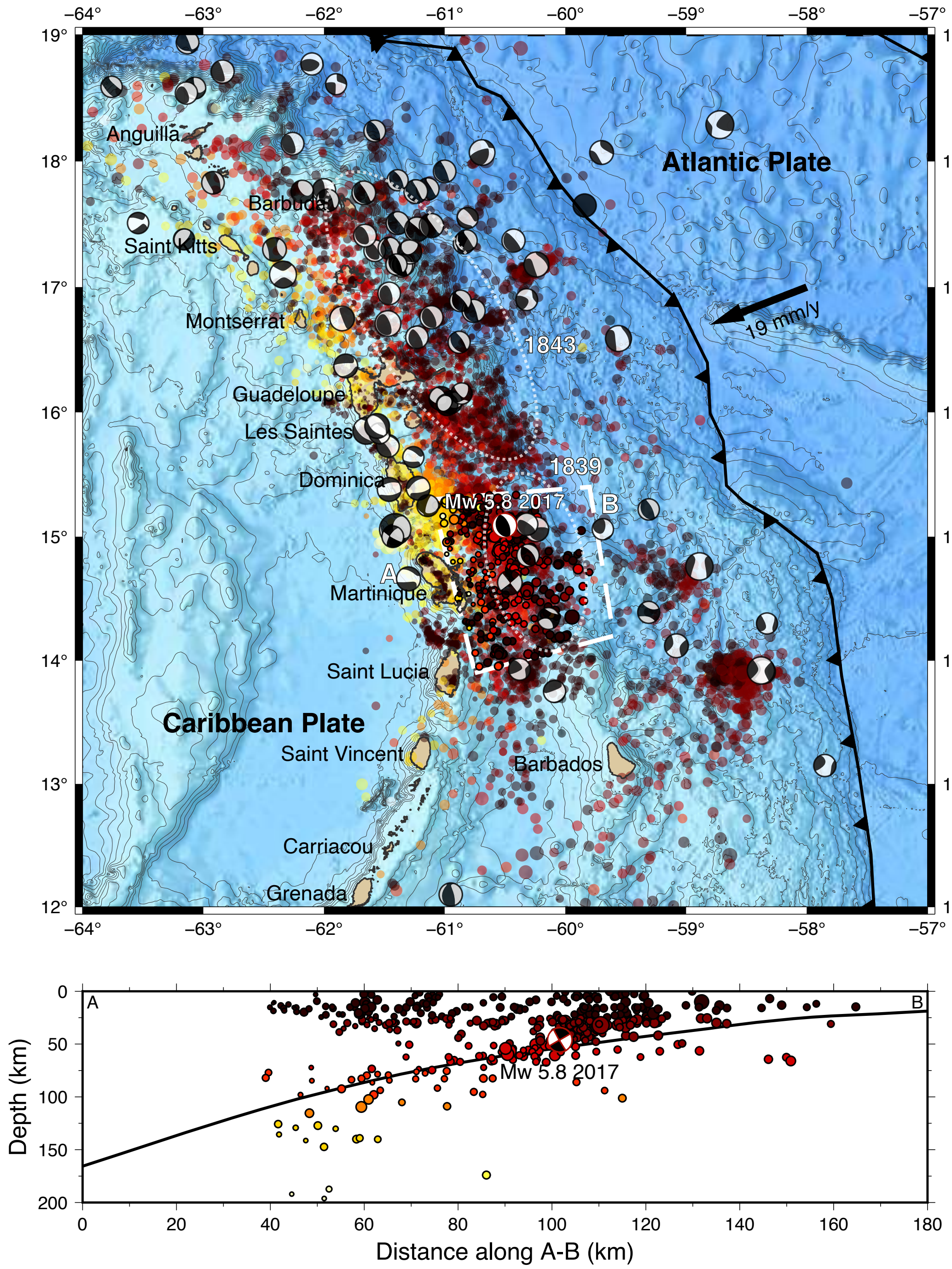

Figure 1. Seismicity of the Lesser Antilles Subduction Zone (LASZ). The dotted ellipses indicate the rupture area of the 1839 and 1843 earthquakes, inferred by Feuillet et al. (2011). The circles, coloured by depth, are the hypocentres from the unified catalogue of the IPGP French observatories (OVSG & OVSM 2020), between 01/01/2014 and 31/12/2019. The dashed white polygon represents the geographical selection made for this study; hypocentres with solid black border within this polygon are recorded by the four broadband stations in Martinique. These hypocentres are also shown on the vertical cross-section, along with the slab model of Paulatto et al. (2017). Focal mechanisms, from GlobalCMT (Dziewonski et al. 1981; Ekström et al. 2012) are for M5+ earthquakes between 1978 and 2019. Focal mechanism for the 03/02/2017 M_w 5.8 event is from SCARDEC (Vallée et al. 2011).

where $\Delta\sigma$ is the static stress drop; μ is the shear modulus; r is the radial distance to the sub-source centre; and, R is the sub-source radius. The formula is valid for $r < R$; slip is zero outside the crack.

RIK model provides a realistic far-field displacement spectrum, with high-frequency ω^{-2} decay (ω being the angular frequency). Such a decay is compatible with the observations on real earthquakes (Brune 1970), and with dynamic models of circular cracks (e.g., Madariaga & Ruiz 2016). In the RIK model, the ω^{-2} decay results from imposing a slip-velocity function with a scale-dependent rise time $\tau(R)$ (Ruiz et al. 2011):

$$\tau(R) = \begin{cases} \frac{\alpha L_0}{V_r}, & \text{if } 2R > L_0 \\ \frac{\alpha(2R)}{V_r}, & \text{if } 2R \leq L_0 \end{cases} \tag{3}$$

where R is the sub-source radius, α is a constant, that we set to 1 in this study; L_0 is a threshold of pulse width; and, V_r is the rupture speed. The scale dependency of rise time only applies for the sub-sources with diameter smaller than L_0. This feature implies a low-pass filtering effect on the final slip spectrum.

The total slip rate of the modelled earthquake is obtained by summing the slip-rate contribution of each sub-source. More details on the method can be found in Ruiz et al. (2011).

2.2 Empirical Green's function (EGF)

2.2.1 Formulation

We use the Empirical Green's Function (EGF) method (Hartzell 1978; Irikura 1986) to account for seismic wave propagation. This technique starts from the representation theorem (Aki & Richards 2002), which expresses the ground displacement $u(x,t)$ at position x and time t :

$$u(x,t) = \int_{\Sigma} s_i(\xi,\tau) * [C_{ijkl}(\xi)v_j(\xi)G_{kl}(x,\xi;t,\tau)]\, d\Sigma(\xi) \tag{4}$$

where $\mathbf{s}$ is the slip vector; $\mathbf{C}$ is the tensor of elastic coefficients; $\mathbf{v}$ is the fault-normal vector; $\mathbf{G}$ is the Green's function; Σ is the fault surface; and the symbol $*$ denotes time convolution.

In the EGF approach, the second term of the convolution in eq. 4 is replaced by the displacement-time history of a real event, $G_{EGF}(x,\xi;\tau)$, located at a position ξ close to the fault and recorded at the station position x, after normalising the convolution by the seismic moment of the EGF event, M_0^{EGF}:

$$u(x,t) = \int_\Sigma \frac{\mu}{M_0^{EGF}} S(\xi;\tau) * G_{EGF}(x,\xi;\tau) d\Sigma(\xi) \quad (5)$$

In this new formulation, S stands for slip amplitude for a constant rake direction on fault plane and μ is shear modulus.

The integral can be solved by its variational formulation for a discretisized fault plane as follows:

$$u(x,t) = \sum_{ij} \frac{\mu^{ij} \cdot l \cdot w \cdot S^{ij}}{M_0^{EGF}} * G^{ij}(x,t) \quad (6)$$

where l and w correspond to length and width of the unit area of the discretisized fault plane, respectively; M_0^{EGF} is the seismic moment of EGF that is associated with the grid point (ij).

The discretisation depends on the size of the EGF event. One can construct a fault grid for a target earthquake by using the ratio of the seismic moment between the EGF and target events as a scale factor:

$$n = \frac{L}{l} = \frac{W}{w} = \left(\frac{M_0^{target}}{M_0^{EGF}}\right)^{1/3} \quad (7)$$

where L and W are the fault length and fault width of the target event, respectively; l and w are the length and width of unit area of the fault grid, respectively; M_0^{target} is the seismic moment of target event.

This approach is based on the assumption of self-similarity of EGF and target events (Aki 1967), which, in this definition, implies proportionality between slip and rupture length.

To satisfy the assumption of similarity between EGF and the target event in eq. 5, the two events should share the characteristics of focal mechanism, location and stress drop. Based on the applications of Del Gaudio et al. (2015, 2018), an earthquake should satisfy the following criteria to be used as EGF: 1) its location should be close enough to that of the target event; 2) its focal mechanism should be compatible to that of the target event (difference of faulting angles must be less than 15° and 30° for dip and strike, respectively); 3) its magnitude should allow for a sufficient signal-to-noise ratio; and, at the same time, it should be at least 2 points smaller than the target magnitude.

2.2.2 Single-EGF vs Multi-EGF approaches

The difference between the single- and multi-EGF approaches lies in the way one associates the grid points of the fault plane with EGF(s): in the single-EGF approach, all the grid points use the same EGF for convolution; in the multi-EGF approach, the nearest EGF to grid point is used. The multi-EGF approach can provide better approximation of observations, as evidenced by past studies (Del Gaudio et al. 2015; McGuire & Ben-Zion 2017; Del Gaudio et al. 2018). As mentioned in Introduction, in case of scarcity of successive recordings, the difference of focal mechanism between the potential EGF events can critically increase such that EGF selection can become another factor of ground motion variability. Therefore, given the moderate seismicity of the studied zone, we considered both approaches in our analyses for further comparison.

The multi-EGF approach requires a few corrections to bring all the EGFs to an equivalent energy level and to account for differences between d^{point} (distance between station and grid point), and d^{hypo} (distance between station and EGF hypocentre). We apply the following steps:

(i) adjustment of EGF spectra to the same shape (see section 3.3.1);

(ii) correction of differences in geometrical spreading: each convolution term, for each grid point, is multiplied by d^{point}/d^{hypo};

(iii) time shift correction: for each grid point, the source time function is shifted by:

$$t_{shift} = \frac{d^{point} - d^{hypo}}{\beta} \tag{8}$$

where β is average shear velocity. We use $\beta = 4.5$ km/s, which is the average S-wave value from Paulatto et al. (2017) tomographic model in the 35-55 km depth range, where the synthetic faults are placed (see next section).

3 EGF SELECTION AND EARTHQUAKE SCENARIOS

In this section, we detail the procedure that we followed to select and correct the empirical Green's functions, and the preparation of earthquake scenarios.

3.1 EGF selection

We extracted from the catalogue of the IPGP Lesser Antilles observatories (see Data and resources) 423 events, between 01/01/2014 and 02/06/2018, whose epicentral locations are within a polygon offshore Martinique, as shown in Fig. 1. The depth of the selected events range between 0 and 196 km. The events follow the general trends of the subduction zone in terms of depth: they advent as a mix of crustal, interface, and intraplate events (see the discussion in Introduction). Thus, it is important to closely examine their depth and focal mechanism.

The catalogue only comprises events which have been recorded at each of the four broadband stations of the 'West Indies' network in Martinique (WI, IPGP 2008c; Anglade et al. 2015): BIM, ILAM, MPOM, and SAM (station locations shown in Fig. 2). We have limited knowledge of site conditions, essentially based on geological maps (Bureau de recherches géologiques et minières 2018): ILAM and MPOM are on rock, BIM and SAM are on soft soils (SAM is on volcanic ash and pyroclastic flow deposits), and site effects can be present at BIM and ILAM.

Out of the 423 events in our initial catalogue, only three could be selected as EGFs, based on the criteria of distance, magnitude, and focal mechanism discussed in Section 2.2.1. In particular, the desired EGFs: i) are located, in depth, in proximity to the subduction zone, as does the M_w 5.8 earthquake of 03/02/2017 that we use as reference; ii) have a magnitude in the interval of 3.5-5.5; iii) have a focal mechanism of reverse faulting—, and sticking to the flat-thrust characteristic of our target event, we only searched for events in the depth range of 25-65 km. Fig. 2 show the locations of the three events that satisfy these criteria while Table 1 provides details on these EGFs. (Details on the determination of focal mechanism of the catalogued events are provided in SI. Moreover, note that, at the moment of submitting this article, a new solution for EGF II was made available in the catalogue—event `ipgp2017hushqz`, see Data and resources—, with a slightly different location; we tested the effect of using this new solution on ground motion variability and verified the validity of the conclusions of the present work, as detailed in SI.)

We determined the source properties of the selected three events (moment magnitude, corner frequency and stress drop) by using the SourceSpec software (Satriano 2020). SourceSpec calculates the earthquake source parameters for an event by inverting the S-wave displacement

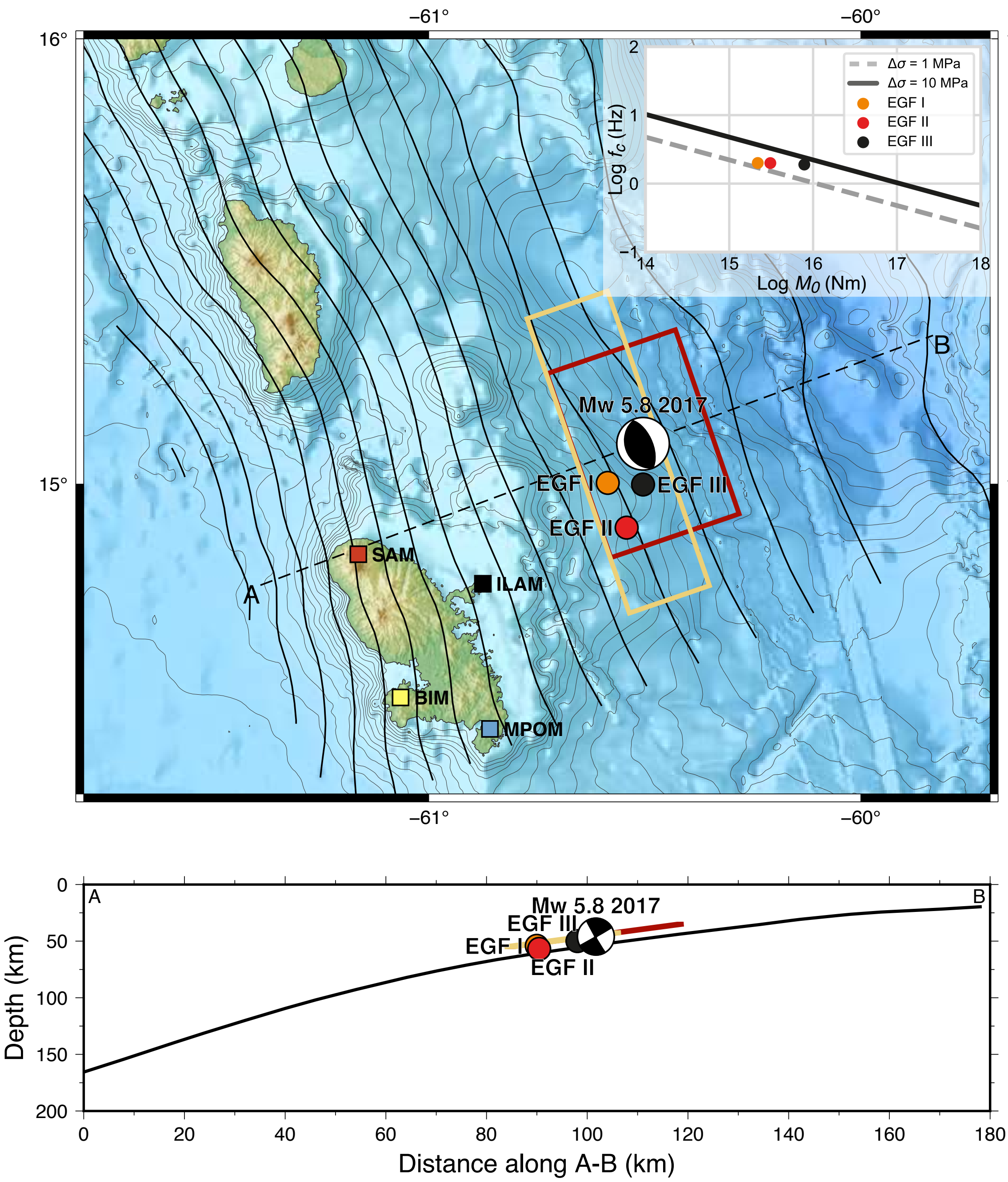

Figure 2. Source and station locations, and source properties of the selected EGFs. Map view of the four selected Martinique stations (WI network), the two fault geometries, the selected EGF events and the focal mechanism of the 2017 M_w 5.8 earthquake (top), and vertical section showing the EGFs and the 2017 focal mechanism (bottom). The slab geometry (from Paulatto et al. 2017) is represented by contour lines (10 km depth interval) in top panel and by the solid line in the depth section. Embedded figure displays the corner frequency vs. seismic moment for each selected EGF.

Table 1. Catalogue information (ID, origin time, location, M_L) for the EGFs used in this study and source properties (M_w, f_c, $\Delta\sigma$) obtained from SourceSpec analysis.

EGF	Catalogue ID	Origin Time (UTC)	Long. (° E)	Lat. (° N)	Depth (km)	M_L	M_w	f_c (Hz)	$\Delta\sigma$ (MPa)
I	`ipgp2016fkyaql`	2016-03-17T18:31:26	-60.56	15.00	54.1	4.12	4.16	2.00	1.99
II	`ipgp2017hushqx`	2017-04-21T10:13:01	-60.54	14.90	56.8	4.82	4.26	1.99	2.89
III	`ipgp2017seplqy`	2017-09-15T10:58:31	-60.50	15.00	50.0	5.04	4.53	1.90	6.16

spectra from the recordings of multiple stations. The mean values of source parameters are computed by the average of the results of all the stations. The standard deviation of each parameter is also calculated; it can increase due to certain factors such as local soil conditions and/or poor signal quality at station. Therefore, we used all available data (stations from networks CU, G, GL, MQ, NA, and WI; network information is detailed in Data and resources) and disregarded the stations with relatively high deviation to increase the robustness of the solution. Table 1 lists the results of moment magnitude M_w, corner frequency f_c, stress drop $\Delta\sigma$ for each selected EGF.

In the following, we will only consider moment magnitudes. Fig. 2 shows the relation between corner frequency and seismic moment of each event with respect to stress drop. The stress drop of each EGF is between 1 and 10 MPa. The stress drop of EGF III is notably higher than that of the other two events.

3.2 Earthquake scenarios

We prepared a set of earthquake scenarios for an interplate M_w 7.5 earthquake, comprising of 320 different kinematic rupture models. To take into account different aspects of source kinematics, we constructed a logic tree where each branch explores a different source parameter (Fig. 3). In the following, we briefly explain these aspects by hierarchical order.

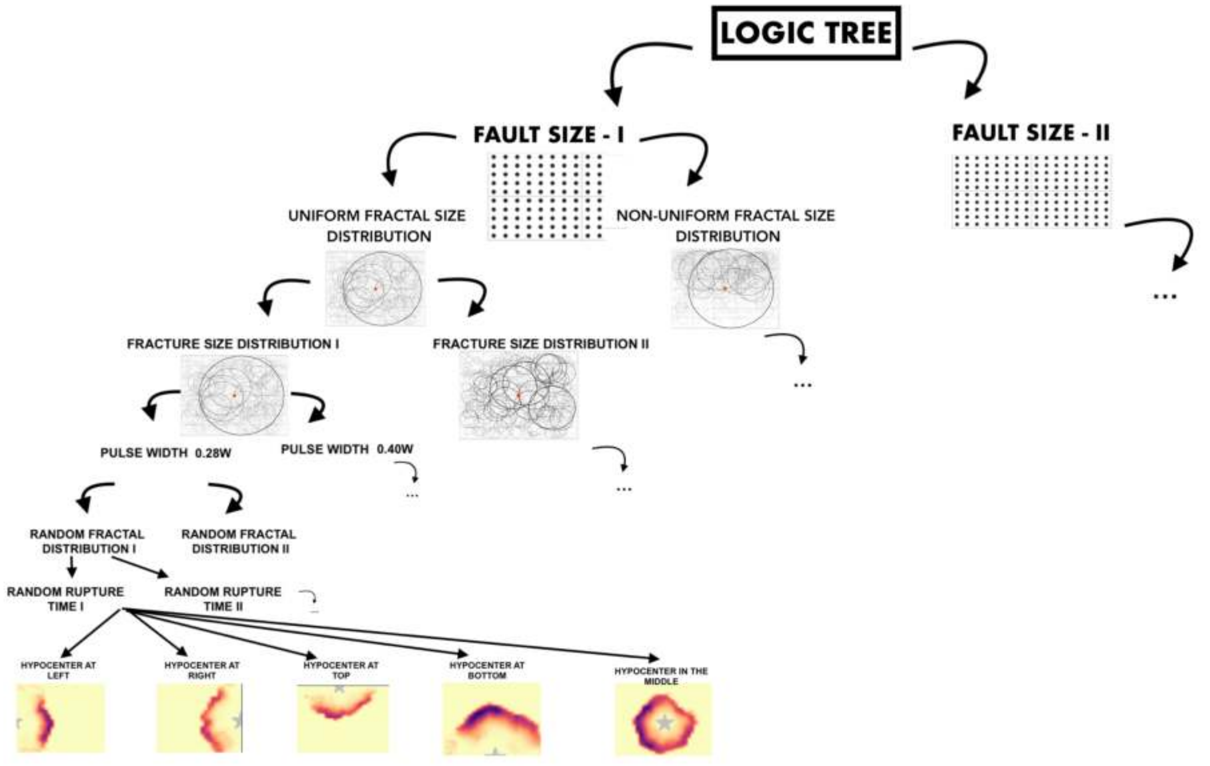

Figure 3. Illustration of the logic tree organisation for generating earthquake scenarios. Three dots indicate the repetition of sub-branches similar to those of neighbour branch.

3.2.1 Fault geometry

The logic tree starts with the main branches of fault geometry. We created two models: 1) a fault with a low aspect ratio (square-like) with dimensions of 50 km $\times$ 40 km; 2) a fault with a high-aspect ratio (rectangular) with dimensions of 80 km $\times$ 25 km.

We fixed the fault location and orientation based on a reference event, the 03/02/2017 M_w 5.8 earthquake (Fig. 2). The focal mechanism of this event was reported as reverse faulting with strike, dip and rake angles of 161°, 30° and 94°, respectively, and hypocentre is located at 46 km depth (SCARDEC data by Vallée et al. 2011). We set our maximum fault depth to 55 km in all cases, by respecting the past documentation on seismogenic zone (e.g., Paulatto et al. 2017). We defined the midpoint of the first type of fault geometry at the hypocentre coordinates of the 03/02/2017 event (15.090° N, 60.504° W). In this way, the fault plane extends between 35-55 km and 42.5-55 km depths for the first and second types of geometries, respectively. Fig. 2 depicts the location of two fault geometries in map view and cross section. The alignment of fault planes are slightly shallower with respect to the slab, but in good agreement with the depth of recorded events.

3.2.2 *Spatial distribution of sub-sources*

We created two sub-branches to test the effect of using uniform or dip-varying spatial distribution of large sub-sources. In uniform-distribution model, we evenly distributed the sub-sources all over the fault plane; in dip-varying distribution model, we define the along-dip probability to have a sub-source as:

$$P(d) = cos^9 \left(\frac{\pi d}{2W} \right),$$

where d is the along-dip distance and W is fault width: $P(0) = 1$ at fault top; $P(W) = 0$ at fault bottom. The power of nine was arbitrarily chosen to increase the relative probability close to the fault top with respect to the fault bottom. From this probability function, we define a sub-source size-dependent probability

$$\bar{P}(R, d) = P(d)^{\gamma(R)}$$
$$\gamma(R) = \frac{R - R_{min}}{R_{max} - R_{min}}.$$

Hence, for the largest sub-source, the probability density function equals $P(d)$; and for the smallest one it equals 1, i.e., being uniform over the fault plane.

3.2.3 *Sub-source size*

We tested the effect of the presence of the largest sub-source, with diameter equal to fault width. The first sub-branch allows for a relatively large range of sub-source sizes: the largest and smallest radii equal 100 % and 5 % of fault width, respectively. We lowered the largest radius to 50 % in the second group.

3.2.4 *Pulse width, L_0*

As mentioned in Section 2.1, this parameter produces a low-pass filtering effect on slip spectrum, and hence can influence the ground motion amplitude. We tested the power of such influence by adding two sub-branches: 1) $L_0 = 0.28$; 2) $L_0 = 0.4$. More explanation on why we have chosen these values is provided in Supplementary Information (SI).

3.2.5 Random parameters, `idum1` and `idum2`

The numerical tool that we use incorporates two parameters, `idum1` and `idum2`, that control the randomness of the spatial distribution of sub-sources and propagation of rupture front on fault grid, respectively. We created two additional orders of sub-branches to account for each of this randomness.

3.2.6 Rupture directivity

We created a last order of sub-branches to test the effect of rupture directivity, by varying the hypocentre location. We prepared five cases based on the relative location of hypocentre on fault plane: left, right, top, bottom, centre.

3.3 EGF correction and coupling with kinematic rupture model

3.3.1 EGF correction

We adjusted all selected EGFs to the same spectral shape that corresponds to a reference spectrum for a M_w 4.2 event. The philosophy of EGF correction is to reduce significant variation of ground motion amplitudes that can possibly arise from the difference of stress drop of selected EGFs (Hutchings et al. 2007; Del Gaudio et al. 2015). For the reference spectrum, we set the stress drop, corner frequency, and seismic moment to the mean of EGFs' values: 1.917 MPa, 2.027 Hz, and 2.5119 $\times 10^{15}$ Nm, respectively. For each station record of each EGF, the adjustment procedure applies as follows:

(i) computation of the Fourier transform of displacement;

(ii) conversion of displacement spectrum in seismic moment unit;

(iii) deconvolution (amplitude division) of the converted spectrum by Brune's spectrum that corresponds to the corner frequency and seismic moment of the uncorrected EGF—this step is similar to the application in Dujardin et al. (2016);

(iv) multiplication of the deconvolved spectrum with the mean seismic moment.

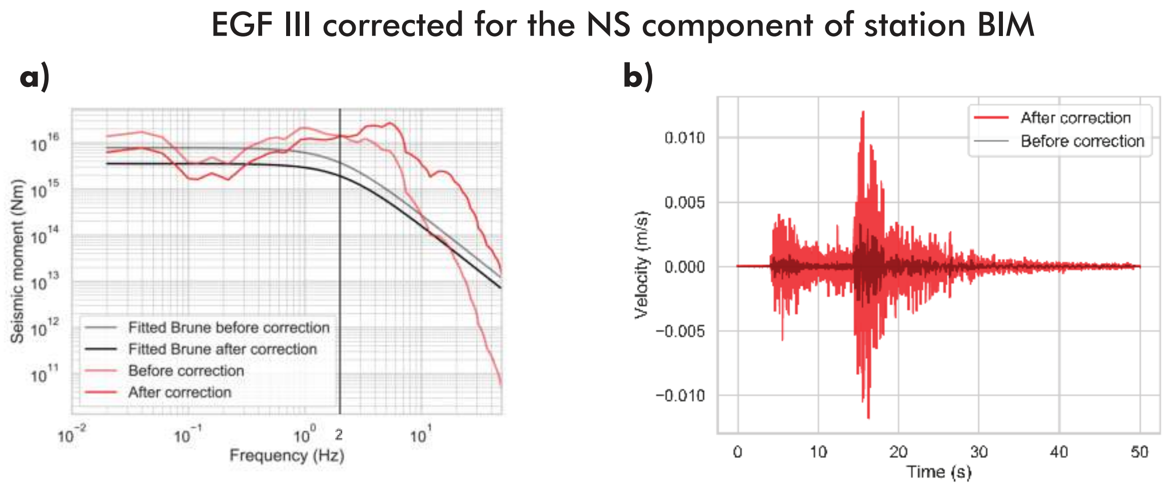

Figure 4. Example of EGF correction. a) Moment spectra of the north-south component of EGF III signal at station BIM before and after correction. b) Velocity-time histories before and after correction.

Operations of steps (iii) and (iv) would provide a flat spectrum beyond the corner frequency when inelastic attenuation is ignored. Here however we preserve the attenuation information on the final spectrum by not including anelastic (and geometric) attenuation in the Brune's spectrum which is deconvolved in step (iii). Final step of signal processing includes: removal of instrumental response, detrending, and band-pass filtering in the frequency band of 0.01-49 Hz.

Fig. 4a shows an example of spectral adjustment of EGF III for the north-south component of station BIM. All the spectra are smoothed with a Hanning window of the 5^{th} degree. We see in the example that the spectrum is deamplified after correction at frequencies below the corner frequency of reference spectrum ($\sim$ 2 Hz) since the seismic moment of the uncorrected EGF is higher than the reference one. The flattening effect of EGF adjustment beyond corner frequency produces an amplification at frequencies above $\sim$ 2 Hz; however, due to the preserved inelastic attenuation, the resultant spectrum still shows a decay for frequencies above $\sim$ 7 Hz. The resulting signal in time domain depicts notable amplification—up to 4 times for peak values—throughout the signal duration due to correction, as shown in Fig. 4b.

3.3.2 Coupling with kinematic rupture model

We discretisized the fault plane based on the ratio of seismic moment between the target and EGF events, that equals 4. Referring to eq. 7, our fault grid contains 1600 points for all rupture models.

For each grid point, the corresponding source time function is convolved with the nearest EGF in 3D space. One example of such partition for the case of a fault with low-aspect ratio (the 1^{st} type of fault geometry in the logic tree) is given in SI (Fig. S1). We then made additional corrections as detailed in Section 2.2.2. The modelled ground motion at a station issued by the target earthquake equals the sum of the corrected convolutions. The velocity and density profile that we used is provided in SI.

The frequency band which we considered for ground motion modelling is 0.5-25 Hz, based on signal quality. We further analysed the signal-to-noise-ratio (SNR) of each EGF recordings for each station. Except for the cases with slightly lower SNR values, all the cases provide SNR values above 5 in the frequency band of 0.5-25 Hz. Therefore, we will refer to this frequency band in the evaluation of our ground motion models.

4 RESULTS

We evaluate the results for the 320 simulated scenarios, through the following parameters: peak-ground acceleration (PGA), spectral acceleration (SA) values at 1, 2 and 5 Hz, and Arias intensity. We made these analyses on the maximum of the three components. Lancieri et al. (2015) showed that these are the most influential parameters on seismic structural analysis.

4.1 Fault geometry and sub-source size cause the highest variability of ground motion

The first question we wanted to address is: ‘Which aspect of the source controls ground motion variability?’. To answer this question, we evaluated the model outputs by considering each branch of the logic tree (Fig. 3). To account for both amplitude and energetic content of the calculated ground motion, we disaggregated the simulation results based on PGA and peak Arias intensity. Fig. 5 shows disaggregation for station ILAM (the analyses on the other stations lead to the same conclusion, as shown in SI). Our analyses on all four stations highlight a distinctive clustering due to the fault geometry and sub-source size: a low aspect ratio of fault geometry brings relatively low energetic ground motion (cluster A); whereas, a high aspect ratio of fault geometry together with smaller slip asperities—i.e., a rectangular fault where sub-

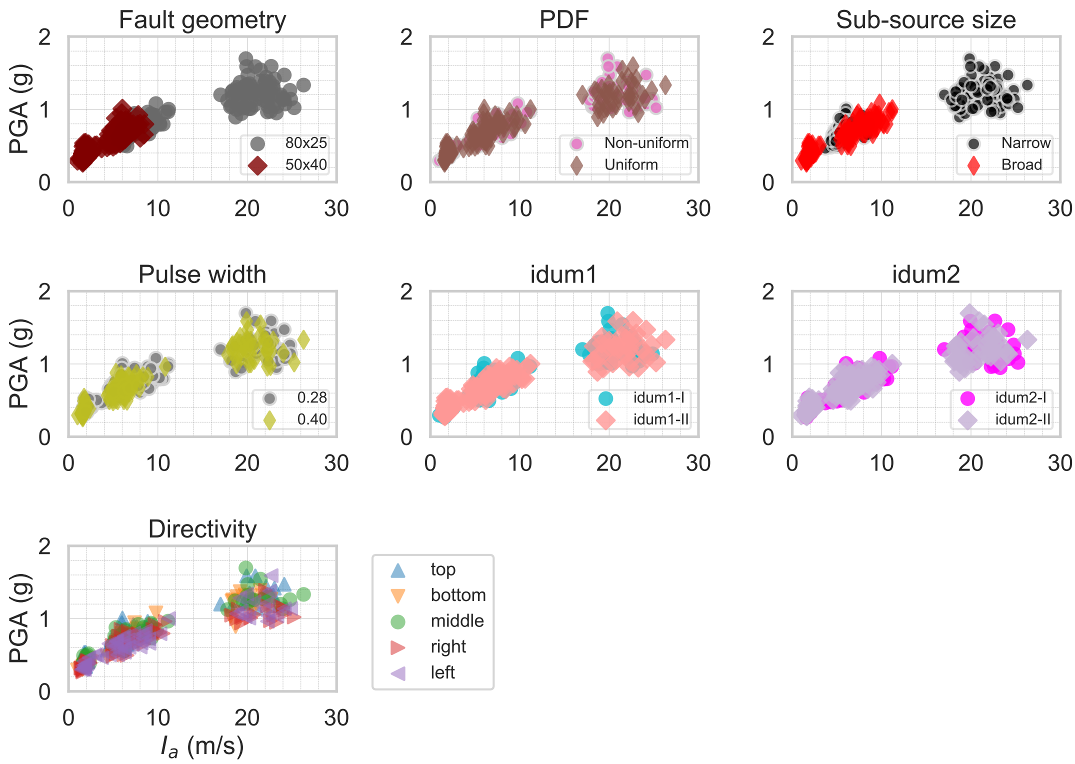

Figure 5. Disaggregation of computed ground motion by PGA and peak Arias intensity for station ILAM. We classified the results by different parameters in each diagram: by fault geometry, spatial distribution of sub-sources (PDF), sub-source size, pulse width, `idum1`, `idum2`, and directivity. The choice of fault geometry and sub-source size parameters are the causative factors of two distinct clusters, which we call 'A' and 'B'.

sources larger than 50% of fault width are forbidden—results in a notable amplification of peak ground motion (cluster B).

Such clustering implies a significant change of wave energy throughout the signal duration and in a broad frequency range (0.5-25 Hz). We picked a representative case from each of the above-mentioned two clusters A and B. We compared the two cases by acceleration-time histories, their Fourier amplitudes, and temporal change of Arias intensities. Fig. 6 displays this comparison for all stations. The cluster B case evicts a higher level of wave energy at all stations: PGA is approximately 2.5 times higher, and the peak Arias intensity can reach to 10 times higher values for all stations.

We found that the combination of a fault geometry with a high aspect ratio and a spatially-condensed largest slip distribution, i.e., smaller patches with greater slip values, makes a double effect of amplification of source energy; and, this double energy boost leads to the clustering of

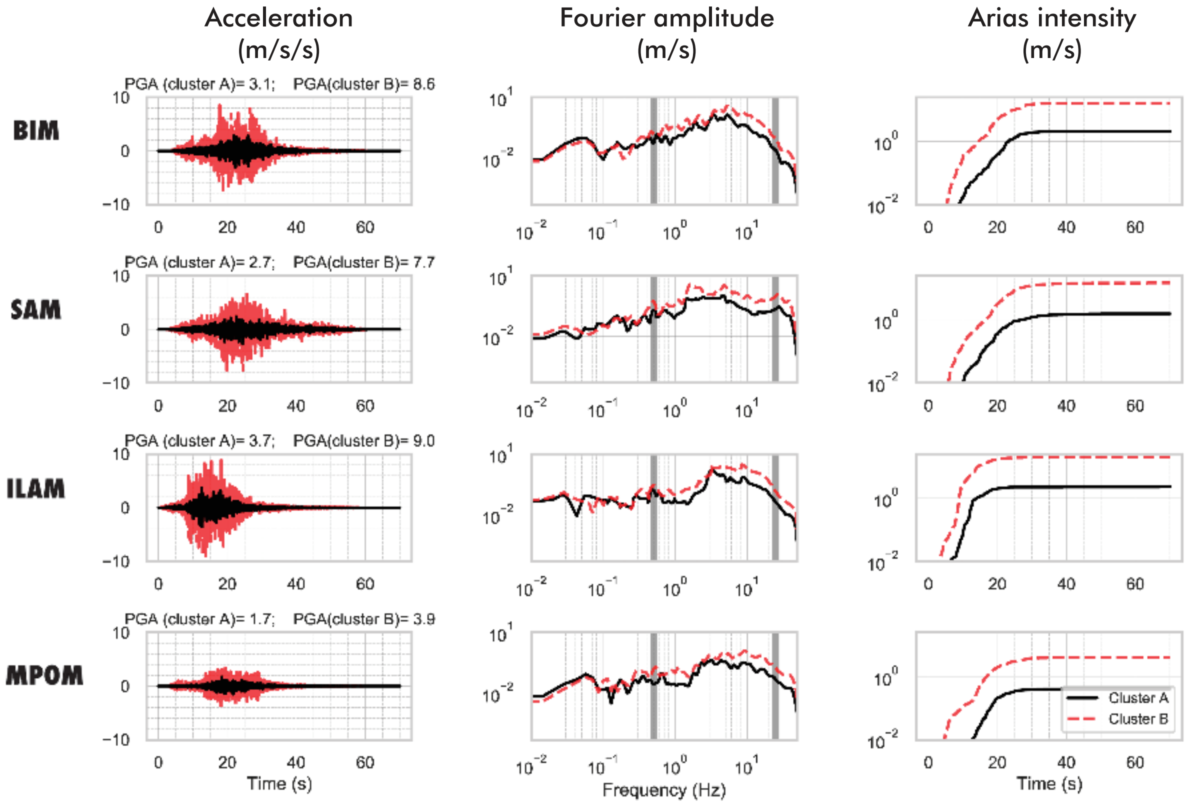

Figure 6. Comparison of acceleration-time histories (left panel), Fourier amplitude (middle panel), and Arias intensities (right panel) between cluster A (in black) and cluster B (in red) (see Fig. 5). We used the north-south component of signals in each comparison. Each row corresponds to the results of a station: BIM, SAM, ILAM, and MPOM, from top to bottom, respectively. The frequency band of 0.5-25 Hz is indicated by grey bars.

ground motion. We compared the two clusters by sub-source distribution (a), final slip distribution (b), and STF (moment-rate time function) and moment spectra (c) (Fig. 7). Our analysis evidences that:

(i) The presence of the sub-source with a diameter equal to fault width (cluster A) results in a spatially extensive slip asperity such that a significant part of the fault plane undergoes relatively large slip. Yet, the lack of such big-size sub-source (cluster B) results in a slip distribution where the largest values are spatially concentrated in relatively small patches. This leads to a partial amplification of source energy in the whole frequency band, in particular above 1 Hz.

(ii) The fault geometry with high aspect ratio (cluster B) can result in a rupture propagation that is longer and in a composite source-time function with multiple peaks and shorter rise time—individual slip-rate functions become spiky (short rise time) in the cluster B case, differ-

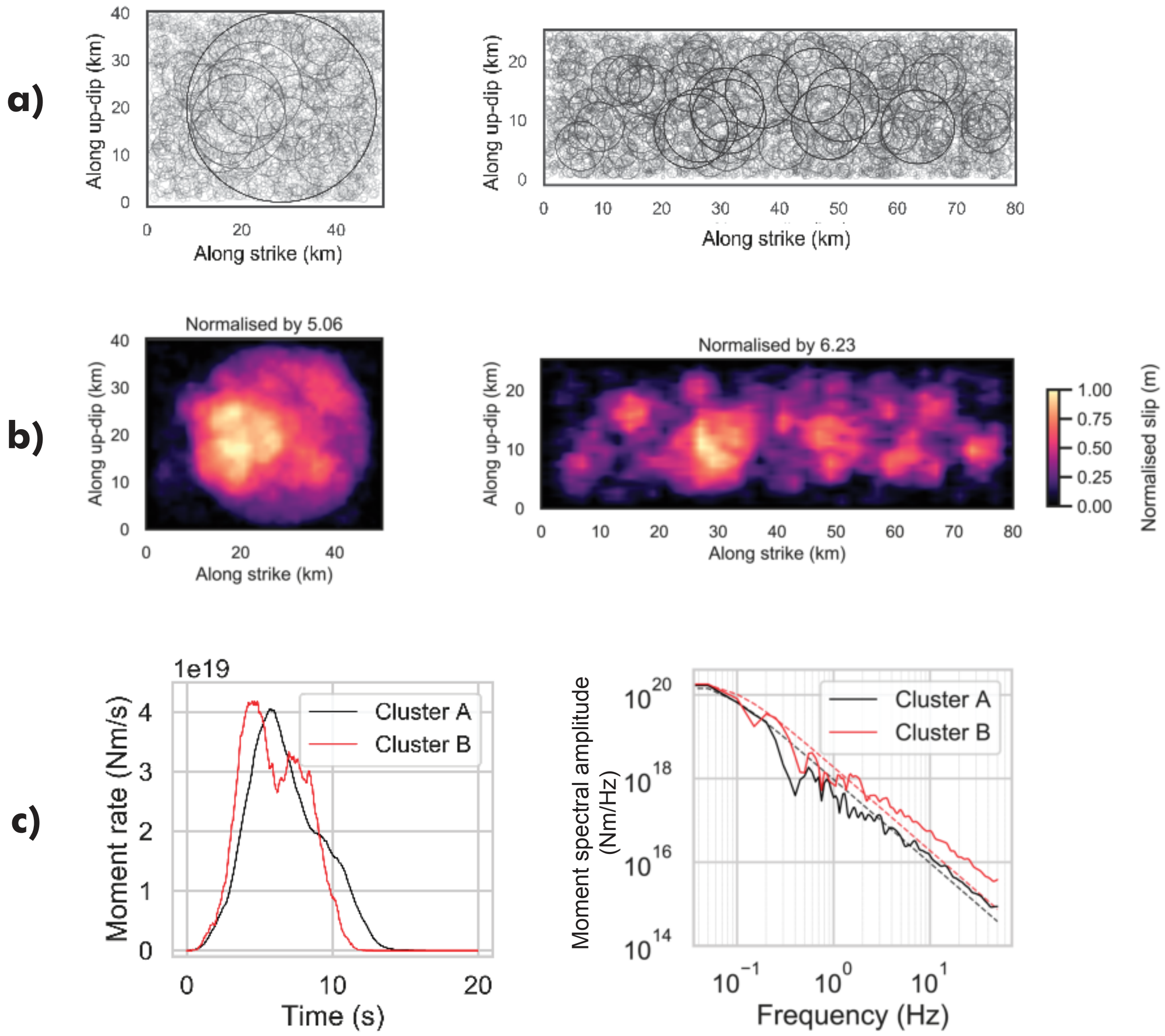

Figure 7. Comparison of source features of the two clusters shown in Fig. 5. a) Comparison of cluster A (left panel) and cluster B cases (right panel) by sub-source distribution. b) Same as a for final slip distribution. c) Comparison of source-time function (left panel) and moment spectra (right panel) between cluster A (in black) and cluster B (in red) cases.

ently than the case of cluster A that has smooth STFs (see details in SI). This complexity also partially contributes to the energy amplification in the whole frequency band.

4.2 Comparison with GMPE: source-related variability influences the compatibility of estimated ground motion with GMPE

The second question we wanted to address is: 'How important is the source-related ground motion variability with respect to the GMPE?'. In previous section, we evidenced two clusters of synthetic ground motion due to the differences of source definition. Here, we evaluate this ground-motion variability by referring to the compatibility of modelled data with GMPE.

Bozzoni et al. (2011) compiled all the available databases in Eastern Caribbean Islands and analysed different GMPEs that have been developed for other regions with similar seismotectonic settings. They recommend the GMPE of Zhao et al. (2006) for the type of events we study here, namely plate interface earthquakes with a reverse faulting mechanism. A similar conclusion was made in a later study by Douglas & Mohais (2009). The GMPE of Zhao et al. (2006) consists of four soil categories: rock, hard soil, medium soil, and soft soil. In the absence of a detailed knowledge on site conditions, we have chosen the site condition of soft soil. We verified by using other site conditions that this choice only causes slight variations of amplitude and does not change our conclusions (see figures in SI).

The two clusters of synthetic ground motion have two different levels of ground motion amplitude by distance. The compatibility of these trends with GMPE, for M_w 7.5 strongly depends on frequency and station. Fig. 8 shows the comparison of synthetic ground motion and GMPE curves for spectral acceleration (SA) analyses at 1, 2, and 5 Hz. We make the comparison separately for each station, and the hypocentral distance at each simulation varies based on the definition of hypocentre. In general, cluster B is associated with higher amplitude of ground motion at all distances. At 1 Hz, the majority of the synthetic ground motion agrees well with GMPE for stations BIM and SAM; but, the ground motion at the same frequency is mostly underestimated for stations ILAM and MPOM. At 2 Hz, SAs for cluster A align with mean GMPE predictions for the stations BIM and SAM, whereas they are closer to lower limit of GMPE predictions for the other two stations. At 5 Hz, the cluster B entirely overestimates the GMPE predictions for all stations except for MPOM, and the agreement of the first cluster with GMPE still remains station-dependent. The comparative analysis of PGA prediction between the synthetic data and GMPEs gives the same conclusion as we show here for SA at 5 Hz: the synthetic data in cluster B overestimates the GMPE predictions for all stations, and the cluster A data mostly fall into the predicted range of GMPEs for only MPOM (details provided in SI).

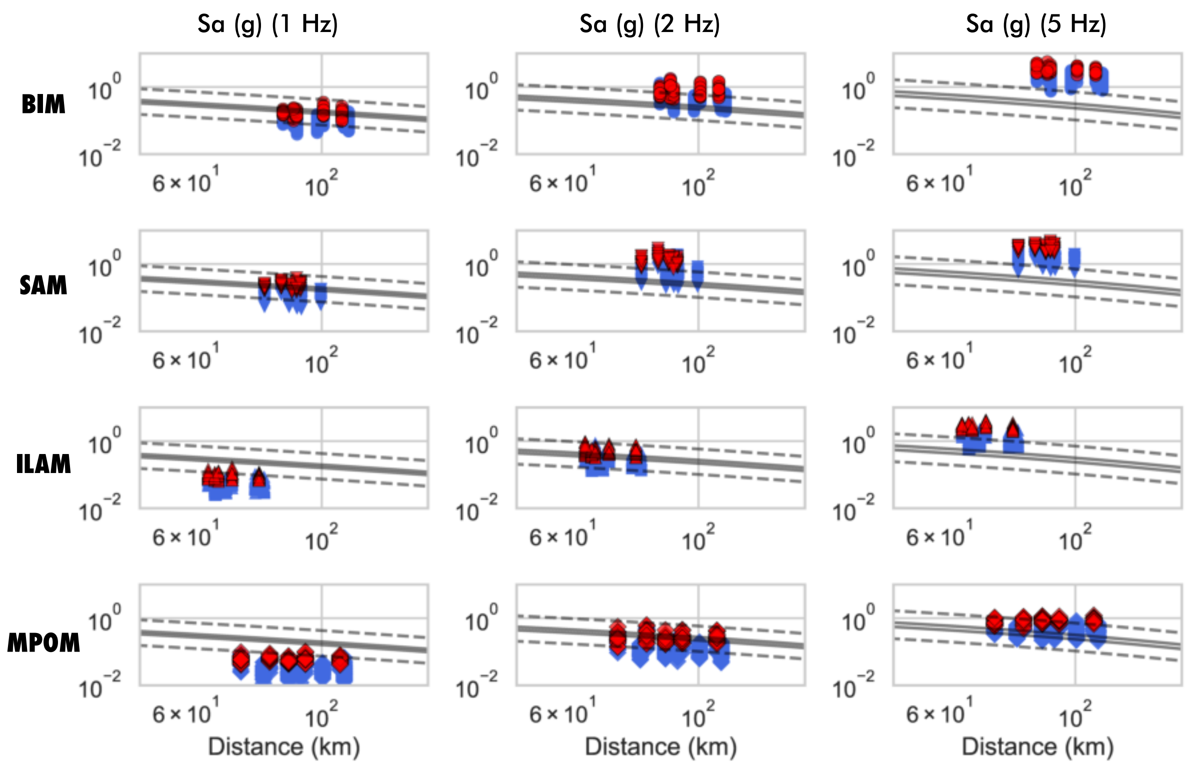

Figure 8. Comparison of cluster A (in blue) and cluster B (in red) cases of synthetic ground motion with GMPE curves from Zhao et al. (2006) (in gray) by spectral acceleration at 1 Hz (left panel), 2 Hz (mid-panel), and 5 Hz (right panel). Mean GMPE curves are shown in solid lines; the lower and upper limits of GMPE curves are shown in dashed lines. Each row stands for the analysis of a station: BIM, SAM, ILAM, and MPOM from top to bottom, respectively.

4.3 EGF selection can emerge as a station-dependent factor of ground-motion variability

The third question we aimed to address is: 'Does EGF selection further influence ground motion estimations'? The analyses in previous sections were based on the multi-EGF approach in order to focus exclusively on the effects of source-related factors on ground motion variability. Here we explore the role of the EGF selection by repeating the logic tree simulations for each single-EGF use.

We found that the predicted ground motion can be highly sensitive to EGF selection: the energy difference of EGFs in a specific frequency band can become a factor of ground-motion variability despite the EGF corrections. We categorised the synthetic data by EGF use as shown

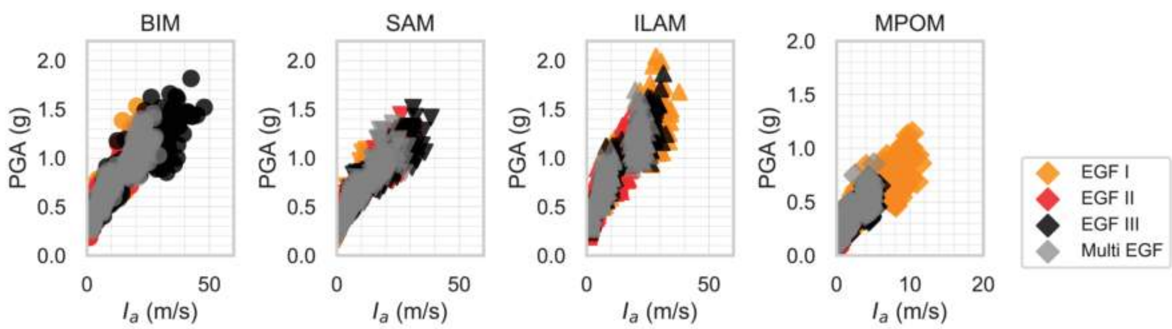

Figure 9. Effect of EGF selection on ground motion. Comparison of peak ground acceleration vs peak Arias intensity results between all EGF approaches. Each diagram shows the results for a station.

in Fig. 9. Stations BIM and MPOM exhibit notably higher ground motion amplitudes for the use of EGF III and EGF I, respectively.

5 DISCUSSION

5.1 Variation of ground motion between stations

The range of ground motion amplitude strongly varies between the four stations; In general, we computed a weaker ground motion amplitude for station MPOM compared to other stations. Fig. 10 shows histograms and kernel density estimations (KDE) of computed PGA for all performed simulations. KDE is a way of visualising the shape of the sample distribution (Parzen 1962; Davis et al. 2011); it is defined as the normalised sum of kernel functions of a certain width computed on the data samples (here we use Gaussian kernels of standard deviation 0.27, 0.26, 0.32, and 0.15 g for stations BIM, SAM, ILAM, and MPOM, respectively; details on KDE can be found in the reference provided in Data and resources). The results point to a similarity between three stations, BIM, SAM and ILAM, in terms of amplitude and standard deviation: Average PGA of the cluster A ranges between 0.57 and 0.75 g for the three stations. On the other hand, this value lowers to 0.31 g for station MPOM. The peak kernel density notably increases, approximately twice, at station MPOM due to the narrow range of PGA, i.e., limited variation, compared to the other stations.

A detailed site characterisation is essential to better assess the variation potential of ground motion between the stations and understand the reason behind it. Recall that we found that the

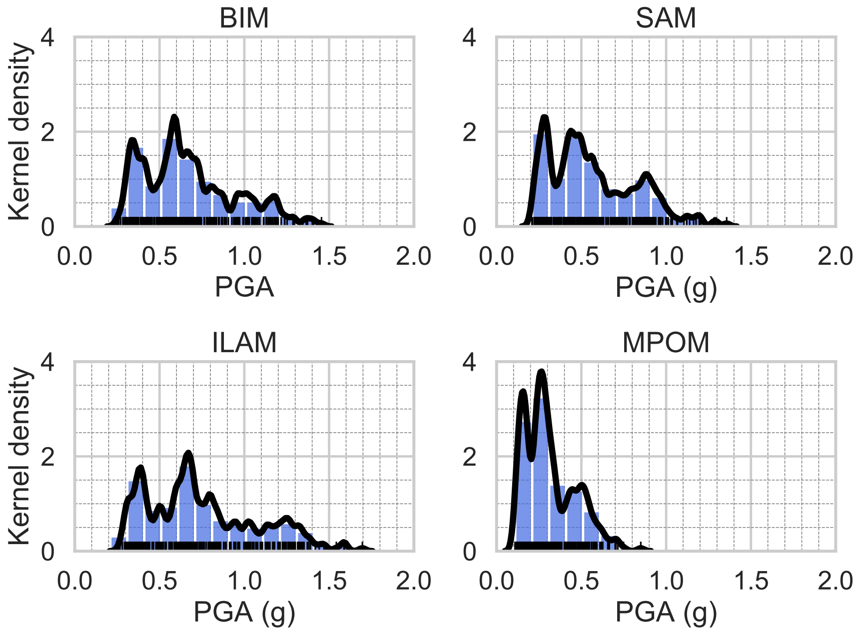

Figure 10. Histograms of peak ground acceleration values at each station, associated with kernel density (black curve). Each rug stands for a simulation result.

significance of ground motion variability with respect to GMPE and the potential of further variability due to EGF selection are station-dependent. Our current knowledge about site conditions is limited and does not allow for further interpretations of the variation of ground motion between stations in our results. Additional analyses to characterise site effects at Martinique stations—as applied in Guadeloupe (Castro et al. 2003)—would be helpful for future seismic hazard studies in Martinique. Moreover, EGF method considers a similarity of the source-to-site propagation path between EGF and target earthquake; it cannot account for further variation of ground motion due to possible site-related complexities due to a strong earthquake. We target a magnitude 7.5 earthquake, and further variation of ground motion due to complex soil behaviour (e.g., soil nonlinearity, and liquefaction) under such a strong earthquake is possible as known by past observations and numerical studies (e.g., Aguirre & Irikura 1997; Ghofrani et al. 2013; Régnier et al. 2013; Oral et al. 2019). Further research on this aspect, together with an enhanced site characterisation, can take the variability analysis a step forward.

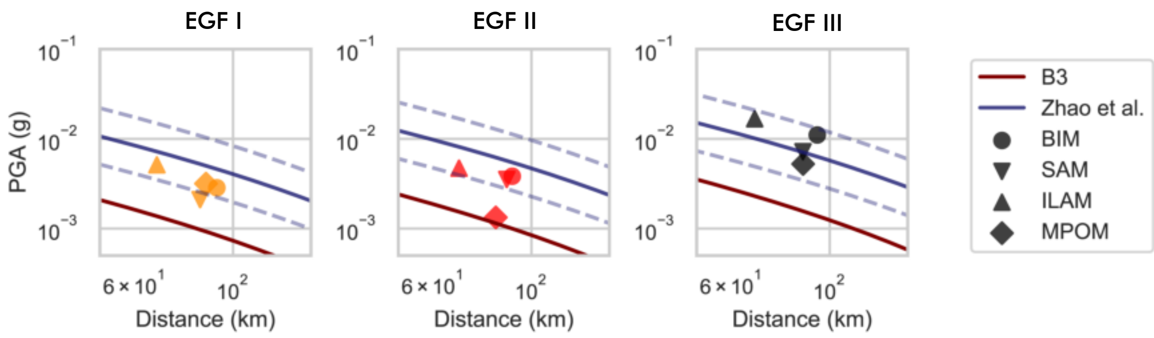

Figure 11. Comparison of PGA prediction curves of Zhao et al. (2006) model (in gray) and B3 model (in red) with observations at four stations: BIM, SAM, ILAM, and MPOM. Results are shown for the three selected EGF events: EGF I (left panel), EGF II (mid-panel), and EGF III (right panel).

5.2 Need for an improved regional GMPE

The absence of a regional GMPE for a magnitude 7.5 earthquake is another limitation for the interpretation of our results; the only regional GMPE, the 'B3' model (Beauducel et al. 2011), also needs revision for moderate events. Here we used the GMPE of Zhao et al. (2006), that was developed with Japanese data, to analyse our synthetic ground motion data, since the B3 model is not recommended for M $\geq$ 6.5 earthquakes. Although past studies qualify the Zhao et al. (2006) GMPE as the best representative of our target earthquake, Kotha (2018) states that the use of a GMPE that has been developed with the data from a different region can become non-ergodic due to the differences of crustal characteristics. Therefore, according to the latter, such GMPEs require additional adjustments of ground motion before application to other regions. In that sense, future mitigation studies would benefit from further research on GMPE applications.

We compared the B3 model and Zhao et al. (2006) GMPE with the EGF recordings, in a range of magnitudes (4.2–4.5) where both GMPEs are valid (Fig. 11). B3 model underestimates all the three events, whereas Zhao et al. (2006) is mostly in agreement with observations. This incompatibility also points to further need to improve regional GMPE applications.

6 CONCLUSIONS

A future M > 7 interplate earthquake is expected offshore Martinique. In this study, we investigated the potential sources of broadband ground motion variability mainly due to source kinematics for a hypothetical M_w 7.5 earthquake.

Our findings are:

(i) The fault geometry and the spatial extension of the largest slip patch are the most determinant source-related factors of ground motion variability. The combination of a rectangular fault with a high aspect ratio and condensed small slip asperities can result in a significant amplification of source energy. Such energy amplification manifests itself by a substantial increase of broadband wave energy and ground motion amplitude throughout the signal duration. We stress that we set the down-dip limit to 55 km, as suggested by Paulatto et al. (2017) for the coupled interface of the subduction zone; more studies are needed to constrain the further role of the fault geometry when considering different depths of the down-dip limit.

(ii) The significance of the source-related ground motion variability with respect to GMPE depends on the evaluated frequency of ground motion and station. Future research on the improvement of regional GMPE application and site characterisation is necessary to constrain the realistic range of ground motion and source parameters.

(iii) EGF selection can be another factor of ground-motion variability. The application of EGF technique for forward modelling in moderately seismic areas such as Martinique requires a special attention to EGF selection, because of potential energy differences between EGF events.

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Data and resources

The seismic catalogue for Lesser Antilles used in this study is available from OVSG & OVSM (2020). Note that event `ipgp2017hushqx` is not present in the catalogue, since it has been superseded by event `ipgp2017hushqz` (see discussion in EGF selection).

Waveform data from networks G, WI, GL and MQ (IPGP & EOST 1982; IPGP 2008c,a,b) was downloaded form the IPGP Data Center (`http://datacenter.ipgp.fr`). Waveform data from networks CU and NA (Albuquerque Seismological Laboratory (ASL)/USGS 2006; KNMI 2006) was obtained through the IRIS Data Management Center (`https://ds.iris.edu/ds/nodes/dmc/`).

The RIKsrf code, used for modelling kinematic source rupture, is available at `https://github.com/fgallovic/RIKsrf`. The SourceSpec code, used to determine earthquake source parameters, is available at `https://github.com/SeismicSource/sourcespec`.

Data analysis has been performed using ObsPy (Krischer et al. 2015). Figures have been produced using the Generic Mapping Tools (Wessel et al. 2019) and Matplotlib (Hunter 2007).

Explanation of seaborn library tools of Python to visualise kernel density plots can be found at `https://seaborn.pydata.org/tutorial/distributions.html` and `https://mathisonian.github.io/kde/`.

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