



## Internal geophysics

## Empirical model for rapid macroseismic intensities prediction in Guadeloupe and Martinique

*Modèle empirique pour la prédiction rapide des intensités macrosismiques en Guadeloupe et Martinique*François Beauducel<sup>a,\*</sup>, Sara Bazin<sup>b</sup>, Mendy Bengoubou-Valérius<sup>c</sup>, Marie-Paule Bouin<sup>a</sup>, Alexis Bosson<sup>a</sup>, Christian Anténor-Habazac<sup>a</sup>, Valérie Clouard<sup>a</sup>, Jean-Bernard de Chaballier<sup>a</sup><sup>a</sup> Institut de physique du globe de Paris, Sorbonne Paris Cité, Univ. Paris Diderot, UMR 7154 CNRS, 1, rue Jussieu, 75238 Paris cedex 05, France<sup>b</sup> Norwegian Geotechnical Institute, N-0806 Oslo, Norway<sup>c</sup> BRGM, Guadeloupe, 97113 Gourbeyre, Guadeloupe

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## ABSTRACT

We describe a simple model for prediction of macroseismic intensities adapted to Guadeloupe and Martinique (Lesser Antilles), based on a combination of peak ground acceleration (PGA) predictive equation and a forward relation between acceleration and intensity. The PGA predictive equation is built from a 3-parameter functional form constrained by measurements from permanent accelerometer stations, mostly associated with Les Saintes crustal earthquake (21/11/2004,  $M_w = 6.3$ ) and its many aftershocks. The forward intensity model is checked on a database of recent instrumental events of various origins with magnitudes 1.6 to 7.4, distances from 4 to 300 km, and observed intensities from I to VIII. Global sigma residual equals 0.8 in the MSK scale, suggesting a larger applicability range than the intermediate PGA predictive equation. The model is presently used by the French Lesser Antilles observatories to produce automatic reports for earthquakes potentially felt.

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## R É S U M É

Nous proposons un modèle simple de prédiction des intensités macrosismiques, adapté à la Guadeloupe et à la Martinique (Petites Antilles), basé sur la combinaison d'une loi d'atténuation des accélérations horizontales maximales (PGA) et d'une relation directe entre accélération et intensité. Le modèle prédictif des PGA est construit à partir d'une équation fonctionnelle à 3 paramètres contrainte par des données provenant de stations accélérométriques permanentes, principalement associées au séisme des Saintes (21/11/2004,  $M_w = 6.3$ ) et ses nombreuses répliques. Le modèle prédictif d'intensité est testé sur une base de données instrumentale de séismes récents, de magnitudes 1,6 à 7,4, de distances 4 à 300 km et d'intensités observées entre I et VIII. Le résidu RMS final est de 0,8 sur l'échelle MSK, ce qui suggère un plus large domaine d'applicabilité que le modèle intermédiaire des PGA. Le modèle est actuellement utilisé par les observatoires des Antilles françaises pour produire des communiqués semi-automatiques, lors de séismes susceptibles d'être ressentis.

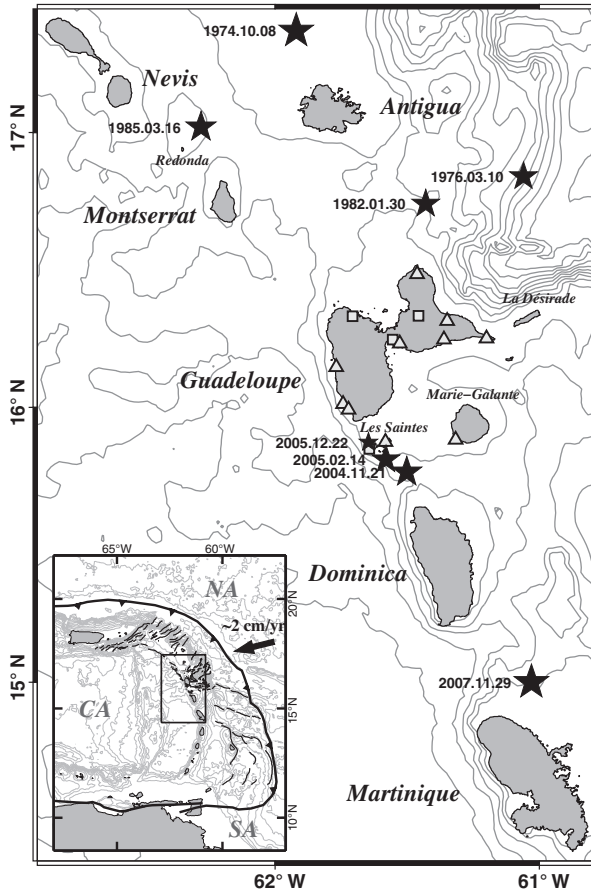
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## 1. Introduction

The Lesser Antilles arc is a zone of convergence between the American plate and the Caribbean plate at a rate of about 2 cm/yr (Lopez et al., 2006). This movement is absorbed by the subduction of the American plate below the Caribbean plate and deformation of the wedge of the upper plate on a 100–250 km-wide zone, producing an extended system of active crustal faults (Fig. 1 insert,



**Fig. 1.** Permanent network of digital accelerometers (TITAN AGECODAGIS, see <http://www-rap.obs.ujf-grenoble.fr/>) in Guadeloupe: soil (squares) and rock (triangles) site conditions (see Bengoubou-Valérius et al. (2008) for further details). Epicenters of some recent instrumental earthquakes are shown as black stars with dates (see text for details). Insert: Tectonic context of Lesser Antilles. CA = Caribbean plate, NA = North American plate, SA = South American plate. Black thick line with triangles: accretionary prism frontal thrust. Black lines: crustal faults from Feuillet et al. (2002). NA Euler vector of Lopez et al. (2006). Bathymetry data are 500 m contour lines (Smith and Sandwell, 1997).

**Fig. 1.** Réseau permanent d'accéléromètres du Rap (numériseurs Titan Agecodagis, voir <http://www-rap.obs.ujf-grenoble.fr/>) en Guadeloupe: conditions de site type sol (carrés) ou rocher (triangles) (voir (Bengoubou-Valérius et al., 2008) pour plus de détails). Les épicentres de quelques séismes instrumentaux sont indiqués par des étoiles avec dates (voir texte). Encart: contexte tectonique des Petites Antilles. CA = plaque Caraïbe, NA = plaque Nord-Américaine, SA = plaque Sud-Américaine. Courbe noire avec triangles: fosse frontale du prisme d'accrétion. Lignes noires: système de failles crustales d'après Feuillet et al. (2002). Vecteur d'Euler pour la plaque NA d'après Lopez et al. (2006). Données de bathymétrie: courbes de niveaux 500 m (Smith et Sandwell, 1997).

(Feuillet et al., 2002)). It results in a high seismicity level (about 1000 detected events per year) located on the subduction interface and within the slab with hypocentral depths ranging from 10 km up to 220 km, and within the deformed Caribbean plate with shallow crustal seismicity from 2 km up to 15–20 km in depth. Very shallow earthquakes occurring below/or very close to Guadeloupe archipelago islands can be felt sometimes with magnitude less than 2.0.

Since the French volcanological and seismological observatories (OVSG and OVSM) located in the Lesser Antilles are maintaining operational real-time seismic networks, they are responsible for detecting and informing local authorities and public of any felt earthquake occurrence and main event characteristics: location (epicenter and depth), type (tectonic or volcanic), magnitude, and maximum reported intensity in Guadeloupe and Martinique islands. Location and magnitude calculation are determined in a systematic way, using hand-picked phase arrivals and hypocenter inversion, and are available within few tens of minutes after an event, thanks to observatory permanent duty. Macro seismic intensities are determined later, as a result of detailed investigations in the field. However, in the case of a strongly felt earthquake, the first need of the local authorities is to get practical information on event location and maximum possible effects in the living areas. If this information can be delivered rapidly, it may be used to evaluate and focus assistance in the most affected zones.

On November 21, 2004, the occurrence of Les Saintes event,  $M_w = 6.3$  and thousands of aftershocks in few days (Bazin et al., 2010; Beauducel et al., 2005; Bertil et al., 2004; Courboulex et al., 2010; IGP, 2004) offered an exceptional new strong-motion database thanks to the French permanent accelerometric network (Pequegnat et al., 2008) installed in 2002–2004. Combined with collected testimonies and official intensity estimations for largest events, this provided a unique opportunity to establish a first local ground motion model adapted to the observatory needs.

In this article, we present the modeling strategy, dataset, results and applications of our empirical model. This work has been previously described in an internal report (Beauducel et al., 2005), named  $B^3$  (from initials of the three original authors), and is presently used in Guadeloupe and Martinique seismological observatories to produce automatic reports.

## 2. Methodology

Our goal is to produce a predictive model of macro seismic intensities with a final uncertainty of about one intensity level, paying special attention to the maximum values that will be published after each earthquake. To be usable in an operative way, the model must be applicable to a wide range of magnitudes and hypocentral distances, and, ideally, independently from its tectonic context or depth.

Due to insular configuration of Lesser Antilles, most of epicenters occur offshore: it concerns 95 of  $M \geq 2.5$  detected events (OVSG-IPGP database). Classical macro seismic intensity models cannot be used because they are

based on maximum intensity at epicenter,  $I_0$  (see for instance Pasolini et al. (2008), Sorensen et al. (2009)), a meaningless parameter for offshore events. Moreover, we do not have sufficient intensity data to well-constrain a predictive model for intensities. We have then proceeded by combining, first, a ground motion predictive equation (GMPE) constrained by peak ground accelerations (PGA) local data, and second, applying a forward empirical relation between intensities and accelerations.

Many empirical relations to predict earthquake ground motions have been developed for engineering purposes (see Abrahamson and Shedlock (1997), Bommer et al. (2010), Douglas (2003), Strasser et al. (2009) for a short review). Due to the necessary high precision for these specific applications (like building damage studies), models are developed using very selected datasets for specific applicability ranges of site conditions, magnitude and depth. Moreover, none of them is valid for magnitudes lower than 4.

Furthermore, a recent study Douglas et al. (2006), shows that ground motions observed on Guadeloupe and Martinique are poorly estimated by commonly-used GMPE, having smaller and more variable amplitudes than expected.

In this work, we do not intend to produce a new GMPE for the engineering community; we need a more general model with certainly higher uncertainty, but applicable

over a wide range of earthquakes to be used in an operative way. In the following, we check results and residuals of our obtained PGA model as an intermediate stage, but in order to validate the choices made to produce automatic reports, we emphasize tests of the final intensity model performance in terms of medians across full range of intensity and distance applicability and beyond.

### 3. Intermediate PGA predictive equation

#### 3.1. Formulation and dataset

Due to the limited database and model purpose, we use one of the simplest form of GMPEs with only 3 parameters (Berge-Thierry et al., 2003):

$$\log(PGA) = aM + bR - \log(R) + c \tag{1}$$

where  $PGA$  is the horizontal acceleration peak (in g),  $M$  is the magnitude,  $R$  is the hypocentral distance (in km), and  $a$ ,  $b$ ,  $c$  are constant parameters.

This functional form implies many hypothesis. In particular, a radial distribution of ground motion around a point source, neglecting geological heterogeneities, tectonic origin, source extension and radiation pattern. Fukushima (1996) also points out that a linear  $\log(D)/M$  formulation is not verified for magnitudes  $\geq 6.5$  for which a  $M^2$  term should be necessary. This concerns magnitudes

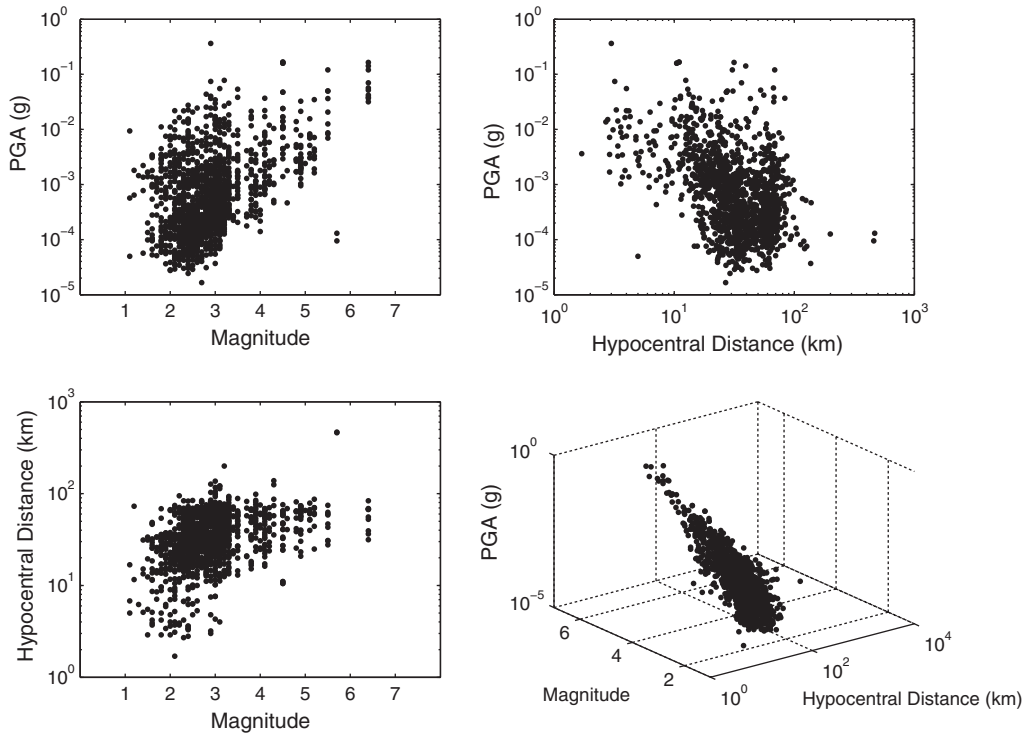


Fig. 2. Presentation of the seismic events dataset: 1430 triggers recorded by 14 permanent accelerometer stations from 2004.11.21 to 2004.12.28. Data are presented in 3-D view for different X-Y combinations of magnitudes, hypocentral distances (in km) and PGA values (in g). In the 3-D graph the view angle has been chosen to highlight the planar characteristic of the dataset.

Fig. 2. Données sismiques utilisées: 1430 déclenchements enregistrés par 14 stations accélérométriques permanentes entre le 21 novembre 2004 et le 28 décembre 2004. Les données sont présentées pour différentes combinaisons X-Y de magnitudes, distances hypocentrales (en km) et valeurs de PGA (en g). Sur le graphe 3D, l'angle de vue a été ajusté pour mettre en évidence l'aspect planaire du jeu de données.

out of our study range, but we will keep in mind that accelerations should be underestimated at long distance for large magnitudes.

To inverse the three parameters, we use seismic data recorded at 14 strong-motion permanent stations in Guadeloupe (see Fig. 1), with mixed site conditions, rock and soil (details about the seismic stations can be found in (Bengoubou-Valérius et al., 2008)), in the period from November 21 to December 28, 2004. The dataset includes about 400 earthquakes associated to 1430 triggers of 3-component acceleration waveforms. These events correspond to Les Saintes main shock  $M_w = 6.3$  and mostly the associated aftershocks, but also some regional events that we voluntarily kept in the database.

Locations and magnitudes come from the seismic catalog of the Guadeloupe observatory (OVSG-IPGP). Magnitudes were computed using the classical formula of duration magnitude from Lee et al. (1975) for events  $M_d \leq 4.5$  (Clément et al., 2000; Feuillard, 1985), and we imposed the moment magnitude from worldwide networks for greater events. This allows us to overcome the problem of duration magnitude saturation for magnitude greater than 4.5. The consistency of magnitude scale ( $M_d$  versus  $M_w$ ) has been checked by Bengoubou-Valérius et al. (2008).

For each event, a value of PGA is calculated as the maximum amplitude of horizontal acceleration signals, using the modulus of a complex vector defined by the two horizontal and orthogonal components  $x(t)$  and  $y(t)$ . The PGA dataset is presented in Figs. 2 and 3. Magnitudes range from 1.1 to 6.3, hypocentral distances from 2 to 450 km, and PGA from 16  $\mu\text{g}$  to 0.36 g.

### 3.2. Best model determination and residuals

To calculate the 3 parameters in Eq. (1), we minimized a misfit function using the  $L_2$ -norm. Due to the inhomogeneous dataset (magnitudes follow a power-law and there is more short-distance values), we applied a simple weighting function by multiplying the misfit by the magnitude and a power of the hypocentral distance. This gave more weight for large magnitudes and long distances.

The inversion scheme yields the following parameters:  $a = 0.61755$ ,  $b = -0.0030746$ , and  $c = -3.3968$ . It produced an RMS residual on  $\log(\text{PGA})$  of 0.47 (a factor of 3 in PGA, see Fig. 4). This value is higher than classical published GMPE results (around 0.3, see Strasser et al. (2009)), and it confirms the observation of Douglas et al. (2006) about abnormal data variability in Lesser Antilles. However, interestingly, this factor corresponds to the average ratio between rock and soil conditions in the observed PGA (Bengoubou-Valérius et al., 2008). This might also reflect the wide range of magnitudes and distances in a too simple functional form. In order to follow some of the key considerations used to develop GMPEs (Bommer et al., 2010), we checked medians and sigmas of PGA residuals (Fig. 4): it shows a very consistent distribution in the full magnitude range (from 2 to 6), while we observe a significant PGA underestimation (median around +0.5 so a factor 3 in amplitude) for  $D < 15$  km.

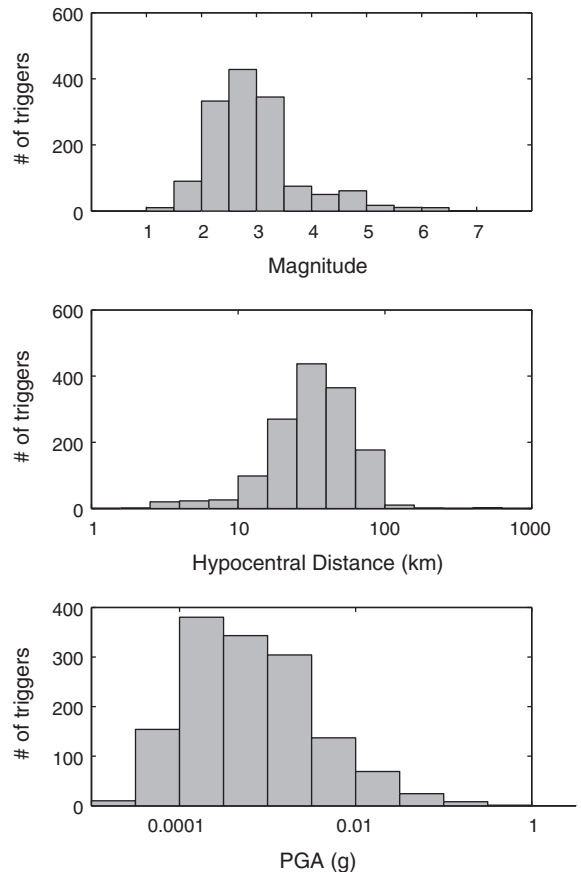


Fig. 3. Histograms of the seismic dataset: number of trigger versus magnitude, hypocentral distance (in km) and PGA value (in g).

Fig. 3. Histogrammes des données: nombre de déclenchements en fonction de la magnitude, de la distance hypocentrale (en km) et du PGA (en g).

Eq. (1) with the parameters found is represented as an abacus in Fig. 5 showing calculated PGA as a function of hypocentral distance (from 3 to 500 km) and magnitudes 1 to 8.

Note that we voluntarily limited the minimum hypocentral distance for each magnitude, as we do not take into account the near fault saturation term. It is reasonable to assume that this minimum hypocentral distance is greater than rupture size. Earthquake magnitude reflects the seismic moment which is proportional to the total displacement averaged over the fault surface (Aki, 1972; Kanamori, 1977). Many authors propose a simple formula to express the relationship between magnitude and fault length or rupture area (Liebermann and Pomeroy, 1970; Mark, 1977; Wells and Coppersmith, 1994; Wyss, 1979). Here we use Wyss's formula (Wyss, 1979):

$$M = \log(A) + 4.15 \quad (2)$$

where  $M$  is the magnitude and  $A$  the rupture surface. We decide to restrict the attenuation law of Eq. (1) to the domain  $R > L$ , where  $L \approx A^2$  is an estimation of the fault characteristic size.

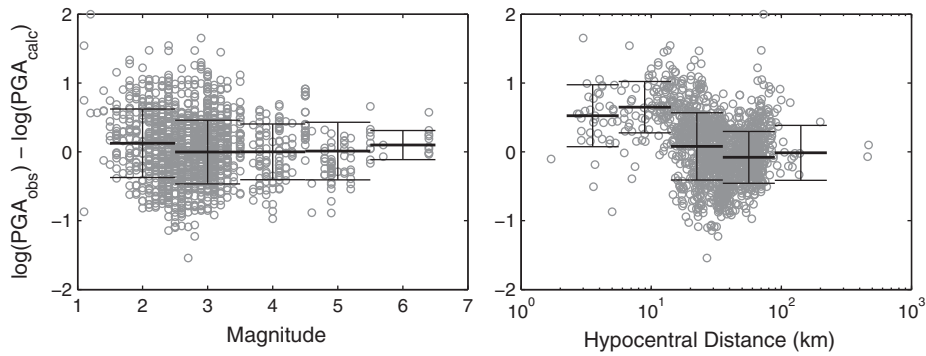


Fig. 4. PGA model residuals distribution: difference between observed and calculated log(PGA) versus magnitude and hypocentral distance (km). Horizontal segments with error bars stand for median values and associated standard deviations for each corresponding intervals. Global sigma of PGA residuals equals 0.47 (a factor of 3).

Fig. 4. Résidus du modèle PGA: différence entre log(PGA) observé et calculé en fonction de la magnitude et de la distance hypocentrale. Les segments horizontaux avec barres d'erreur représentent les valeurs médianes et l'écart-type associé pour chaque intervalle. L'écart-type global des résidus est égal à 0.47 (un facteur 3).

### 3.3. Examples of predicted and observed PGA

Fig. 6 shows representative events with observed PGA compared to our model predictions. We do not limit examples to the events from the dataset which reflects the previous residual analysis (Fig. 4), but present events in the period 2004 to 2007 with various depths, in crustal or subduction context, and for which sufficient triggers were available. As seen in Fig. 6, most of PGA values are predicted within the model uncertainty. Medians of log(PGA) residuals are equal to +0.15, +0.28, +0.10, +0.19, +0.24, and -0.01 for Fig. 6a to f events, respectively.

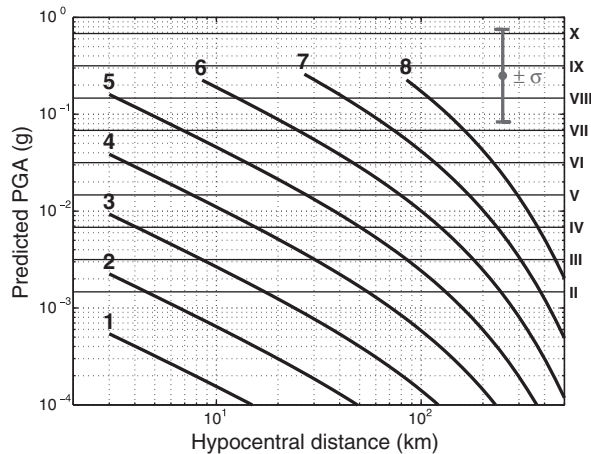


Fig. 5. The  $B^3$  prediction model: simulation of PGA (left Y-axis and log dotted horizontal grid) and MSK intensities (right Y-axis with roman numerals and solid thin horizontal lines) versus hypocentral distance (X-axis) and magnitude (thick solid lines and numbers). Uncertainty interval ( $\sigma =$  factor 3 in PGA) is indicated as gray vertical error bar. MSK is defined in Medvedev et al. (1967).

Fig. 5. Modèle  $B^3$ : simulation des PGA (axe des ordonnées à gauche et grille logarithmique horizontale) et intensités MSK (axe des ordonnées de droite avec chiffres romains et lignes horizontales) en fonction de la distance hypocentrale (abscisses) et de la magnitude (lignes épaisses et chiffres en gras). L'intervalle d'incertitude ( $\sigma =$  facteur 3 sur le PGA) est indiqué par une barre d'erreur verticale grise. L'échelle MSK est définie dans Medvedev et al. (1967).

We denote, for these 6 particular examples, a light tendency for PGA underestimation, which seems independent from magnitude. This is consistent with Fig. 4 residual analysis. The only significant PGA misfit appears for one soil condition station in the near field ( $\approx 15$  km) for Les Saintes aftershocks (Figs. 6b and c), that is systematically underestimated by a factor of about 10.

We also compare these results with two published GMPE adapted to shallow crustal events: Sadigh et al. (1997) and Ambraseys (1995). The Sadigh et al. (1997) model is very similar to our PGA model for magnitudes  $\geq 5.0$  (Figs. 6a, c and f) but has poor fitting for lower magnitudes (Figs. 6b, d and e) with a systematic overestimation. The Ambraseys (1995) model has a globally poor fitting, with an overestimation of PGA, particularly for  $M < 5.0$ .

## 4. Macroseismic intensities

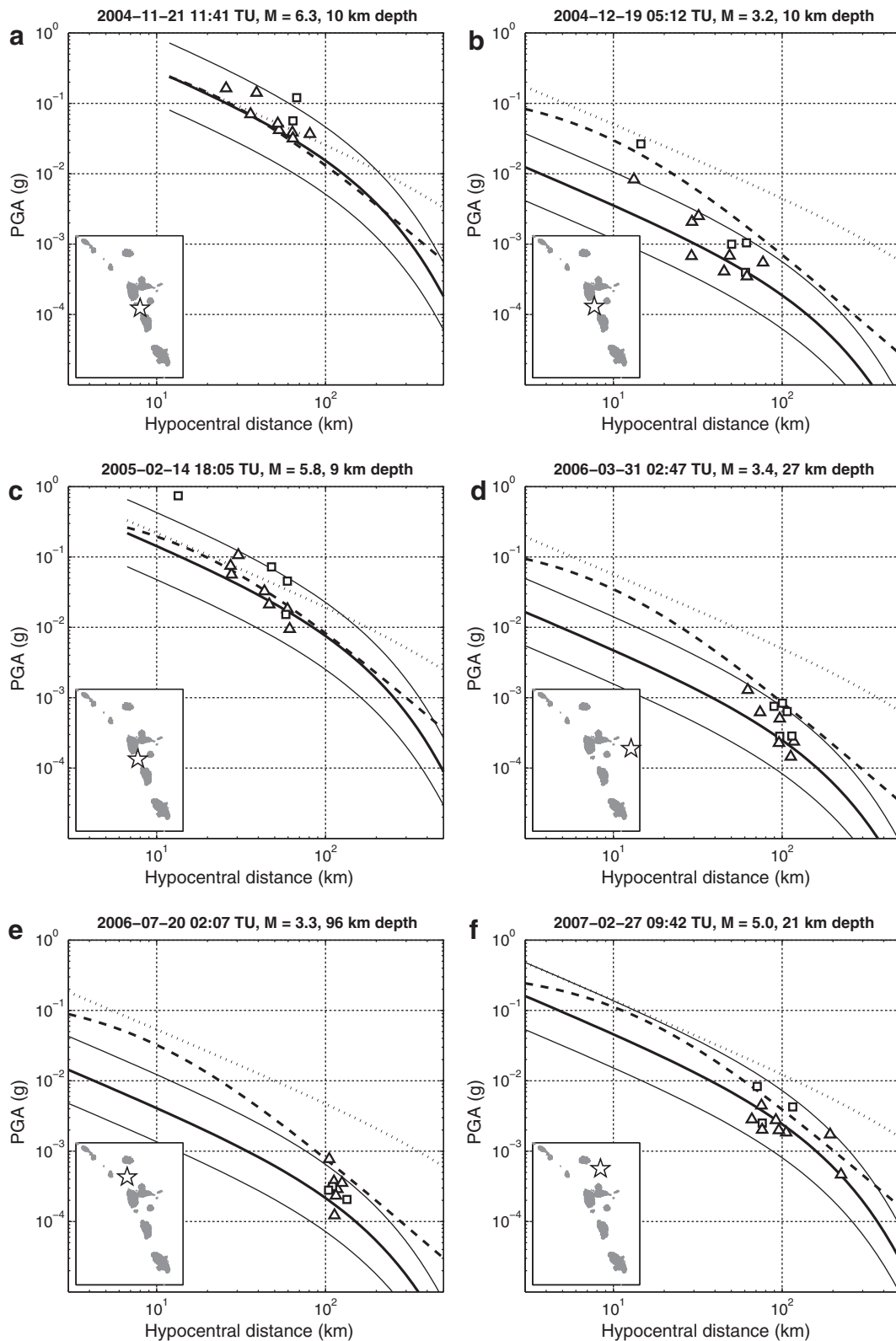
### 4.1. Formulation

Although we know that the spectral frequency content of ground acceleration and peak velocity have important implications on building damage, establishing a direct relation between a single PGA value and macroseismic intensity has proved its efficiency in many cases (Chiaruttini and Siro, 1981; Margottini et al., 1992; Murphy et al., 1977; Wald et al., 1999). For the Lesser Antilles, we follow the suggestion of Feuillard (1985) who studied the historical and instrumental seismicity using the simple empirical relation of Gutenberg and Richter (1942):

$$I = 3\log(\text{PGA}) + 3/2 \tag{3}$$

where  $I$  is the mean intensity (MSK scale), PGA is maximum acceleration (in  $\text{cm.s}^{-2} \approx \text{mg}$ ). Combining Eqs. (1), (2) and (3) made the final empirical model formulation (hereafter called the  $B^3$  prediction):

$$\begin{cases} I = \frac{1.85265M - 0.0092238R - 3\log(R) + 0.3096}{M - 4.15} \\ R > 10 \end{cases} \tag{4}$$



**Fig. 6.** PGA prediction (solid thick curve) and uncertainty (solid thin curves) for various magnitudes and depths. The recorded PGA values are presented in squares in the case of soil site condition and in triangles for rock site condition. Are also shown other attenuation laws: Sadigh et al. (1997) (dashed curve) and Ambraseys (1995) (dotted curve). Inset maps show epicenter location for each event (star). *a*) Les Saintes main shock, *b*) and *c*) are aftershocks. *d*) is a shallow subduction event located east of Guadeloupe. *e*) is a deep subduction event located north of Guadeloupe. *f*) is a shallow crustal event located south of Antigua.

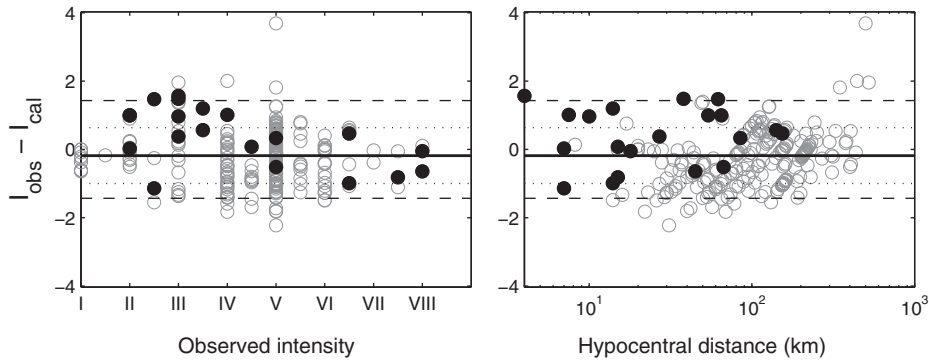


Fig. 7. Intensity model residuals distribution for 20 earthquakes (254 macroseismic observations): difference between observed and calculated intensities versus observed intensity and hypocentral distance (km). Solid black circles indicate the maximum observed intensity for each event. Thick black line = median value (−0.2). Dotted lines = standard deviation (±0.85). Dashed lines = PGA standard deviation equivalent (±1.4).

Fig. 7. Distribution des résidus du modèle prédictif des intensités pour 20 séismes (254 observations macrosismiques): différence entre intensité observée et calculée en fonction des intensités observées et de la distance hypocentrale (km). Les disques noirs indiquent l'intensité observée maximum pour chaque événement. Ligne épaisse = valeur médiane (−0,2). Lignes pointillées = écart-type (±0,85). Lignes tiretées = écart-type PGA équivalent (±1,4).

Note that following the MSK scale, intensity must be an integer value. In this article, we decided arbitrarily to round  $I$  to the nearest and smallest integer (e.g.,  $I = 6.0$  to 6.9 correspond to intensity of VI).

The resulting model for intensities is presented as right Y-axis in Fig. 5. Following Eq. (3), the 0.47 uncertainty on our predicted  $\log(PGA)$ , would imply an uncertainty on  $I$  of  $\pm 1.4$ , on which we should add the uncertainty of Eq. (3) itself, which is unknown.

#### 4.2. Intensity model residuals

We test our model on a database of 20 recent earthquakes for which we have intensity reports (a total of 254 observations) as well as instrumental magnitudes and hypocenter locations. Events are from various origins with magnitudes 1.6 to 7.4, distances from 4 to 500 km, and observed intensities from I to VIII. This wide panel of event characteristics allows us to check our model applicability.

We present in Fig. 7 the intensity residuals versus observed intensity and hypocentral distance. Global standard deviation equal 0.8, with a near zero median value. Residuals are also well distributed over the intensity and distance ranges. Since this database is not statistically sufficient, we will keep uncertainty on intensities deduced from the PGA residuals, i.e.,  $\sigma = 1.4$  corresponding to 68 confidence interval. We also checked that maximum observed intensity for each event is strictly below this probability level (see Fig. 7 solid circles).

#### 4.3. Examples of simulated and observed intensities

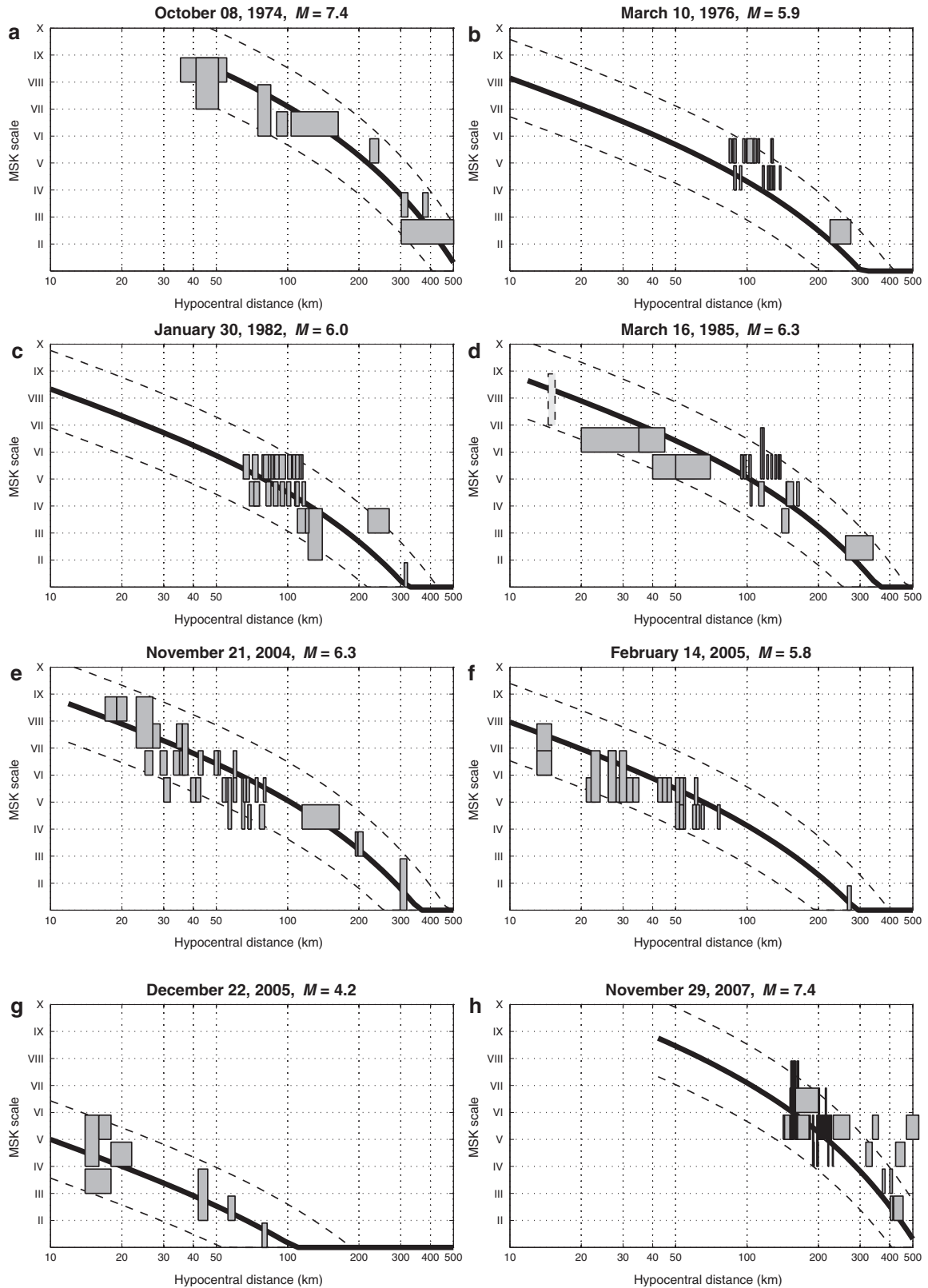
In Fig. 8, we detail eight examples of the most significant events with observed and predicted intensities (see epicenters in Fig. 1).

Fig. 8a shows the October 10, 1974 “Antigua” earthquake (McCann et al., 1982; Tomblin and Aspinall, 1975),  $M_s = 7.4$ , a shallow 30 km-depth with normal-fault mechanism,  $M_s$  from NEIC USGS, location and MSK intensities from McCann et al. (1982). Maximum intensities and distance of observations vary from VIII at 45 km in Antigua to II at 400 km in Virgin Islands. All the observations (9 sites) are within the  $B^3$  prediction uncertainty limits. The median of intensity residuals equals  $-0.6$ , sigma is 0.5. This is an unexpected positive result since the model is extrapolated for magnitudes larger than Les Saintes ( $M_w = 6.3$ ); so this magnitude 7.4 is formally out of our interval of validity. Note also that near-field intensities (at 45 km) seem correctly fitted by the model while this hypocentral distance is very close to our limit defined by Eq. (2), which gives  $L = 42$  km.

Fig. 8b shows the March 10, 1976 earthquake, a magnitude  $M_b = 5.9$ , 56 km-depth on subduction interface north of Guadeloupe ( $M_b$  from USGS-NEIC, location and MSK intensities from Feuillard (1985)). Maximum intensities and distances of observations vary from V in Le Moule (Guadeloupe) at 85-km, to II in Martinique at 150 km distance. Most of the 22 observed intensities are underestimated (median of residuals is  $+0.4$ ) but still within one sigma uncertainty ( $RMS$  equals 0.5).

Fig. 8c shows the January 30, 1982 earthquake, a magnitude  $M_w = 6.0$ , 63 km-depth on subduction interface north of Guadeloupe ( $M_w$  and location from Global CMT Project, MSK intensities from Feuillard (1985)). Maximum intensities and distances of observations vary from V in various urban districts of Guadeloupe and Antigua at 90 km distance, to II in Barbuda (130 km). Most of the 34 observed intensities are within the  $B^3$  uncertainty limits, with a zero median and  $RMS$  on intensity residuals equal to 0.7.

Fig. 6. Prédiction des PGA (courbe épaisse) et incertitudes (courbes fines) pour différentes magnitudes et profondeurs. Les PGA observés sont présentés par des carrés pour les conditions de site type sol, et par des triangles pour les conditions de site type roche. Sont aussi indiquées d'autres lois d'atténuation: Sadigh et al. (1997) (courbe tiretée) et Ambraseys (1995) (courbe pointillée). Les cartes en encart indiquent la position de l'épicentre pour chaque événement (étoile). a) Choc principal du séisme des Saintes, b) et c) sont des répliques. d) Séisme superficiel sur le plan de subduction à l'est de la Guadeloupe. e) Séisme profond de subduction au nord de la Guadeloupe. f) Séisme crustal superficiel au sud d'Antigua.



**Fig. 8.** Examples of  $B^3$  predicted intensities for 8 instrumental earthquakes: observed macroseismic intensities (MSK) are presented versus hypocentral distance (km). Gray thick curve stands for the predicted intensity for given magnitude, dashed curves indicate uncertainties, solid rectangles represent



Fig. 8d shows the March 16, 1985 “Redonda” earthquake (Feuillet et al., 2010; Girardin et al., 1991), a magnitude  $M_w = 6.3$ , 10 km-depth normal-fault ( $M_w$  and location from Global CMT Project, MSK intensities from Feuillard (1985)). Maximum intensities and distances of observations vary from VI at 30 km in Montserrat to II at 300 km in Martinique. We added a supposed intensity of VII–VIII (light gray dashed rectangle) because important cliff collapses have been observed in the Redonda island, at 10 km-distance from epicenter. All the 23 observed intensities are within the  $B^3$  uncertainty limits ( $RMS = 0.7$ ) with zero median. Note a very local amplification effect that occurred in the region of Pointe-à-Pitre (Guadeloupe) with an intensity of V to VI at 120 km from the hypocenter.

Fig. 8e shows the November 21, 2004 Les Saintes main shock earthquake of magnitude  $M_w = 6.3$ ,  $M_w$  from Global CMT Project, location from Bazin et al. (2010), EMS98 intensities (see definition in Grunthal et al. (1998)) from an official survey by the BCSF (Cara et al., 2005). Maximum intensities and distances of observations vary from VIII at 20 km in Les Saintes to IV at 140 km in Martinique, and correspond to detailed studies carried on by BCSF in 33 different urban districts. All the 29 observed intensities are within the  $B^3$  uncertainty limits ( $RMS = 0.6$ , median =  $-0.9$ ).

Fig. 8f shows the largest Les Saintes aftershock, on February 14, 2005 of magnitude  $M_w = 5.8$ , located south of Terre-de-Haut ( $M_w$  and location from Global CMT Project, MSK intensities from OVSG-IPGP). Maximum intensities and distances of observations vary from VII at 14 km in Les Saintes to IV at 74 km in Anse-Bertrand (Guadeloupe). All the 25 observed intensities are within the  $B^3$  uncertainty limits ( $RMS = 0.3$ , median =  $-1.0$ ) with a global light overestimation.

Fig. 8g shows one of the numerous Les Saintes aftershocks, on December 22, 2005 of magnitude  $M_d = 4.2$ , located north of Terre-de-Bas ( $M_d$ , location and MSK intensities from OVSG-IPGP, unpublished). Maximum intensities and distances of observations vary from V at 15 km in Basse-Terre to II at 58 km in Saint-François (Guadeloupe). All the 7 observed intensities are within the  $B^3$  uncertainty limits ( $RMS = 0.6$ , median =  $-0.3$ ).

Fig. 8h shows the November 29, 2007 Martinique intermediate-depth (152 km) intraslab earthquake of magnitude  $M_w = 7.4$ ,  $M_w$  and location from Bouin et al. (2010) and Global CMT Project, with EMS98 intensities from an official survey by the BCSF (Schlupp et al., 2008). Maximum intensities and distances of observations vary from VII at 150 km in Martinique to II at 400 km in St-Barthelemy, and correspond to detailed studies carried on by BCSF in 70 different urban districts in Guadeloupe and Martinique, plus other islands reports. Most of the 74

observed intensities are within the  $B^3$  uncertainty limits ( $RMS = 0.83$ , median =  $-0.1$ ), but we note three underestimated intensities at long distances: V in Saint-Vincent (250 km) and Trinidad (500 km), and IV in Anguilla (443 km). This may be due to local site amplifications because of low frequency content of the seismic waves.

These eight examples confirm that  $B^3$  model seems able to predict average intensities within a global residual of  $\sigma = 1.4$  degree in the MSK scale, for events of magnitudes up to 7.4 in Lesser Antilles context with various hypocentral distances. This value corresponds to 68 of confidence interval and gives a convincing maximum possible intensity even when local site effects are observed.

## 5. Automatic intensity report

These good results and the apparent robustness of the  $B^3$  model made us confident of the release of a semi-automatic theoretical intensity report at the Guadeloupe and Martinique observatories. For each located event, maximum intensity is computed for all towns of Lesser Antilles islands. If at least one location reaches an intensity of II, it means that the event has been potentially felt and an automatic report is produced, waiting for seismologist validation.

This simulation allows us: (1) to confirm that inhabitants may have (or not) felt the event when intensity interval varies from II to III in a town; and (2) to publish immediately and blindly (without any testimonies) the information of a possible felt earthquake when the predicted maximum intensity reaches IV, which means a 68 confidence level for an intensity between I–II and IV.

The report (see an example in Fig. 9) includes a synthetic text resuming the date, location and type of event, the maximum intensity prediction value and corresponding town name and distance. To better take into account potential site effects and increase the precision of the result, the average prediction is given together with the upper limit value ( $I + \sigma = I + 1.4$ ) for potential site effects, and MSK intensities are indicated in half-unit values, i.e.,  $I = 6.0$  to  $6.4$  is “VI”, and  $I = 6.5$  to  $6.9$  is “VI–VII”. The exhaustive list of urban districts for which theoretical intensity reaches at least II is given. Note that it includes all islands in the Lesser Antilles, while our model has been mainly checked with Guadeloupe and Martinique intensities. This may constitute a future extension of our study.

The report also includes a location map that presents the islands and towns, earthquake epicenter and theoretical isoseist curves using a shaded color map. A detailed table legend explains the MSK scale and corresponding name, color, PGA interval, potential damage and human perception.

intensity observations. a), d), e), f) g) are shallow crustal earthquakes, b) and c) are  $\approx 60$  km-depth subduction slab interface, h) is an intermediate depth intraslab subduction.

Fig. 8. Exemples des intensités prédites  $B^3$  pour 8 séismes instrumentaux: intensités macrosismiques observées (MSK) en fonction de la distance hypocentrale (km). La courbe épaisse grise représente l'intensité prédite pour une magnitude donnée, les courbes tiretées indiquent l'incertitude, les rectangles pleins représentent les intensités observées. a), d), e), f) g) sont des séismes crustaux, b) et c) sont des séismes à l'interface de subduction à  $\approx 60$  km de profondeur, h) est un séisme de subduction intraslab de profondeur intermédiaire.



## Rapport préliminaire de séisme concernant la Guadeloupe et Îles du Nord



Observatoire Volcanologique et Sismologique de Guadeloupe – IPGP

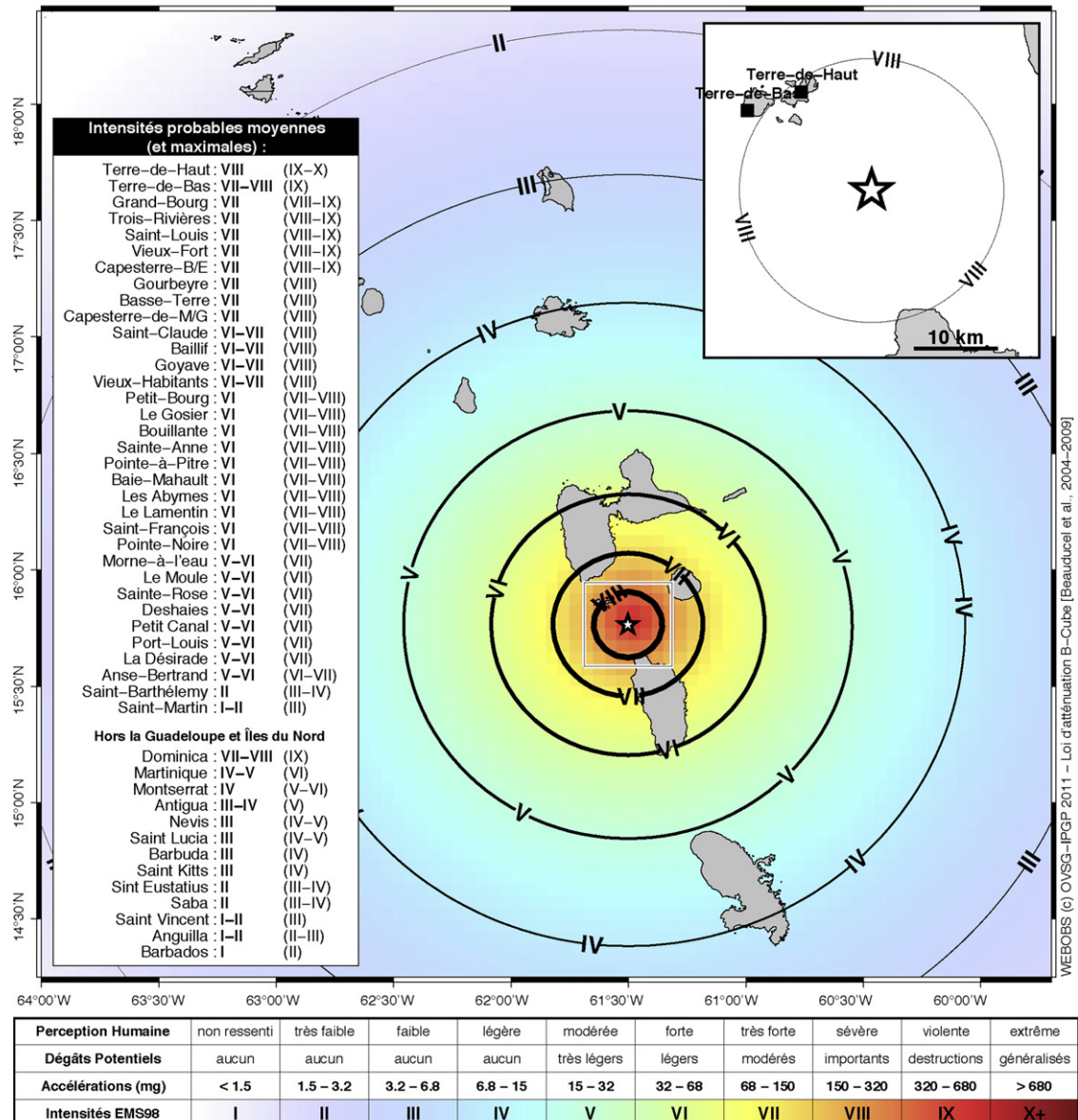
Le Houëmont – 97113 Gourbeyre – Guadeloupe (FWI)

Tél: +590 (0)590 99 11 33 – Fax: +590 (0)590 99 11 34 – infos@ovsg.univ-ag.fr – www.ipgp.fr

Gourbeyre, le 21 novembre 2004 10:00 locales

### Magnitude 6.3, 15.76°N, 61.50°W, profondeur 10 km dimanche 21 novembre 2004 11:41:08 TU

Un séisme fort (magnitude **6.3** sur l'Échelle de Richter) a été enregistré le **dimanche 21 novembre 2004 à 07:41** (heure locale) et identifié d'origine **Tectonique**. L'épicentre a été localisé à **14 km** au sud de **Terre-de-Haut**, à 10 km de profondeur (soit une distance hypocentrale d'environ 18 km). Ce séisme a pu générer, dans les zones concernées les plus proches, une accélération moyenne du sol de **160 mg (\*)**, correspondant à une intensité macrosismique de **VIII** (dégâts importants potentiels). Suivant le type de sols, les intensités peuvent cependant avoir atteint localement l'intensité **IX–X** (destructions potentielles).



## 6. Discussion and conclusions

We propose a simple empirical model for macroseismic intensities prediction for observatory operational purpose. The model is based on intermediate PGA model that has been adjusted using a shallow crustal normal-fault sequence of events. The functional form is only 3-parameters dependent which implies many assumptions and simplifications, but makes it also extremely robust with an uncertainty higher than usual GMPE (a factor of 3). This can be explained also by the fact that we do not select specific site conditions in the database, mixing rock and soil stations. The obtained PGA model has strong potential limits and may not be very useful for engineering purposes, but it exhibits a better fit than previous existing GMPE for Lesser Antilles. Its application domain should be limited to crustal events, magnitude range up to 6.3, and distance range up to 100–200 km.

The deduced intensity model is tested on a wider range of magnitudes, distances and source types of earthquakes. We suggest that the  $B^3$  model is able to correctly predict intensities within  $\pm 1.4$  ( $1\sigma$ ), for magnitudes up to 7.4 and hypocentral distance up to 300 km. At longer distances, we observe a clear underestimation of intensities. A major result of our work is that the final equation seems to exhibit a larger applicability range than intermediate PGA predictive equation. In particular, greater magnitudes and other types of earthquakes such as those located in the subduction slab are well modeled within the given uncertainties.

This model is currently used to produce automatic reports in Guadeloupe (since January 2005) and Martinique (since September 2008) observatories in order to anticipate potentially felt events immediately after the location and magnitude calculation. On a total amount of about 10,000 located events in Guadeloupe, a third has been potentially felt (minimal intensity of II) and has produced an automatic report. Following the observatory convention, only 200 reports were effectively sent as a public communiqué, when the minimum theoretical intensity reached IV or, in case of lower intensity (II or III), when immediate testimonies were received from inhabitants.

During more than 5 years of continuous seismic monitoring and thanks to inhabitants testimonies, the  $B^3$  model is daily controlled by observatory team:

comparisons between observations and predicted intensities exhibit an average uncertainty less than  $\pm 1$  unit in the MSK scale.

The reports were also used for seismic hazard awareness and education of the public and local authorities. Particularly, explaining the fundamental difference between magnitude and intensity of an earthquake, the MSK scale, the uncertainty of prediction due to the law's empirical aspect and simplicity, and the potential site condition effects, thus earthquake-resistant construction advice.

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## References

- Abrahamson, N., Shedlock, K., 1997. Overview (of modern attenuation relationships). *Seismol. Res. Lett.* 68 (1), 9–23.
- Aki, K., 1972. Earthquake mechanism. *Tectonophysics* 13 (1–4), 423–446.
- Ambraseys, N., 1995. The prediction of earthquake peak ground acceleration in Europe. *Earthquake Engin. & Struct. Dyn.* 24 (4), 467–490.
- Bazin, S., Feuillet, N., Duclos, C., Crawford, W., Nercessian, A., Bengoubou-Valérius, M., Beauducel, F., Singh, S., 2010. The 2004–2005 Les Saintes (French West Indies) seismic aftershock sequence observed with ocean bottom seismometers. *Tectonophysics* 489 (1–4), 91–103.
- Beauducel, F., Anténon-Habazac, C., Bazin, S., de Chaballier, J., Nercessian, A., Feuillet, N., Jacques, E., Bertil, D., Boudon, G., Le Friant, A., Tapponnier, P., Hirn, A., Lépine, J., Bernard, P., Komorowski, J., King, G., OVSG team, 2005a. The Mw 6.3 earthquake of Les Saintes (Guadeloupe) on November 21, 2004. In: *European Seismological Commission Annual Workshop*. IAVCEI.
- Beauducel, F., Bazin, S., Bengoubou-Valérius, M., 2005b. Loi d'atténuation B-Cube pour l'évaluation rapide des intensités sismiques probables dans l'Archipel de Guadeloupe. Internal Report pp 16, Institut de Physique du Globe de Paris. [http://www.ipgp.fr/~beaudu/download/2004\\_Beauducel\\_B3.pdf](http://www.ipgp.fr/~beaudu/download/2004_Beauducel_B3.pdf).

**Fig. 9.** Example of observatory communiqué published in case of potential felt event: here an a posteriori simulation of Les Saintes main shock (data from OVSG-IPGP). The  $B^3$  model is used to estimate the probable macroseismic intensities. Are indicated the exhaustive list of towns or neighborhood islands where the event could be felt, with maximum intensity in case of site amplification (after Beauducel et al. (2005))

Title: "Preliminary report of earthquake in Guadeloupe and Northern Islands"

Main text: "A strong earthquake (magnitude 6.3 on the Richter Scale) was recorded on Sunday, November 21, 2004 at 07:41 (local time) and identified with tectonic origin. The epicenter was located 14 km south of Terre-de-Haut, 10 km-depth (hypocentral distance of about 18 km). This earthquake may have generated, in the closest areas from epicenter, an average ground acceleration of 160 mg (\*), corresponding to macroseismic intensity of VIII (severe potential damages). However, depending on the type of soil, the intensities may have reached locally an intensity of IX-X (potential destructions)."

Towns list: "Average (and maximum) probable intensities:"

Table: "Human perception / Potential damages / Accelerations (mg) / MSK Intensity"

Note: "(\*) 'mg' is a unit of acceleration equal to one thousandth of Earth's gravity"

**Fig. 9.** Exemple de communiqué publié par l'observatoire en cas de séisme ressenti: ici une simulation a posteriori du séisme des Saintes (données OVSG-IPGP). Le modèle  $B^3$  est utilisé pour estimer les intensités moyennes probables. Est mentionnée la liste exhaustive des communes ou îles voisines ayant pu ressentir le séisme, avec les intensités maximales (en cas d'effets de sites) (d'après Beauducel et al. (2005)).

- Bengoubou-Valérius, M., Bazin, S., Bertil, D., Beauducel, F., Bosson, A., 2008. CDSA: A New Seismological Data Center for the French Lesser Antilles. *Seismol. Res. Lett.* 79 (1), 90.
- Berge-Thierry, C., Cotton, F., Scotti, O., Griot-Pommer, D., Fukushima, Y., 2003. New empirical response spectral attenuation laws for moderate European earthquakes. *J. Earthquake Eng.* 7 (2), 193–222.
- Bertil, D., Bazin, S., Mallarino, D., Beauducel, F., 2004. Séisme des Saintes: rapport de synthèse. Tech. rep., Centre de Données Sismologiques des Antilles (CDSA), BRGM/IPGP/UAG.
- Bommer, J., Douglas, J., Scherbaum, F., Cotton, F., Bungum, H., Fah, D., 2010. On the selection of ground-motion prediction equations for seismic hazard analysis. *Seismol. Res. Lett.* 81 (5), 783.
- Bouin, M.-P., Bouchon, M., Coutant, O., Bazin, S., Latchman, J., 2010. Source parameters of the Mw 7.4 Martinique intermediate-depth earthquake (Leeward islands) of November 29, 2007: A slab-pull event with horizontal fault plane. In: EGU General Assembly 2010, held 2–7 May, 2010, Vienna, Austria, p. 5555.
- Cara, M., Bertil, D., Feuillet, N., Jacques, E., Tapponnier, P., Guéguen, P., Bengoubou-Valérius, M., Sira, C., Lebrun, B., Beauducel, F., 2005. Séisme des Saintes (Guadeloupe) du 21 novembre 2004, note préliminaire. Tech. rep., Bureau Central de Sismologie Française.
- Chiaruttini, C., Siro, L., 1981. The correlation of peak ground horizontal acceleration with magnitude, distance, and seismic intensity for Friuli and Ancona, Italy, and the Alpine belt. *Bull. Seismol. Soc. Am.* 71 (6), 1993.
- Clément, C., Bernard, P., Viodé, J., Anténor-Habazac, C., Lépine, J., Beauducel, F., 2000. Compilation et validation du catalogue de sismicité des observatoires IPGP des Antilles. Tech. rep., Ministère de l'Aménagement du Territoire et de l'Environnement, Institut de Physique du Globe de Paris.
- Courboux, F., Converset, J., Balestra, J., Delouis, B., 2010. Ground-motion simulations of the 2004 mw 6.4 Les Saintes, Guadeloupe, earthquake using ten smaller events. *Bull. Seismol. Soc. Am.* 100 (1), 116.
- Douglas, J., 2003. Earthquake ground motion estimation using strong-motion records: a review of equations for the estimation of peak ground acceleration and response spectral ordinates. *Earth Sci. Rev.* 61 (1–2), 43–104.
- Douglas, J., Bertil, D., Roullé, A., Dominique, P., Jousset, P., 2006. A preliminary investigation of strong-motion data from the French Antilles. *J. Seismol.* 10 (3), 271–299.
- Feuillard, M., 1985. Macrosismicité de la Guadeloupe et de la Martinique. Ph.D. thesis, Institut de Physique du Globe de Paris.
- Feuillet, N., Leclerc, F., Tapponnier, P., Beauducel, F., Boudon, G., Le Friant, A., Deplus, C., Lebrun, J., Nercessian, A., Saurel, J., et al., 2010. Active faulting induced by slip partitioning in Montserrat and link with volcanic activity: New insights from the 2009 GWADASEIS marine cruise data. *Geophys. Res. Lett.* 37.
- Feuillet, N., Manighetti, I., Tapponnier, P., Jacques, E., 2002. Arc parallel extension and localization of volcanic complexes in Guadeloupe, Lesser Antilles. *J. Geophys. Res.* 107, 2331.
- Fukushima, Y., 1996. Scaling relations for strong ground motion prediction models with  $m_2$  terms. *Bull. Seismol. Soc. Am.* 86 (2), 329.
- Girardin, N., Feuillard, M., Viodé, J., 1991. Réseau régional sismique de l'arc des Petites Antilles; sismicité superficielle (1981–1988). *Bull. Soc. geol. France* 162 (6), 1003.
- Grunthal, G., Musson, R., Schwarz, J., Stucchi, M., 1998. European Macro-seismic Scale 1998 (EMS-98). *Cahiers du Centre Européen de Géodynamique et de Séismologie* 15.
- Gutenberg, B., Richter, C., 1942. Earthquake magnitude, intensity, energy, and acceleration. *Bull. Seismol. Soc. Am.* 32 (3), 163–191.
- IPGP, 2004. Bilan mensuel de l'activité volcanique de la Soufrière de Guadeloupe et de la sismicité régionale. Public reports of OVSG-IPGP ISSN 1622-4523, Institut de Physique du Globe de Paris. <http://www.ipgp.fr>.
- Kanamori, H., 1977. The energy release in great earthquakes. *J. Geophys. Res.* 82 (20), 2981–2987.
- Lee, W., Lahr, J., N.C.E.R., 1975. HYPO71 (revised): a computer program for determining hypocenter, magnitude, and first motion pattern of local earthquakes. US Dept. of the Interior, Geological Survey, National Center for Earthquake Research.
- Liebermann, R., Pomeroy, P., 1970. Source dimensions of small earthquakes as determined from the size of the aftershock zone. *Bull. Seismol. Soc. Am.* 60 (3), 879.
- Lopez, A., Stein, S., Dixon, T., Sella, G., Calais, E., Jansma, P., Weber, J., LaFemina, P., 2006. Is there a northern Lesser Antilles forearc block? *Geophys. Res. Lett.* 33 (L07313).
- Margottini, C., Molin, D., Serva, L., 1992. Intensity versus ground motion: a new approach using Italian data. *Eng. Geol.* 33 (1), 45–58.
- Mark, R., 1977. Application of linear statistical models of earthquake magnitude versus fault length in estimating maximum expectable earthquakes. *Geology* 5 (8), 464.
- McCann, W., Dewey, J., Murphy, A., Harding, S., 1982. A large normal-fault earthquake in the overriding wedge of the Lesser Antilles subduction zone: The earthquake of 8 October 1974. *Bull. Seismol. Soc. Am.* 72 (6A), 2267.
- Medvedev, S., Sponheuer, W., Karnik, V., 1967. Seismic intensity scale version 1964. *Inst. Geody. Publ.* 48.
- Murphy, J., O'Brien, I., 1977. The correlation of peak ground acceleration amplitude with seismic intensity and other physical parameters. *Bull. Seismol. Soc. Am.* 67 (3), 877.
- Pasolini, C., Gasperini, P., Albarello, D., Lolli, B., D'Amico, V., 2008. The attenuation of seismic intensity in Italy, part I: Theoretical and empirical backgrounds. *Bull. Seismol. Soc. Am.* 98 (2), 682.
- Pequegnat, C., Gueguen, P., Hatzfeld, D., Langlais, M., 2008. The French accelerometric network (RAP) and national data centre (RAP-NDC). *Seismol. Res. Lett.* 79 (1), 79–89.
- Sadigh, K., Chang, C., Egan, J., Makedisi, F., Youngs, R., 1997. Attenuation relationships for shallow crustal earthquakes based on California strong motion data. *Seismol. Res. Lett.* 68 (1), 180.
- Schlupp, A., Sira, C., Cara, M., Bazin, S., Michel, C., Régnier, J., Beauval, C., Feuillet, N., De Chabalière, J., Barras, A., et al., 2008. Séisme de Martinique du 29 novembre 2007. Synthèse sismologique et étude macrosismique BCSF2008-R1, Bureau Central Sismologique Français 266.
- Smith, W., Sandwell, D., 1997. Global sea floor topography from satellite altimetry and ship depth soundings. *Science* 277 (5334), 1956.
- Sorensen, M., Stromeyer, D., Grunthal, G., 2009. Attenuation of Macro-seismic Intensity: A New Relation for the Marmara Sea Region, Northwest Turkey. *Bull. Seismol. Soc. Am.* 99 (2A), 538.
- Strasser, F., Abrahamson, N., Bommer, J., 2009. Sigma: Issues, insights, and challenges. *Seismol. Res. Lett.* 80 (1), 40–56.
- Tomblin, J., Aspinall, W., 1975. Reconnaissance report of the Antigua, west Indies, earthquake of October 8, 1974. *Bull. Seismol. Soc. Am.* 65 (6), 1553.
- Wald, D., Quitoriano, V., Heaton, T., Kanamori, H., 1999. Relationships between peak ground acceleration, peak ground velocity, and modified Mercalli intensity in California. *Earthquake Spectra* 15, 557.
- Wells, D., Coppersmith, K., 1994. New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. *Bull. Seismol. Soc. Am.* 84 (4), 974–1002.
- Wyss, M., 1979. Estimating maximum expectable magnitude of earthquakes from fault dimensions. *Geology* 7 (7), 336.