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Field survey and numerical simulation of the 21 November 2004 tsunami at Les Saintes (Lesser Antilles)

Anne Le Friant,[1] Philippe Heinrich,[2] and Georges Boudon[1]

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[1] Although a few historical tsunamis have occurred in the Lesser Antilles region, their characteristics are poorly documented due to the ephemeral nature of the associated signatures. Recently, a tsunami was generated following a magnitude Mw 6.3 earthquake that occurred on 21 November 2004 between Guadeloupe and Dominica. This was one of the two largest historical earthquakes recorded in this area in the last century. A field survey allowed us to characterize the tsunami which affected Les Saintes, the southern coast of Basse-Terre (Guadeloupe) and northern Dominica. We used these data to constrain a numerical simulation of tsunami generation and propagation. The 21 November tsunami provides a unique opportunity to further constrain the models of brittle deformation in the back arc region proposed by previous tectonic investigations, to characterize the tsunami signatures and to improve regional hazards evaluation. **Citation:** Le Friant, A., P. Heinrich, and G. Boudon (2008), Field survey and numerical simulation of the 21 November 2004 tsunami at Les Saintes (Lesser Antilles), *Geophys. Res. Lett.*, *35*, L12308, doi:10.1029/2008GL034051.

1. Introduction

[2] On 21 November 2004, at 11:41:07 UTC, a strong earthquake occurred offshore, near Les Saintes in the central part of the Lesser Antilles arc (Figure 1). The earthquake had a magnitude (Mw) of 6.3 and caused significant damage to infrastructure, particularly in the small islands of Les Saintes and in the Trois-Rivières area of Southern Basse-Terre where a five-year old girl was killed. It generated a small tsunami which affected the southern coasts of Basse-Terre (Guadeloupe), Les Saintes and the northern coasts of Dominica [*Zahibo et al.*, 2005; *Beauducel and Anténor-Habazac*, 2006; *Douglas et al.*, 2006; *Duclos et al.*, 2007]. The 21 November 2004 tsunami is the first event in historical time to affect the coast of Guadeloupe archipelago following an intra-plate earthquake.

[3] The Lesser Antilles arc results from the subduction of the North American plate beneath the Caribbean plate. Historical earthquakes that affected Guadeloupe have been generated mostly at the plate interface (e.g.: M: 8, February 8, 1843) but also within the Caribbean plate with epicenters much closer to populated areas (e.g., 1851, 1897 and 1914) [*Bernard and Lambert*, 1988]. Recent tectonic studies show that the northern part of the arc is the site of trench parallel extension, which is accommodated by trench-perpendicular, normal or oblique faults [*Feuillet et al.*, 2004]. The first fault system forms a series of fault-bound grabens that are perpendicular to the arc. Slickensides indicate north-south extension. The second fault system is composed of a series of "en echelon" faults oriented parallel to the arc which accommodate a component of sinistral motion along the strike of the arc. The 21 November 2004 earthquake that is interpreted as a shallow normal faulting event, occurred on the Roseau normal fault (Figure 1) that belongs to this second fault system, N. Feuillet (manuscript in preparation, 2008). The CDSA (Centre de Données Sismologiques des Antilles, IPGP-BRGM) provided the epicentral coordinates at 15° 45.03′N, 61° 32.34′W with a focal depth of 14 km. The CMT inversion has been performed by different institutions yielding the following focal geometries: Harvard University (data from http://www.seismology.harvard.edu/CPTsearch.html): strike = 317°, dip = 44°, slip = −88°, focal depth = 12km; The National Earthquake Information Center of the USGS (NEIC, data from http://neic.usgs.gov/neis/eq_depot/2004): strike = 327°, dip = 35°, slip = −92°, focal depth = 6 km; and Geoscope (IPGP-INSU, data from http://www.ipgp.jussieu.fr/rech/sismo/fr-site/CMT/2004): strike = 336°, dip = 34°, slip = −54°.

[4] The 21 November 2004 tsunami propagation has been modelled using the numerical code from *Heinrich et al.* [2000]. The ground deformation has been calculated using Okada's formulas based on shear faulting theory [*Okada*, 1985]. These formulas give the ground displacement as a function of seismic parameters. The initial water surface elevation is assumed to be given by the permanent vertical deformation of the ocean bottom. The model uses the classic shallow water assumption because frequency dispersion plays a minor role for short propagation distances. The nonlinear long wave equations are solved by means of a staggered-grid finite-difference method using a Godunov-type scheme. The tsunami propagation is modelled in an area of 34.1×32.6 km^2 combining the swath bathymetry data gathered during the Aguadomar cruise (R/V *L'Atalante*, 1999) with on-land data provided by the French National Geographic Institute (IGN). Data for shallow water (<100 m) areas are from the SHOM (Service Hydrographique et Océanographique de la Marine). The model with a grid step of 100 m cannot take into account the vegetation density so that a final run-up height is not calculated. Thus the computation is stopped at the flow depth on the shoreline, the later being taken as a perfect reflector [*Heinrich et al.*, 2000].

[5] The objectives of this article are: 1/to present results of the 21 November 2004 tsunami field survey; and 2/to simulate the tsunami propagation from the source area to Les Saintes and to the south coasts of Guadeloupe. Numer-

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[1] Institut de Physique du Globe de Paris and CNRS UMR 7154, Equipe Géologie des Systèmes Volcaniques, Case 89, Paris, France.

[2] Laboratoire de Détection et de Géophysique, Commissariat à l'Energie Atomique, Bruyères-le-Châtel, France.

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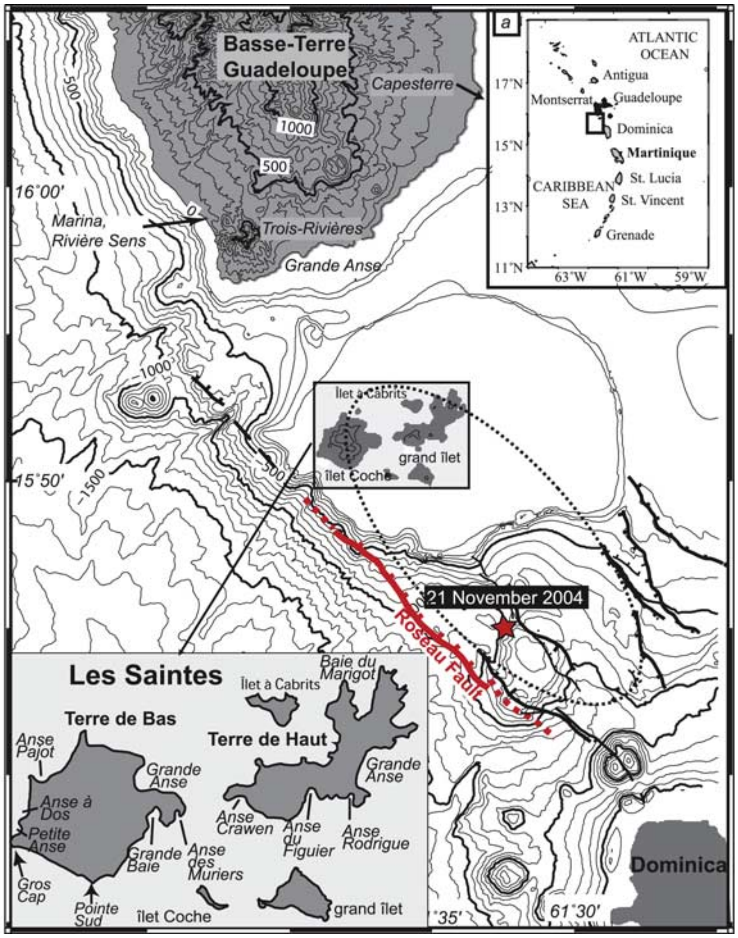

Figure 1. Map of the main active faults between Basse-Terre (Guadeloupe) and Dominica are reported from *Feuillet et al.* [2004] and in N. Feuillet (manuscript in preparation, 2008). Bathymetry and topography: contour interval is 100 m, 500 m contour lines are annotated. Star is the epicenter of the 21 November 2004 earthquake. Dashed line ellipse shows the extent of earthquakes locations [*Duclos et al.*, 2007].

ical simulations have been constrained by tsunami signatures to test values of parameters of the earthquake.

2. Tsunami Field Survey

[6] We conducted our field survey in Guadeloupe (Basse Terre) and Les Saintes few days after the earthquake. We added some complementary results from the field survey of [*Zahibo et al.*, 2005] to our study.

[7] On the basis of eyewitness records, a series of observations is reported in Table 1 showing that the sea receded and then rose back during the earthquake. At Terre de Haut (Baie de Marigot), the sea level dropped by 1 m to 1.20 m and the water receded over a distance of 80 m about 5 minutes after the earthquake. This sequence happened at least twice. In Anse Rodrigue, the coral reefs were exposed. At Terre de Bas, in Anse des Muriers and Grande Anse, the sea level dropped 1.5 m to 2 m after the earthquake; *Zahibo et al.* [2005] reported that at Anse à dos, a fisherman said that water receded a distance of 2–3 m just after the earthquake and rose back to normal level. At 3 Rivières, on Guadeloupe, one fisherman reported that his boat dropped down about 50 cm and then rose back [*Zahibo et al.*, 2005]. On the northern coast of Dominica, the sea receded over 10 m about 10 minutes after the earthquake.

[8] Characteristics of the observed tsunami signatures have been reported in Table 1. Two main types of signatures have been observed (Figure 2 and Table 1): (1) seaweed, floated trees and other objects found directly on the beaches which are representative of the real run-up values; (2) fishes, seaweed, fishing nets plastered against some cliffs which represent a higher run-up. The observed run-up and the maximum flood length can reach respectively 3.50 and 42 m in Terre de Haut (Les Saintes), 2.0 and 22 m in Terre de Bas (Les Saintes) and less than 1 m and 24 m in Basse-Terre (Guadeloupe). In Terre de Bas, some dead fishes were reported at a height of 1.80 m above normal sea level. A restaurant owner reported that in Grande Anse, the wave reached a house located at a distance of 22 m from the usual sea shore with an estimated run-up height of around 2 m (Figure 2). At Anse Pajot, a height of 0.5 m was reported by *Zahibo et al.* [2005]. In Terre de Haut, at Anse Rodrigue, an inhabitant reported that a trunk (2 m length, ~40 cm diameter) has been transported on the beach up to 42 m in distance from the usual sea shore (estimated run-up: 2 m). A positive wave reached a house at Baie de Marigot, 15 m from the usual sea shore. At Anse Crawen, some dead fishes were reported on the cliff at 2.80 m above normal sea level. In Basse-Terre island (Guadeloupe), the maximum flood

Table 1. The 21 November 2004 Tsunami: Run-Up Heights (H) and Maximum Flood Length (L) Recorded During the Field Survey[a]

	Tsunami Deposits			Sea Recession	
Location	Observations	L(m)	H(m)	L (m)	H (m)
	Terre De Haut-Les Saintes				
Baie de Marigot	flooding (restaurant)	13–15	1	80	1–1.2
Grande Anse	seaweed	32	2		
	seaweed + rope		3		
Anse Crawen	seaweed	10	0.8		
	seaweed	*1*	*3.5*		
	fish	*1*	*2.8*		
Anse Figuier	seaweed + net	16	1.6		
	(E)	24	1.5–2		
	seaweed (W)	*7*	*2.4*		
	seaweed + pebble, wood + shell (E)		*2.5*		
Anse Rodrigue	tree log	42	2		
	Terre De Bas-Les Saintes				
Anse des Muriers				∼5–10	1.5
				5	**0.8**
Grande Anse	flooding	22	2		2
			0.7		
Petite Anse	seaweed	12.5	1.5	**2–3**	
Anse Pajot			**0.5**		
Grande Baie	*shell, sand, fishnet*		*1.5*		
	fish, sand		*1.8*		
	Basse-Terre Guadeloupe				
Capesterre	seaweed + wood	16	0.3		
Grande Anse, 3 Rivières	north, wood	13.5	0.3		0.5 *
	south, wood	24	0.3		
Rivière Sens, Marina				**Yes**	**Yes**

[a] Values from *Zahibo et al.* [2005] (in bold). Higher run-up values (in italic) are attributed to short waves produced by the interaction of the tsunami with complex bathymetry.

distance reached 24 m at Grande Anse with a 0.3 m run-up. Finally, *Zahibo et al.* [2005] reported some fresh rockslides and landslides on the south coast of Terre de Bas between "Pointe-Sud" and "Gros-Cap". As a result of the confusion among the population following the earthquake, the precise timing for the impact of the tsunami is unclear although it seems that it happened from 4 to 15 minutes after the earthquake, depending on the areas.

3. Propagation of the Tsunami Throughout the Southern Part of Guadeloupe Archipelago

[9] The ocean bottom deformation has been calculated using the fault location from the CDSA and the fault parameters (referred hereafter to the standard ones), defined by a dip angle of 50°, a fault length of 15 km, a strike angle of 320°, and a 1m slip. The failure depth was chosen such that the upper edge of the failure plane would be at the surface. The resulting initial sea surface (Figure 3a) is composed of a large trough with an amplitude of −0.5 m and a 0.3 m amplitude positive wave. The maximum water height calculated by the model is shown in Figure 3b. In order to best fit the available field observations, a series of sensitivity tests has been performed by varying fault parameters within a range of realistic values from the standard ones (location of the source, length and width of the fault, dip, strike). When using lower dip values (35° for USGS or 44° for Harvard), larger biases between model and observations are obtained (up to 20% on the calculated maximum height values). Note that a 50° fault dip is in good agreement with the value proposed by *Duclos et al.* [2007] on the basis of relocation of aftershocks recorded by a network of Ocean Bottom Seismometers (OBS). Variations of the strike value between 315° and 325° are not significant (less than 5% for calculated maximum water heights). By using a slip of 1.5 m on the fault (instead of 1.0 m), the maximum water height calculated along the shoreline is proportionately increased. Numerous sensitivity tests have been also performed on the fault location. By using the USGS location, maximum water heights are lower than observed (up to 50% on the southern coast of Terre de Haut). Maximum water heights are obtained on Terre de Bas using a source 13 km north from the USGS location (4 km towards SW of Terre de Bas) whereas they have been reported on the southern coast of Terre de Haut.

[10] Using the standard source, the temporal constraints are respected, with the sea receding back during the first 3 minutes on the south coast of Terre de Bas and the sea level dropping by less than 1 m (Figure 3a). In Trois Rivières (Basse-Terre, Guadeloupe), the sea receded back and dropped down about 0.5 m after 7 minutes, as observed by *Zahibo et al.* [2005]. In Terre de Haut, the sea rose up after about 7 minutes on all the southern coasts (Figure 3a). The main positive wave reached Marigot Bay about 9 minutes after the earthquake which is coherent with eye witnesses (5–10 minutes reported). Figure 3b compares the maximal water heights after a 21 minutes modelling time with the observed run-up values on the beaches. The highest values of run-up (about 3.5 m on cliffs) are not reported since they are attributed to very short waves, produced by the tsunami interaction with complex bathymetry, and the 100 m resolution model cannot reproduce their propagation. The calculated water heights are in agreement with most of the reported run-up values (Terre de Haut: Marigot Baie, Grande Anse, Anse Rodrigue, Anse Figuier, Anse Crawen; Terre de Bas: Anse Pajot).

Figure 2. Tsunami signatures observed one week after the earthquake (Les Saintes): (a) Grande Anse, Terre de Bas, maximum flood length: 22 m, run-up height: 2 m; (b) Anse Rodrigue, Terre de Haut, charred tree carried by the tsunami, maximum flood length: 42 m; and (c) Anse Crawen, Terre de Haut, sea weed (run-up height: 3.50 m), fish (run-up height: 2.80 m).

[11] The main discrepancies are located in Terre de Bas, the first one in Petite Anse on the SW coast, the second one in Grande Anse on the NE coast.

[12] In Petite Anse, the observed 1.5 m run-up is probably due to the amplification in the bay (around 200 m long), which is not represented in our 100 m resolution model as observed on Figure 3b. With respect to Grande Anse, we note that the high value (2 m) is an isolated record on the northern coast where observed run-up values are usually lower than on the southern coast. Analysis of tsunami propagation shows that the first positive wave, with a period of about 8 minutes, propagates around the W and E heads of Terre de Bas and Terre de Haut respectively. The wave attenuates progressively as it propagates along the N coasts of both islands, which accounts for the calculated water heights smaller than 40 cm in Figure 3b. The maximum water heights modelled in Grande Anse originate from the first wave penetrating the channel between Terre de Bas and Terre de Haut. This positive wave, with a maximum amplitude of about 0.5 m, is composed of several crests with periods of around 2 minutes. After the channel widening in front of Grande Anse, the maximum amplitude decreases by a factor of 3 and does not significantly amplify in this large bay. From these results, the observed run-up could be associated to the very short wave lengths, which the model partially captures. Another hypothesis is that the 2 m run-up is produced later and originates from short waves induced by multiple reflections between Terre de Haut, Terre de Bas and Ilet à Cabris.

4. Discussion and Conclusion

4.1. The 21 November 2004 Tsunami

[13] Field surveys from this study and *Zahibo et al.* [2005] confirm the occurrence of a tsunami following the 21 November 2004 earthquake in the southern part of Guadeloupe archipelago. Results from field surveys indicate that the maximum run-up height was about 2 m on the beaches. Most of the run-up height values were confirmed by inhabitants, who described typical tsunami movements. For some of the deposits without witnesses, we cannot exclude an origin by storm waves which occurred at the same time of the tsunami. Using the standard fault parameters, numerical simulations reproduce the chronology and the amplitude of the first movement of the sea, and most of the tsunami heights reported on the beaches. From these numerical results, we can deduce than such an earthquake can produce the observed tsunami.

[14] In order to account for mismatches between observed and calculated values in Terre de Bas (Petite Anse and Grande Anse), other sensitivity tests have been performed on the tsunami source. The hypothesis of a ‘‘tsunami earthquake’’ generated by a submarine landslide following the earthquake has been considered [*Rabinovich et al.*, 2003]. Numerical simulation using the same earthquake source located 5 km offshore Terre de Bas has been performed to test the occurrence of a large submarine landslide in this area. (We use the assumption that, in some conditions, both an underwater slump and a seismic dislocation produce tsunamis of total comparable energy [*Okal and Synolakis*, 2003]). In this case, numerical results on the south coasts of Terre de Haut show that the calculated water heights along the shoreline are much lower than the observed ones.

[15] From these tests, discrepancies between observed and calculated values in Terre de Bas could thus be attributed to: 1/a more complicated geometry of the fault with a northward extension in the direction of Terre de Bas; 2/the low 100 m resolution of the digital terrain model; 3/the spatial resolution of the model and some multiple effects attributed to complex bathymetry.

[16] Considering the earthquake as the source of the tsunami, we explain the propagation and high impact of waves on islands by: on the one hand, the shallow depth of the earthquake, on the other hand, the complex bathymetry

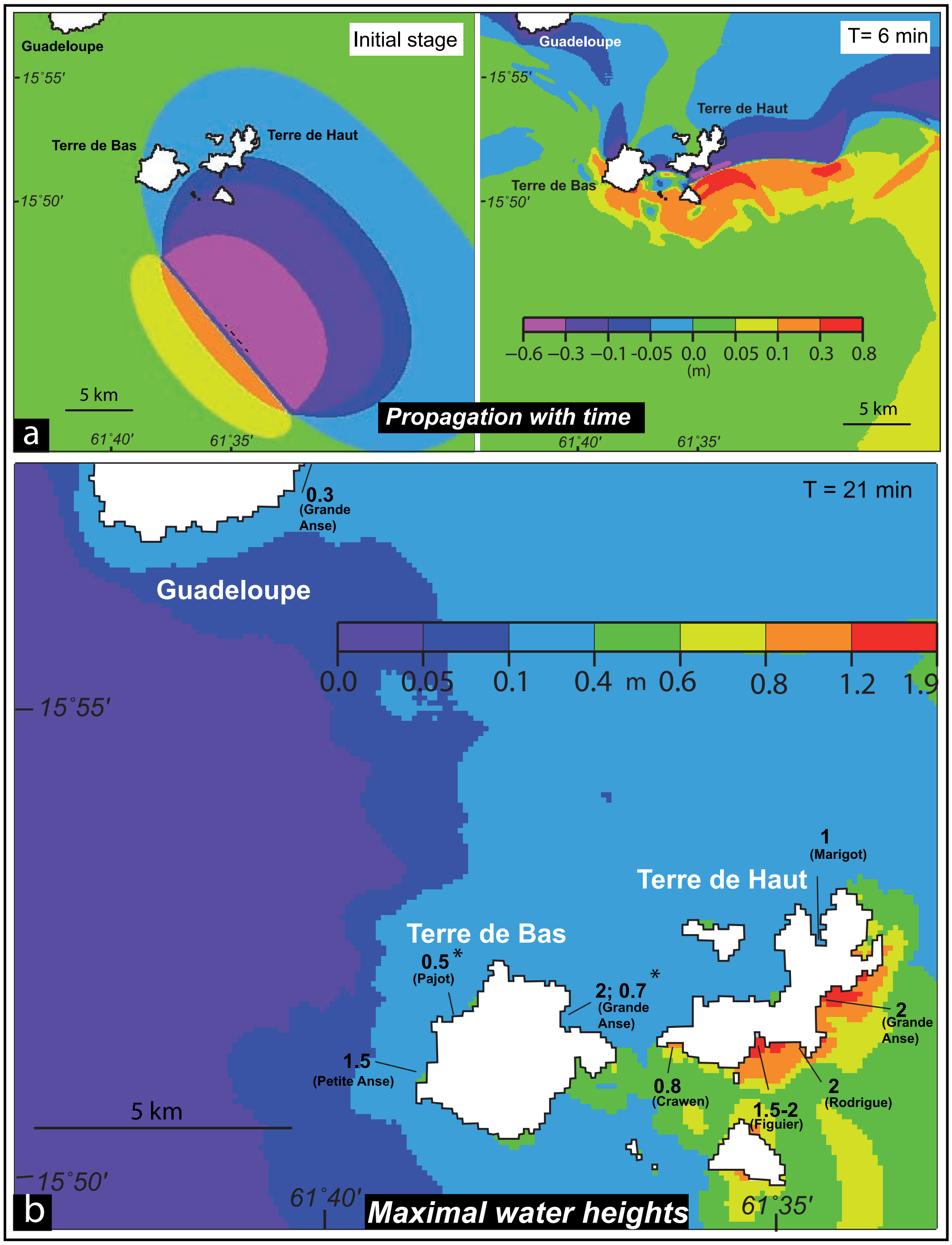

Figure 3. Numerical simulation of the tsunami propagation using the following parameters (length = 15 km, strike = 320°, dip = 50°, slip = 1 m). (a) Water heights are reported at different times. (b) Maximal water heights after a 21 minutes modelling time. Run-up values from field survey are reported (values with asterisk are from *Zahibo et al.* [2005]).

of the area (shallow submarine shelf surrounding Les Saintes and presence of bays amplifying water heights). We note that the recent 29 November 2007 earthquake (Mw = 7.4) which occurred offshore the north part of Martinique with a focal depth of 152 km, did not generate any recorded tsunami.

4.2. Tsunamis in the Lesser Antilles Arc

[17] The 21 November 2004 is the first tsunami in historical time to affect the coasts of the Guadeloupe archipelago following an intra-plate earthquake. The tsunami triggered by the 1843, Mw 8 shock north-east of Guadeloupe affected the coast of Antigua. A tsunami that impacted the coasts of Guadeloupe in 1867 [*Bernard and Lambert*, 1988] was triggered by the "Porto Rico" earthquake of 18 November 1867 with an epicenter in the Virgin Islands (North of the Lesser Antilles arc). If several tsunamis produced by earthquakes occurring offshore have already been recorded during the historical period in the Lesser Antilles [*Lander et al.*, 2002], only partial data exists pertaining to their characteristics and origin. The 21 November 2004 earthquake provides a unique opportunity to have both: 1/the precise characteristics of the earthquake; 2/characteristics of the tsunami signatures including the observed tsunami heights and the eyewitness records by the local population in the days following the earthquake.

[18] Significant tsunamis in the Lesser Antilles arc can also be produced by the entrance of volcanic products into the sea as on 26 December 1997 and 13 July 2003 in Montserrat when the active lava dome collapsed [*Herd et al.*, 2005]. *Boudon et al.* [2007] show that 47 flank-collapses have affected the Lesser Antilles volcanoes where this type of behaviour is characteristic and repetitive.

[19] Although destructive tsunamis are infrequent compared to seismic or volcanic activity in the Lesser Antilles, their consequences could be catastrophic on these islands where most of the population occupies costal areas. In the event of a much larger earthquake than the 21 November 2004 shock, authorities will face serious difficulties in alerting the population because a tsunami could reach the coastline of neighbouring islands in less than 10 minutes. Taking into account the high level of seismic and volcanic activity in the Lesser Antilles arc, hazards related to tsunami have to be considered as well as mitigation strategies.

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G. Boudon and A. Le Friant, Institut de Physique du Globe de Paris, 4 Place Jussieu, F-75252 Paris CEDEX 05, France. (lefriant@ipgp.jussieu.fr)

P. Heinrich, Laboratoire de Détection et de Géophysique, Commissariat à l'Energie Atomique, F-91680 Bruyères-le-Châtel, France.