THE EARTHQUAKE AND TSUNAMI OF NOVEMBER 21, 2004 AT LES SAINTES, GUADELOUPE, LESSER ANTILLES

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ABSTRACT

A strong earthquake ($m_b = 6.3$; $M_s = 6.1$; $M_w = 6.3$) occurred on 21 November 2004 in the Dominica Passage separating Guadeloupe and Dominica, in the Lesser Antilles, and generated a weak tsunami with maximum amplitudes of +70 and -80 cm on neighbouring islands. We conducted field surveys on the islands of "Les Saintes", in the immediate vicinity of the epicenter on November 27, 2004 and February 12, 2005, and report here on the resulting dataset.

1. Introduction

The earthquake which occurred on November 21, 2004 at 11:41:07 UTC (07:41 local time) in the Dominica Passage, Lesser Antilles (Figure 1) was the strongest in this area since 1969. Preliminary epicentral coordinates given by the National Earthquake Information Center of the U.S. Geological Survey are 15.677°N, 61.650°W, with a focal depth of 14 km, and conventional magnitudes m_b = 6.3, M_s = 6.1. The USGS Moment Tensor Solution has a moment of 3.2×10^{18} Nm (M_w = 6.3), and a centroid location at 15.681°N, 61.693°W, 6 km depth; its focal geometry is: strike ϕ = 327°, dip δ = 35°, slip λ = -92°. The Harvard CMT inversion yields a comparable geometry (ϕ = 317°; δ = 44° deg. λ = -88°) with a moment of 3.35×10^{18} Nm and a centroid at 15.81°N, 61.63°W with a depth of 12 km. Thus the earthquake is readily interpreted as a shallow normal faulting event taking place in the back-arc; the slight deficiency of M_s relative to m_b could be indicative of a somewhat fast strain release, suggestive of a higher-than-normal stress drop. This is further supported by the analysis of estimated energy (Newman and Okal, 1998), which yields a slowness parameter Θ = -4.59, slightly greater than predicted by scaling laws (-4.90). As of the time of writing, the earthquake had 8 aftershocks with $m_b \geq 5$, the latest and largest aftershock to date (m_b = 5.7 on February 14, 2005) having inflicted additional damage in the epicentral area.

Figure 1. Map of the Caribbean basin showing the location of the earthquake of November 21, 2004.

A five-year old girl was killed and two other persons injured in Trois-Rivières (Guadeloupe, approximately 35 km from the epicenter; see Figure 1 for locations). One person was injured in Capesterre (Guadeloupe) and ten people suffered minor injuries in Petites-Anses (Island of Terre–de-Bas, Les Saintes, 20 km from the epicenter). Many buildings were destroyed or damaged in locations as far away as Pointe-à-Pitre, 65 km away from the epicenter, as well as in Portsmouth, Dominica (25 km from the epicenter; see Figures 2-4). To the North, the earthquake was felt in Antigua and Barbuda (150 km) and St Kitts and Nevis (190 km) and to the South as far away as Saint Lucia (220 km). This event was widely discussed and commented in the local newspaper "France-Antilles" (Guadeloupe) and on local television. However, any information about the possible generation of a tsunami by the earthquake was notably absent from media reports, which motivated the field surveys carried out in the aftermath of the event. We give below a sample of photographs and witness reports.

Figure 2. Houses at Trois-Rivières, Guadeloupe damaged during the earthquake (Photographs by N. Zahibo and A. Yalçıner). In the last photograph, the islands of Les Saintes, where the earthquake was destructive, can be seen in the background.

Figure 3. Houses damaged by the earthquake at Petites-Anses, Terre-de-Bas Island (Les Saintes, Guadeloupe; Photographs by N. Zahibo and A. Yalçıner).

Figure 4. Roman Catholic and Methodist Churches at Portsmouth, Dominica damaged during the earthquake (Wayne Abraham, http://dominicapsn.freeyellow.com/gallery.html).

2. Background: historical tsunamis in Guadeloupe and Dominica

Figure 5. Seismicity of Guadeloupe and Dominica (left), and distribution of earthquakes with magnitudes greater than 5.0 (HTDB/ATL, 2002). Note that, before the November 2004 earthquake, the latter were concentrated at the trench.

As documented on Figure 5 (HTDB/ATL, 2002), the seismicity of the area is generally high, but most earthquakes remain weak, with only eight events (listed in Table 1) exceeding a magnitude of 6.

Of those, the pre-instrumental event of 08 February 1843, estimated at M = 8.3 by Shepherd and Lynch (1992), occurred to the Northwest of Guadeloupe. It was disastrous in the economic capital of Pointe-à-Pitre, where 1500 people were reported killed, amounting to one-third of the population at the time, and was felt strongly (at MMI IX to X) in St Kitts, Montserrat, Martinique, St. Lucia and other islands, and was also felt as far away as Surinam, Bermuda and South Carolina. This earthquake was accompanied by a tsunami at Antigua where the sea rose 1.2 m (Lander *et al.*, 2002). However, the motion of the sea on the coast near Pointe-à-Pitre was, in fact, rather weak, the water barely inundating a few low-lying steps along the city's quays, with similar effects in Basse-Terre and Les Saintes (Guadeloupe), and in Dominica (Sainte-Claire Deville, 1867).

Table 1. List of local earthquakes with magnitude exceeding 6.0

Year	Month	Day	Lat (N)	Lon (W)	Depth	M
1843	2	8	16.5	62.2	33	8.3
1897	4	29	16.1	61.3	33	7.5
1906	12	3	15	61	100	7.9
1969	12	25	16.08	59.77	8	6.5
1969	12	25	15.79	59.7	7	7.5
1982	1	30	16.74	61.43	63	6.0
1995	3	8	16.56	59.56	8	6.3
1996	9	24	15.19	61.44	146	6.0

The earthquake of December 25, 1969 (m_b = 6.4; M_s = 7.5; M_0 = 7.8 × 10^{19} Nm; Stein *et al.*, 1982) was felt on Guadeloupe, Dominica, Martinique, St. Vincent, Antigua and Barbados. It was accompanied by a weak tsunami recorded at Barbados, Antigua and Dominica, with a maximum amplitude of 46 cm at Barbados. The single tide-gauge record of this event at Dominica (maximum amplitude 12 cm) is presented in Figure 6.

Figure 6. Tsunami of December 25, 1969 recorded at Dominica (Shepherd, 2001).

In addition, a tsunami was generated on February 17, 1843 by a submarine eruption "half-way between Guadeloupe and Marie-Galante", when a water column of 30 m was ejected from fissures in the ground (Lander *et al.*, 2003).

All other tsunamis reported to have reached Guadeloupe and Dominica originated from distant earthquakes. The first such event is the strong earthquake at Lisbon, Portugal on November 1, 1755, whose tsunami was recorded throughout the Caribbean, from Barbados to Cuba, with run-up reported to have reached 3.6 m at Samana Bay, Dominica (Lander *et al.*, 2002).

The tsunami from the strong earthquake of November 18, 1867 in the Virgin Islands (with an estimated magnitude of 7.5) was recorded in Guadeloupe with an amplitude of about 10 m at Deshaies and only 1 m at Basse-Terre and Fond Curé (Terre-de-Haut, Les Saintes; Zahibo and Pelinovsky, 2001); this event was modelled by Zahibo *et al.* (2003).

A moderate earthquake (m_b = 6.3; M_w = 6.3) occurred on March 16, 1985, causing damage and injuries to six people in Guadeloupe; a tsunami reaching several centimeters was recorded at Basse-Terre, Guadeloupe (Lander *et al.*, 2002).

The last tsunami recorded in Guadeloupe before 2004 took place on 13 July 2003, when a wave with an amplitude of about 1 m reached Deshaies (Northern Guadeloupe), following the penetration of the sea by a large pyroclastic flow during the volcanic eruption at Montserrat, 65 km away (Pelinovsky *et al.*, 2004).

In conclusion, at least seven verified occurrences of tsunamis took place in Guadeloupe and Dominica between 1843 and 2003, most of them originating from submarine earthquakes. Taking into account that strong earthquakes with magnitude greater than 7.0 occurred in this area in the past 200 years, and also the documented hazard from distant tsunamis, we may conclude that the probability of a large tsunami at Guadeloupe in the future is high.

3. Field surveys of the 2004 Les Saintes tsunami

Unfortunately, no instrumental records of the 2004 tsunami are available, since no tide gauges are presently operational in Guadeloupe. (One such instrument did operate in the past at Basse-Terre, and provided a record of the 1985 tsunami.) In addition, a heavy storm took place on the day of the earthquake (November 21, 2004), and prevented the observation of weak oscillations of the sea level, as witnesses reported what turned out to be mostly storm surges, especially on the coast of the island of Marie Galante.

We conducted our field inspection at Trois-Rivières (Southern Guadeloupe) on November 23, 2004, two days after the earthquake and found the first witness of the tsunami in this coastal location. Detailed surveys took place on November 27, 2004, and on February 12, 2005.

Basse-Terre (part of the main Island of Guadeloupe) (see Figure 7 for location of all points, and tsunami heights in cm).

Figure 7. Map of the main island of Guadeloupe.

Village of Trois-Rivières. One person (a 5-year old girl) was killed, at least two other injured, and several houses destroyed or damaged in this village (Figure 3). In the port (15°58'084N, 61°38'695W), one fisherman reported that his boat dropped down about 50 cm during the earthquake and then rose back; he was afraid his boat could hit the sea bottom and tip over. A panorama of this port is shown in Figure 8.

Figure 8. Panorama of the port of Trois-Rivières, where the reported tsunami depression was about 50 cm

Marina de Rivière Sens (city of Basse-Terre). One witness informed us that the water dropped down a few cm and then rose back during the earthquake. A panorama of the beach where the tsunami was recorded is shown in Figure 9.

Figure 9. Panorama of the Marina de Rivière Sens, where the tsunami was reported as a weak depression.

Island of Terre-de-Bas, Les Saintes (see Figure 10 for location of points and wave amplitudes).

Figure 10. Map of Terre-de-Bas Island.

Village of Grande Anse, Bay "Anse des Muriers" (15°51'260N, 61°36'968W). A ship captain reported that 3 minutes after the earthquake, the sea receded 5 m (and dropped 80 cm) and rose back to its still level, over perhaps 1 minute. Photographs of this bay are given in Figure 11.

Figure 11. Panorama of the bay and interview of the tsunami witness in Bay "Anse des Muriers".

Figure 12. Panorama of the bay "Grande Anse", and interview with restaurant owner (left); the tsunami reached the house on the beach (right).

Beach of Grande Anse (15°51'547N, 61°37'476W). A restaurant owner informed us that the tsunami began as an ebbing phase, and then a positive wave reached a house on the beach; we surveyed this run-up as 70 cm (see Figure 12). According to this witness, the wave shape was

like an undular bore, which could have resulted from significant wave dispersion on this locally very gently sloping beach.

Village of Petites Anses. At least eight houses were destroyed and twenty-five damaged in this village (Figure 3). At the small bay "Anse à Dos" (see Figure 10 for location), a fisherman said that water receded a distance of 2 to 3 m just after the earthquake, and then rose back to normal level.

Bay "Anse Pajot" (see Figure 10 for location). A watermark at a height of about 50 cm was found on February 12, 2005 during the second survey around Terre-de-Bas (Figure 13). Early observation of these traces by local inhabitants suggests their deposition by storm surges, even though no major precipitation occurred since the day of the tsunami.

Figure 13. Watermarks in the bay "Anse Pajot".

Bay "Anse à Chaux" (see Figure 10 for location). Large watermarks are also visible on the beach in this bay (Figure 14). Here again, storm surges are preferred as their origin. According to reports from fishermen, storm waves approach mainly from the North, and this explains why such watermarks would be found only in those two bays, favorably open to the prevailing winds.

The southwest part of the coast, between capes "**Pointe-Sud**" and "**Gros Cap**" (see Figure 10 for location), facing directly towards the earthquake epicenter, features many fresh rockslides and landslides (Figure 15), identified by local residents as triggered during the earthquake. There, the coast is locally very steep (with cliffs as high as 30 m), and the identification of potential tsunami deposits is thus very difficult. On the South-east coast, from "Grande Baie" to "Pointe Frégate", the beach is lower (Figure 16), but we could not find definitive tsunami traces.

Figure 14. Visible traces of the wave runup in the bay "Anse à Chaux".

Island of Terre-de-Haut, Les Saintes. As one witness reported, an "unusual" surge was observed in "Baie du Marigot" (see Figure 7 for location), but there were no reports of earthquake damage from that island.

As a complement to the tsunami dataset, we quote below a message from Mr. Wayne Abraham, an amateur seismologist on Dominica, founder/coordinator of the Dominica Public Seismic Network and webmaster of the website *http://dominicapsn.freeyellow.com*: "Ten to twenty minutes after the main 6.3 shock, credible witnesses including a retired high-school teacher and a younger high-school teacher reported a significant drawing back of the sea in the Portsmouth harbour leaving fish stranded. The younger of the two even entered the area where the sea drew back and started throwing fish back into the withdrawn sea before he was beckoned to get out as there may be a possible danger of tsunami. There were no photos of the withdrawn sea but a photo was taken just after it returned, before the second - so called – wave".

Figure 15. Locations of rock- and land-slides on the Southwest coast of Terre-de-Bas.

Figure 16. Beach on the west part of the bay "Grande Baie", Terre-de-Bas.

Finally, we would like to point that two of the authors (NZ and EP) felt the earthquake and observed the appearance of resonant water oscillations in swimming pools immediately after the earthquake. Both pools are located in the northeastern part of Guadeloupe (Pointe-à-Pitre and Baie-Mahault), and in the latter case, the water overtopped the basin walls due to the small size of the pool. The seiches were polarized in the direction of the main shock (essentially north-south).

4. Conclusion

We have presented the results of field surveys of the earthquake and tsunami of November 21, 2004 in Guadeloupe. As expected, this earthquake, with magnitude 6.3, generated only a weak tsunami with run-up not exceeding 70 cm and depressions of at most 80 cm. This event constitutes at least the seventh tsunami documented in the Guadeloupe-Dominica area. However, it is rather unique among recent events in its location as a shallow normal faulting event in the back-arc. The earthquake was remarkably destructive, notably in Terre-de-Bas, due to a combination of a tendency towards to a fast source, a shallow depth, and probably site amplification of ground motion in the sedimentary basin under Petites Anses. While the tsunami amplitudes remained minimal, this earthquake serves to emphasize the constant tsunami risk in the area, notably in view of the numerous landslides triggered by the seismic event.

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