ISSN 8755-6839

SCIENCE OF TSUNAMI HAZARDS

Journal of Tsunami Society International

Volume 29 Number 3 2010

TSUNAMI CATALOG AND VULNERABILITY OF MARTINIQUE (LESSER ANTILLES, FRANCE)

Accary, F.[1,2], Roger, J.[2]*

[1] Université Paris 1 Panthéon-Sorbonne, Laboratoire de Géographie Physique, UMR 8591, 1 place Aristide Briand, 92195 Meudon Cedex, France.

[2] Ecole Normale Supérieure, Laboratoire de Géologie, UMR 8538, 24, rue Lhomond, 75231 Paris cedex 5, France

*e-mail: jeanrog@hotmail.fr

ABSTRACT

In addition to meteorological hazards (hurricanes, heavy rainfalls, long-period swells, etc.), the Caribbean Islands are vulnerable to geological hazards such as earthquakes, landslides and volcanic eruptions caused by the complex tectonic activity and interactions in the region. Such events have generated frequently local or regional tsunamis, which often have affected the island of Martinique in the French West Indies. Over the past centuries, the island has been struck by destructive waves associated with local or regional events - such as those associated with the eruption of the Saint-Vincent volcano in 1902 and by tsunamis of distant origin as that generated by the 1755 Lisbon earthquake.

The present study includes a classification of tsunamis that have affected Martinique since its discovery in 1502. It is based on international tsunami catalogs, historical accounts, and previous scientific studies and identifies tsunamigenic areas that could potentially generate destructive waves that could impact specific coastal areas of Martinique Island. The potential threat from tsunamis has been greatly increasing because of rapid urban expansion of coastal areas and development of tourism on the island.

Key- words: Tsunami, earthquakes, landslides, volcanic eruptions, Martinique, Caribbean, risk, hazards, vulnerability.

1. INTRODUCTION

1.1 Generalities

The Caribbean region, with its complex geodynamic and climatic context, is particularly prone to tsunami generation (O'Loughlin and Lander, 2003). The Caribbean tectonic plate is bordered to the north and south by numerous strike-slip faults where major earthquakes can occur. The magnitude Mw 7.0 Haiti earthquake of 12 January 2010 (Leroy et al, 2010) is a recent example of a destructive seismic event - similar to others that has occurred in the past along the Northern Caribbean margin (Pararas-Carayannis, 2010). Also, destructive earthquakes occur along the eastern boundary of the Caribbean plate (Germa, 2008) where there is active subduction with the North American plate at a rate of 2 cm/year, as well as along the western boundary – particularly along the Pacific coast - which is characterized by a higher rate of subduction of 9 cm/year (Grindlay et al, 2005).

Martinique is located within the Lesser Antilles islands group along the Atlantic subduction zone. This group is distinguished from the Greater Antilles (to the North), which is separated by the Anegada Strait between Puerto-Rico and the Virgin Islands (Fig. 1). The volcanic arc, which constitutes the Lesser Antilles, is over 850 km long and 450 km wide (Zahibo and Pelinovsky, 2001). Its formation results from tectonic processes associated to the subduction of the Atlantic plate beneath the Caribbean plate in two distinct phases: the first from the Eocene to the Oligocene (50 to 20 Myr BP), and the second during the Miocene (10 Myr BP) (OVSG-IPGP, 2005). Martinique and the neighbouring island of Sainte Lucie are located near the center of the volcanic arc and were created by the volcanic activity of these two phases (MacDonald et al, 2000). Numerous volcanoes are still active in the Lesser Antilles and some of them had eruptions and associated collateral events which generated tsunamis: Montserrat (Herd et al, 2005), Guadeloupe (Feuillard et al, 1983), Saint-Vincent (Le Friant et al, 2009), Mount Pelée on Martinique (Pararas-Carayannis, 2006; Leone and Lesales, 2008), Kitts in Saba, Liamiuga in St Kitts and Nevis and the Kick'em Jenny submarine volcano (Smith and Shepherd, 1993, Pararas-Carayannis, 2006) (Fig. 1).

Associated with such geological activity, the tropical climate of the archipelago results in violent storms, frequently causing coastal landslides that can generate local tsunamis. Also, along with the geological hazards associated with earthquakes, volcanic eruptions represent a real tsunamigenic threat. The mechanisms of tsunami generation from volcanic eruptions, debris avalanches, pyroclastic flows and collateral flank failure mechanisms in the Lesser Antilles - and Martinique in particular - have been examined and evaluated (Pararas-Carayannis, 2006). Also several historical catalogs have been compiled for tsunamis and tsunami-like events that have occurred in the region (Lander, 1997; Lander et al, 2002; O'Loughlin and Lander, 2003; Lander et al, 2003), with a special focus on the Lesser Antilles (Zahibo and Pelinovsky, 2001, Saffache, 2005b). However, there seems to have been no specific study of the tsunami hazard in Martinique itself. Thus, the primary objective of the present study is to review the pre-existing databases on events that impacted Martinique and to propose a new catalog, composed only of the well-known and documented tsunamis. Furthermore, the present study reviews briefly the island's vulnerability, with a special emphasis on La Trinité Bay. However, in order to understand the historical accounts of tsunamis that have affected Martinique in the past, we need to review its geographical and geo-tectonic setting.

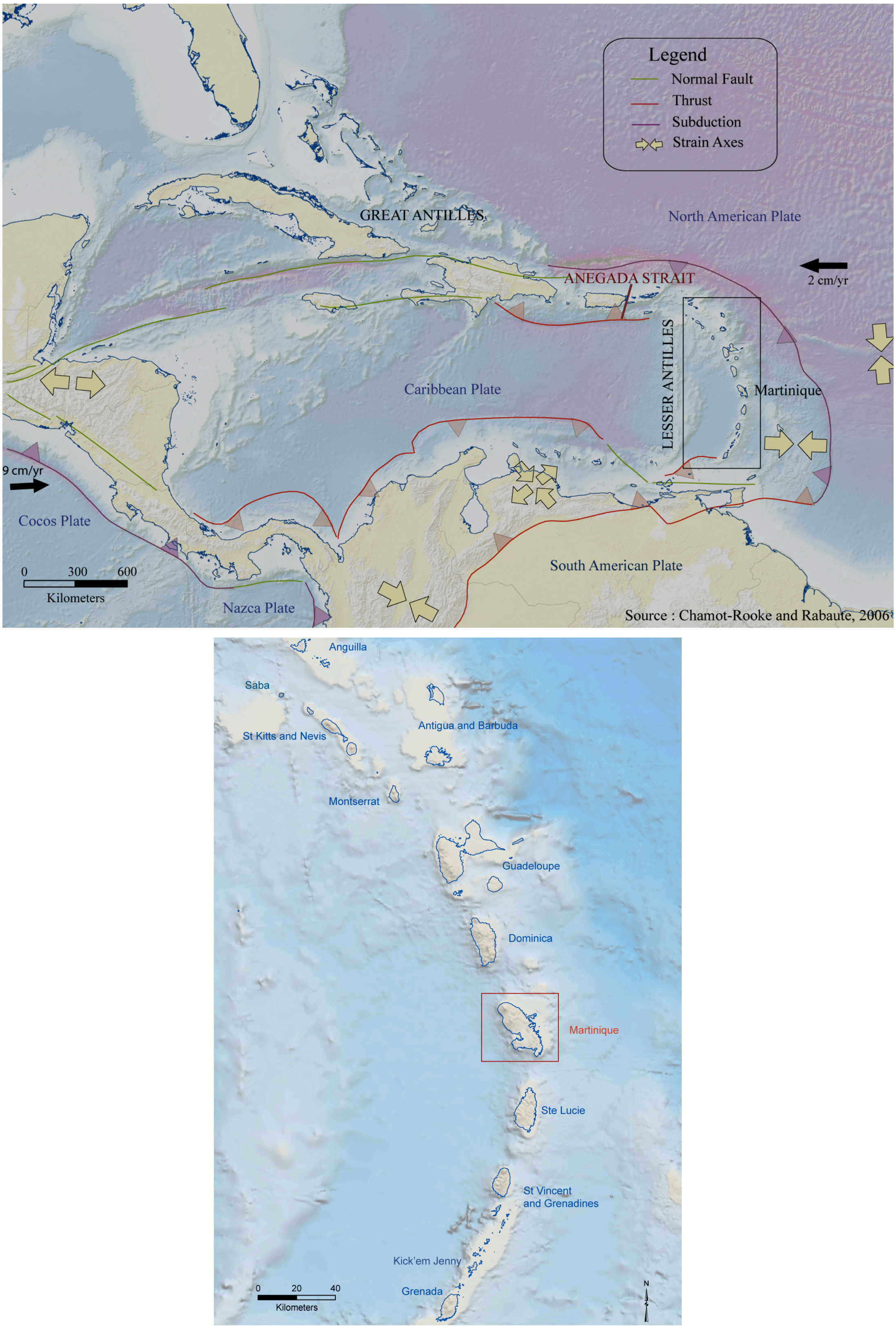

Fig. 1: Geodynamical context of the Antilles (tectonic scheme from Chamot-Rooke and Rabaute, 2006; bathymetric data from GEBCO (IOC, IHO and BODC, 2003) and geographic location of Martinique Island within the Lesser Antilles.

1.2 Martinique

1.2.1 Geography

Martinique is a volcanic island located upon a subduction zone and which has Mount Pelée, an active volcano (Westercamp and Tazzieff, 1980; MacDonald et al, 2000, Pararas-Carayannis, 2006). The island exhibits various reliefs ranging from swamplands near the sea to volcanoes. Mount Pelée reaches 1398 m in height and three other peaks exceed 1000 m. If we draw a line between Fort-de-France (west coast) and La Trinité (east coast) The highest reliefs are found in the northern part of the island (Fig. 2). The southern part of the island is mainly constituted of low hills and swamplands. The littoral exhibits alternation between steep cliffs in the north and sand beaches (Les Anses d'Arlet, la Caravelle, St Anne, etc.) and mangrove forests (Le Lamentin for example) in the south (Saffache, 2005a).

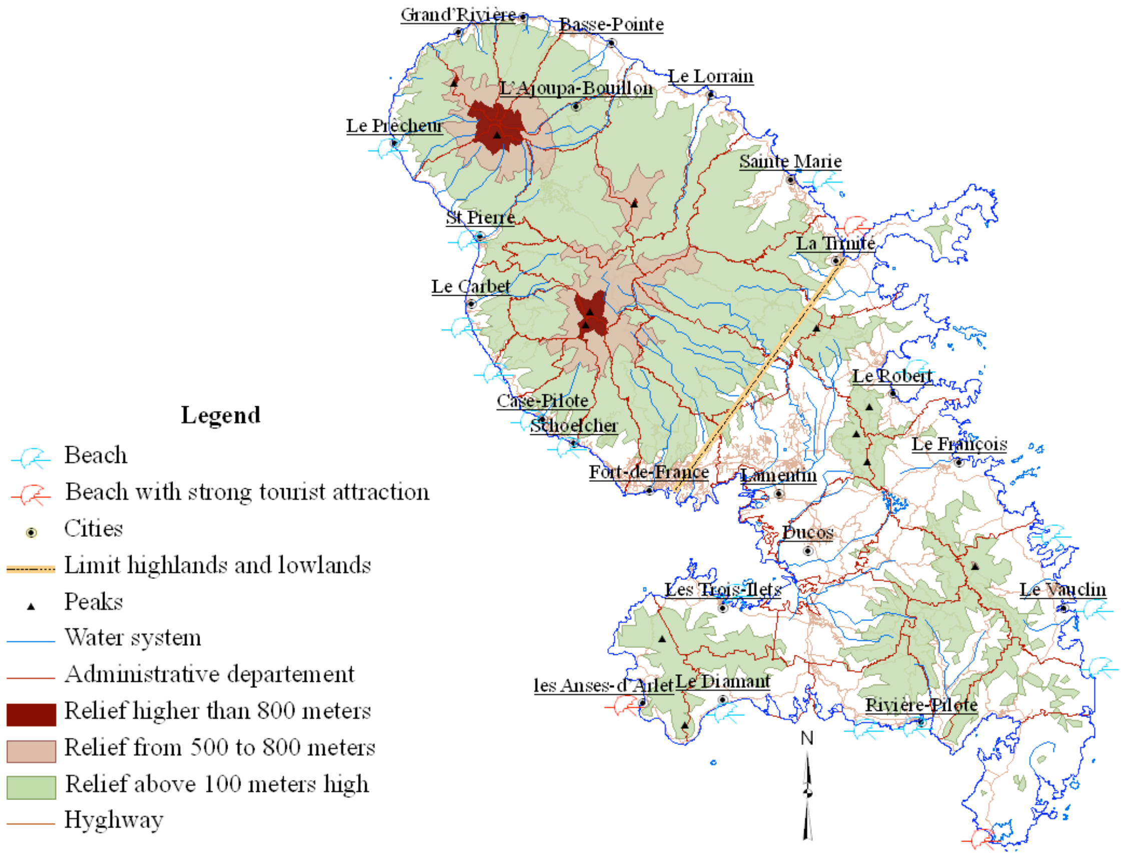

Fig. 2: Geography of Martinique Island. The yellow line indicates the limit between the hilly landscape (northern part) and the plain (southern part).

The great 2004 Sumatra event demonstrated that a steep continental slope and coastal features such as coral reefs, mangrove forests and lagoons help reduce the degree of a tsunami's impact by slowing down its propagation and absorbing or reflecting part of its energy (Kathiresan and Rajendran, 2005, Kunkel et al, 2006). However other coastal features can increase a tsunami's adverse impact by resonance amplification or by inducing strong currents generation usually in bays or harbours (Sahal et al, 2009, Roger et al, 2010a). Beaches with gentler slopes also tend to amplify the wave heights due to a shoaling effect.

1.2.2 Historical Development of Martinique

In pre-colonial times, the island of Martinique was subjected to two successive waves of human settlement, first in the 4th century BC (with the arrival of the Arrawak people) and then in the 13th century AD (with the Caribbean people) (Lalung, 1948). Following the arrival of the Europeans in 1502 and the settlement of French colonists in 1635 (Lambolez, 1905; Chauleau, 1993; Charbit, 2006), the island was integrated into the French colonial empire and its population increased tenfold thanks to triangular trade (Charbit, 2006; Clément, 2009). Nowadays, Martinique has a population of over 400.000 (INSEE, 2009), which is mostly concentrated in the conurbation of Fort-de-France, Schoelcher and Le Lamentin (Calmont and Vassoigne, 1999), as well as in a few other towns deemed attractive, such as Sainte Marie and Le Robert. These five agglomerations concentrate nearly fifty percent of the population of the island (INSEE, 2009).

The bay of Fort-de-France concentrates poles of economic activity, political and decision-making centres and luxury commuter towns (Schoelcher) (Calmont and Vassoigne, 1999). Some southern cities benefit from the attractiveness of heliotropical tourism, which attracts about 700.000 visitors every year (Schleupner, 2007). The increase in tourist influx along the coastal zones and the popularity of seaside activities require that a study of the tsunami hazard has a high priority and must be undertaken, thus we begun by documenting historical tsunami data into the following catalogue.

2. TSUNAMI CATALOG

2.1 Data

The conclusions of the present study rely mainly on the historical database of tsunamis that have been recorded in Martinique and the neighbouring islands. Material used for this database includes original historical documents (testimonies, letters, etc.), which are considered as primary sources, whereas secondary sources are derived from recent studies, tsunami catalogues, simulation results, etc.

2.1.1 The Catalog

Existing historical tsunami catalogs provide a general idea of the tsunami hazard in the Antilles. These catalogs are archived and updated by different government organizations such as NOAA (U.S. National Oceanic and Atmospheric Administration) and the Tsunami Laboratory at Novosibirsk (Russia), or compiled by research of historical records (Lander et al, 2002; O'Loughlin and Lander, 2003; Saffache et al, 2003). Although derived from the same original historical data – which includes dates, source areas, wave heights or other miscellaneous information - these catalogs produce different results because of differences in the methodology of compilation. In our study, all of these existing catalogs have been analysed and inter-correlated in order to produce a single, better-documented tsunami catalog.

The worldwide tsunami catalog from NOAA provided at the following internet site (http://www.ngdc.noaa.gov/hazard/tsu_db.shtml) and that of the Tsunami Laboratory of Novosibirsk (http://tsun.sscc.ru/proj.htm) do not index all the tsunamis that have occurred but only the most significant.

Catalogs by O'Loughlin and Lander (2003) and Lander et al. (1997, 2002, 2003) list tsunamis for the entire Caribbean. The catalog by Saffache et al. (2003) includes earthquakes and abnormal sea level rises that have occurred in the French Antilles (Guadeloupe and Martinique Islands). Although helpful, these catalogs have a broader regional focus and do not provide sufficient information on specific events to be adequate for a risk assessment study of Martinique. To properly assess the risk, it is necessary to review carefully local historical archives as indicated subsequently.

2.1.2 Historical Documents

Analysis of historical documents (Du Tertre, 1668, Boyer-Peyreleau, 1823; Hess, 1902; Lacroix, 1904; Lambolez, 1905), and particularly of various testimonies recorded in Martinique archives (http://www.manioc.org; http://gallica.bnf.fr), highlights details that were omitted from earlier catalogs and scientific papers. Most of these documents report on the 1902 catastrophe on the island (Hess, 1902, Lacroix, 1904) and some provide useful information on its historical development since 1635 (Royer-Peybeleau, 1826; Du Tertre, 1668, Lambolez, 1905). Review of these accounts is helpful in documented the destructive impact of tsunamis on the local population, on the resulting losses and on reactions (Hess, 1902; Lambolez, 1905). Moreover, these accounts provide an important amount of information for specific locations, as for example the impact of the May 5, 1902 tsunami in the vicinity of the Guérin factory (Hess, 1902), as well as on records of false alarms and the lack of proper warning by public authorities during the eruption of the Mount Pelée volcano (Lambolez, 1905). However, in spite of the wealth of details that can be found in these historical sources, many more historical documents pertaining to the Martinique's maritime trade were lost due to the destruction of archives (by the 1902 eruption of Mount Pelée). Hopefully, research studies may help compensate for these gaps in knowledge.

2.1.3 Scientific Studies

Some tsunamis have been investigated in detail through scientific research. Such research provides details, which can complement the data already gathered through historical analysis. Events that have been researched include the 1755 Lisbon earthquake and tsunami (Baptista et al, 1998; Chester, 2001; Baptista et al, 2003; Barkan et al, 2009; Roger and Baptista, 2009; Roger et al., 2010a, 2010b), the 1761 earthquake (Baptista et al, 2006), and those associated with recurring eruptions of the submarine volcano Kick'em Jenny (Smith and Shepherd, 1993, Pararas-Carayannis, 2006). These studies help visualise what could happen in an areas where information is lacking and help assess the generating sources and impacts of potential tsunamis.

2.2 Data Selection

2.2.1 Storm Surges

In reviewing the data in existing catalogs attention was paid in identifying and excluding storm surges that may have been wrongly listed as tsunamis. It appeared that numerous phenomena recorded as tsunamis in Martinique were in fact storm surges generated by storms and hurricanes, which are frequent in the Antilles region (Royer-Peybeleau, 1826; Lambolez, 1905; Saffache et al, 2003; O'Loughlin and Lander, 2003). Thus, seventeen events (in 1642, 1694, 09/12/1756, 08/24/1757, 08/14/1766, 09/05/1776, 10/12/1780, 08/14/1788, 09/06/1816, 10/21/1817, 09/21/1818, 07/26/1825, 09/20/1834, 09/09/1872, 09/04/1883, 08/18/1891 and 08/08/1903) had to be taken away from our catalogue because they had been generated by hurricanes. For example, Revert's account (1949) lists a total of 34 hurricanes between 1633 and 1903. Among hurricane generated storm surges, seven events (in 1642, 1694, 1756, 1757, 1766, 1780 and 1883) were particularly destructive to crops and ships. The worse of these storm surges appears to have been that of August 18, 1891, which wrecked the city of Le Lamentin (Lambolez, 1905) and caused severe damages (Revert, 1949).

2.2.2 Uncertain Tsunamis

After cross-matching data gathered from different scientific studies, some tsunamis had to be left out of the catalogue, since no evidence indicates that they actually reached Martinique. Among these, many are of volcanic origin, whether at the global scale associated with the 1883 eruption of the Kratatau volcano in Indonesian (Choi et al, 2003; Pararas-Carayannis, 2003), or at the scale of the Lesser Antilles with the low intensity eruptions of the Kick'em Jenny (Smith and Shepherd, 1993) and of the Souffrière Hills in Montserrat (1824, 1897, 1997), 320 kms away from Martinique. Finally, this selective process also excludes the formation of an 'ephemeral mud island' as the one off the coasts of Trinidad at various points in time, specifically in 1853, 1874, 1911, 1928, 1934) (O'Loughlin and Lander, 2003).

2.3 Criterion of Validity

The criterion of validity used in the present study is different from that which was used in the catalog compiled by the Laboratory of Tsunamis of Novosibirsk (www.tsun.sscc.ru/) and that used by O'Loughlin and Lander (2003). The scale of validity used for the Martinique catalog adhered to factual information as specifically as possible (Table 1). Thus, events reported as 'abnormal oscillations' by some observers (with degree 1 on the tsunami scale), were separated from tsunamis that appear more frequently in different sources (with degree 4), or from those to which all sources systematically refer (degree 5). Degree 2 corresponds both to known tsunamis, but about which it is not certain whether they impacted Martinique or not (degree 2a) and to tsunamis that may have occurred but were not recorded in Martinique, in spite of a violent earthquake or a landslide recorded by observers (2b). In other words, such events may be known to have occurred, but none of the sources available either suggests that the event in question caused a tsunami or that it affected Martinique. However, it was decided to include them in the study because it is possible that such events were not recorded on the island simply because there were no observers on site, or for other reasons (occurring at night, micro tsunami, etc.).

3. RESULTS AND DISCUSSION

3.1 Results

Overall, the present study included at least thirty-three tsunamis, of which only five did not reach Martinique according to original references. These included the 1831 Granada tsunami, the 1874 and 1880 Dominica tsunamis and the 1985 and 2004 Guadeloupe tsunamis (Table 2). In addition to date and localisation, the catalog indexes the origin, the degree of validity associated to some tsunamis, as well as some parameters such as amplitude and run up. Also, the catalog lists various other notes and information, regarding contradictions that were found in the researched sources (as for example, the 1751 tsunami). The catalog stands out due to the heterogeneity of the level of information available for each event. Thus, some tsunamis, such as those of 1755 or 1902, benefit from the abundance of details in well-documented sources and additionally conducted research. However, other events such as the 1657 and 1874 tsunamis are very poorly documented, since they occurred a long time ago (1657 was the year of the first earthquake ever perceived by the colonists, who had only just settled on the island in 1635), or because of the sparseness of damage caused by the reported 'abnormal oscillations' (as for the 1874 event).

3.1.1 Detailed Analysis

A more detailed review of the various tsunamis reported in the database has allowed the present study to group some events in accordance to their origin characteristics (seismic, volcanic), or in accordance to the propagation characteristics (local, regional, or far-field tsunamis). Of all the events indexed in the catalog, only four are absent from Figure 3 (the Hispaniola earthquake of 1751; the Lisbon earthquake of 1755; the Surinam earthquake of 1767 and the Costa Rica earthquake of 1991).

Figure 3 shows the origin of twenty-six tsunamis generated near the Lesser Antilles, of which twenty-one were observed on Martinique. These include the tsunamis which occurred on the following dates: 6 April 1690; September 1702; 6 March 1718; 30 November 1823 and 1824; 30 November 1827; 26 October 1829; 26 July 1837; 11 January 1839; 8 February 1843; 18 November 1867; 8 November 1876; 5 May 1902; 7 May 1902; 8 May 1902; 9 May 1902; 20 May 1902; 30 August 1902; 16 February 1906; 24 July 1939; 25 December 1969; 22 April 1991 and 21 November 2004.

Of the thirty-three tsunamis listed in the catalog, half are of seismic origin generated mainly around the Virgin Islands (as the 18 November 1867 event) and Guadaloupe (as the 1843, 1969, 1985 and 2004 events). Tsunamis in the region are also generated from volcanic sources and more than ten of those recorded were associated with the volcanoes of the Caribbean archipelago (i.e. Kick'em Jenny, Souffrière Saint-Vincent, Mount Pelée and the 'Souffrière' of Montserrat). Tsunamis generated by landslides in the region seem to be under-represented in the diagram – with only one event being included. However, it should be noted that landslides could be triggered by both seismic and volcanic events. It is therefore necessary to take into account that 13% of all tsunamis are of multiple origins (Fig. 4).

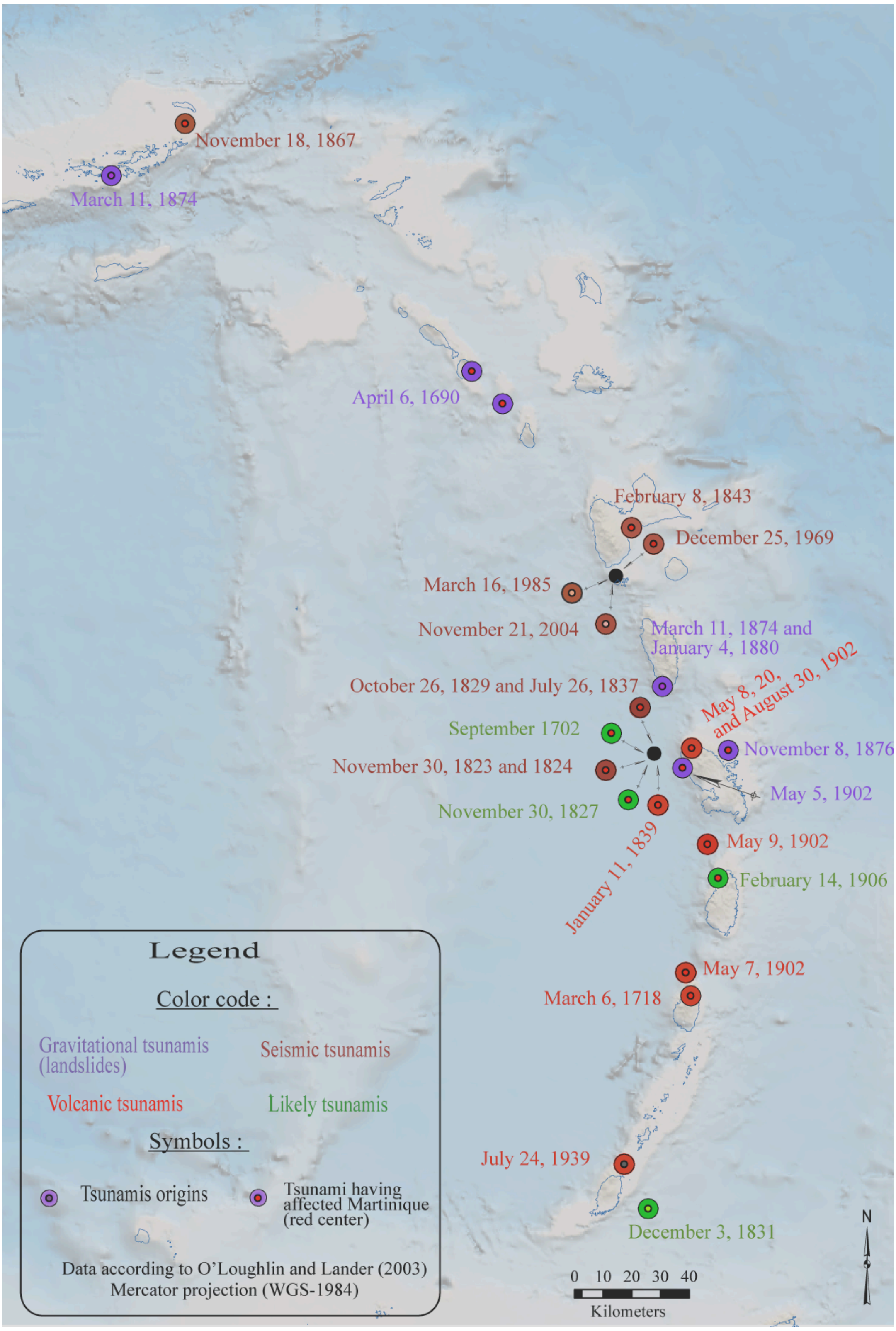

Fig. 3: Sources of tsunamis in the arc of the Lesser Antilles.

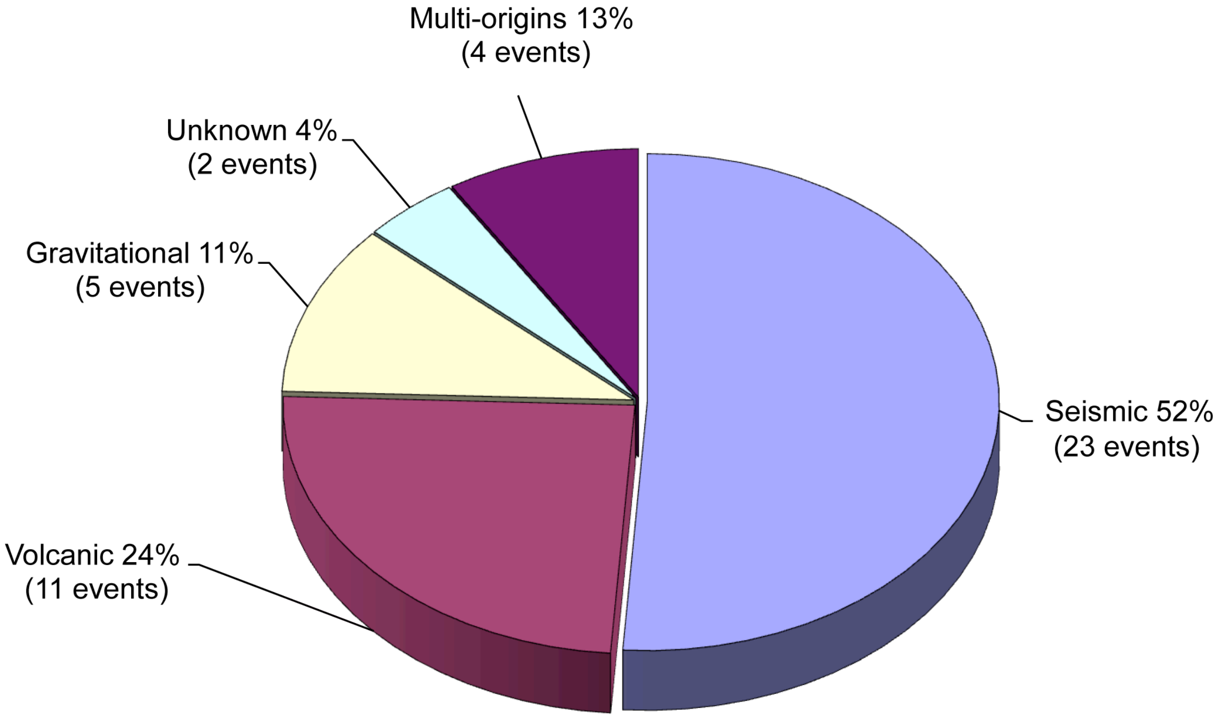

Fig. 4. Distribution of tsunamis according to origin.

Lastly, two events (1829 and 1837) are of unknown origin. This lack of information is attributed to the inadequacy of historical accounts and the inability to determine the tsunami source mechanism. Thus, these two events may have been caused either by a passing hurricane or by an earthquake. It should be noted that in those times, the violence of hurricanes could foster 'jolts' that were thought to be earthquakes. However, this confusion regarding the origin of tsunamis only affects 6% of the total number (i.e. the two events).

The second diagram (Fig. 5) illustrates the prevalence of local tsunamis (comprising of 49% of the total) over regional tsunamis (comprising of 36%). Martinique is therefore mostly subjected to tsunamis originating near neighbouring islands such as Saint Vincent, or Guadaloupe. The only tsunami of distant origin is represented by the single Lisbon tsunami of 1755.

Although many tsunamis have been observed on the coasts of Martinique, few have been located with geographic accuracy. Thus, in the majority of cases, the original references mention Martinique without attempting to classify the coasts on the island that were affected by tsunami wave action.

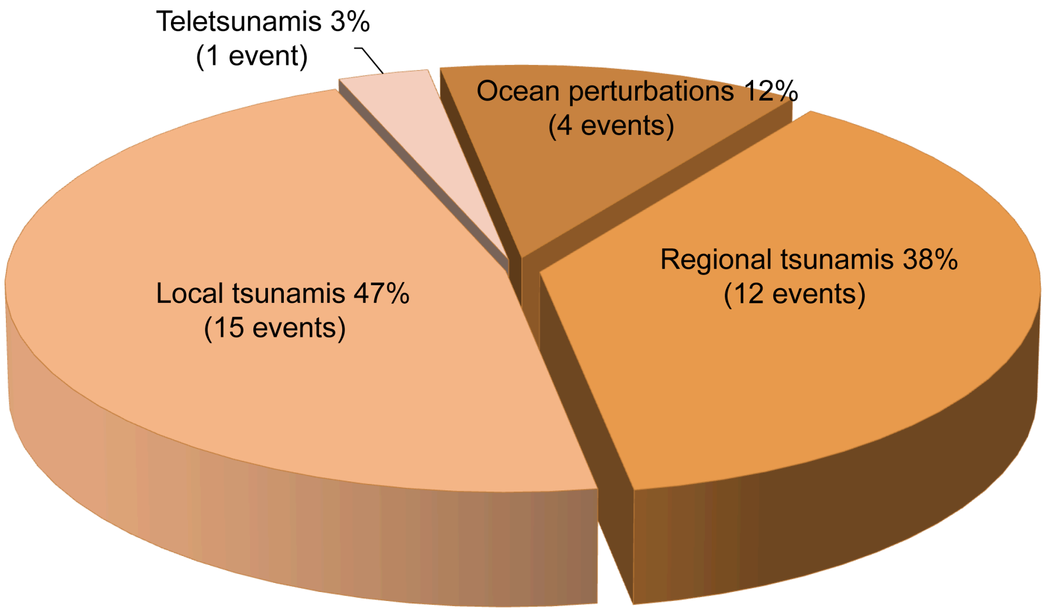

Fig. 5. Classification of tsunamis according to impacted zone.

The map (Fig. 6) shows towns in Martinique that were affected by tsunamis, according to observations found in different reference sources. These indicate which of the coastal areas are particularly vulnerable to tsunami impact. Among them, is the coastal area along the flanks of the volcano stretching from Macouba to The Carbet via Le Précheur (Northwest), but also the coast stretching from Case-Pilote to Trois-Ilets, along the bay of Fort-de-France and, finally, the tourist area stretching from Sainte Marie to the Robert, near the presqu'isle of the Caravelle (La Trinité). Other sites could have been impacted but lack of educated population to document what happened limited most of the observations in major towns.

Figure 7 helps visualise the cities that are most vulnerable to the tsunami hazard in Martinique. Saint Pierre (27%) and La Trinité (26%) are the towns that would be most affected. The 27% mentioned for St Pierre indicate that 27% of the listed tsunamis in the catalog affected St Pierre. The destruction of the capital city of Saint Pierre during the cataclysmic eruption of 1902 was a definitive blow since it resulted in the deaths of the city's population (28.000 people), but also its status as capital at the benefit of Fort-de-France. La Trinité presents an original profile in so far as it is affected to locally produced tsunamis (such as those of 1876, 1902, etc.), but also to tsunamis of distant origin (such as that of 1755), which makes this location as the most sensitive on the island in terms of exposure to the tsunami hazard. Some towns in the North of the island (Basse-Pointe, Macouba, le Précheur) are also exposed to 'oscillations', as it was shown in 1902, when Mount Pelée was particularly active.

However, it should be noted that an overwhelming majority of the population on Martinique is concentrated in coastal towns and areas, which are particularly vulnerable to tsunamis (Goiffon, 2003).

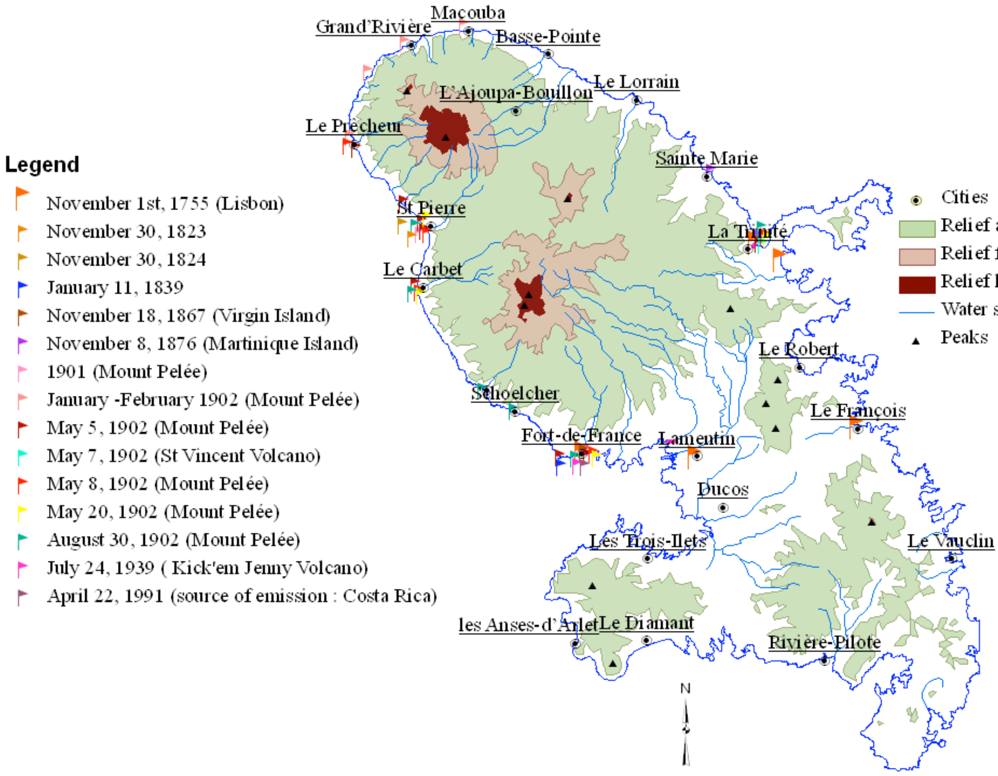

Fig. 6. Cities in Martinique impacted by past tsunamis.

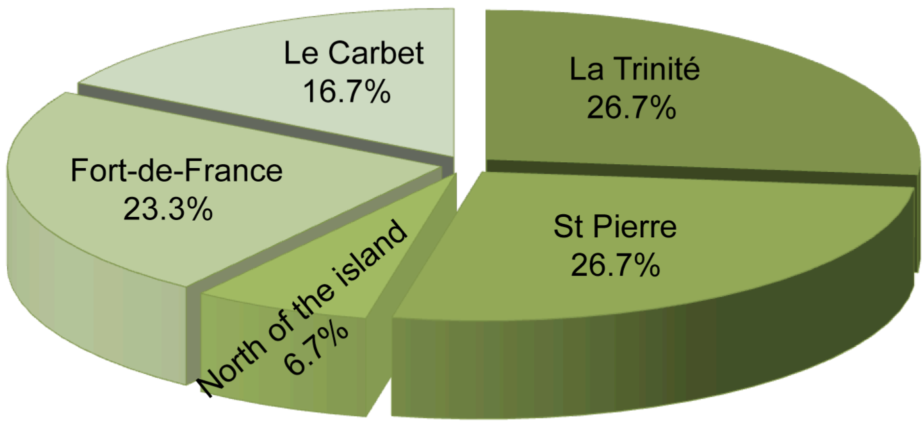

Fig. 7. Towns in Martinique affected by tsunami hazard.

3.1.2 Major Events

1755 November 1

The tsunami of 1 November 1755 is the only event of distant origin ever recorded in Martinique. The 1755 earthquake and tsunami were extremely destructive in Lisbon. The tsunami was recorded in Madera and in Morocco (Barkan et al, 2009) and reached the American continent and the Caribbean region (Roger et al, 2010a, 2010b, 2010c). The first of its waves reached the Island of Martinique in the afternoon and its subsequent effects lasted for about four hours (from 14:00 hrs to 18:00 hrs). This gap is consistent with the results obtained by numerical simulations, since the tsunami's origin time was at about 09:30 on November 1 and took over 7 hours to reach the coasts of Martinique (Roger et al, 2010). The Presqu'isle of Caravelle and the small town of La Trinité (west coast) were the first ones affected. Subsequent tsunami wave refraction around the island was observed as in the Baleares during the tsunami of Zemmouri in 2003 (Alasset et al, 2006) - and the bay of Fort-de-France was flooded. This phenomenon of wrap around is well described by Yeh et al. (1994). At the same time there was a rise in sea level along the coasts, the level of some rivers. There was sharp increase in sea level at Lamentin (Fort Royal) and Epinette (La Trinité), leading to further inland inundation (Lambolez, 1905; Baptista et al, 1998; Baptista et al, 2003; Lander et al, 2003; Roger et al, 2010b).

The Tsunamis of 1902

Various tsunamis that occurred in 1902 (on May 5th, 7th, 8th, 20th and 30th) affected extensive areas stretching from Grand-Rivière, in the North of the island, to La Trinité, via the area of Le Prêcheur, le Carbet–Case Pilote and the Trois Ilets. Fig 6 shows the various areas that were flooded. Inspite of the diversity of tsunami origins, the waves exhibited high concentrations at the same localities. Thus, the tsunami generated by the May 5th lahar flow impacted St-Pierre, the Carbet, Fort-de-France and La Trinité, as was the tsunami generated by the eruption of La Souffrière on the Island of St-Vincent, although with lesser intensity.

3.2 Discussion

Documenting through a regional study - within the framework of the Caribbean - the tsunamis that affected the island of Martinique allows to identify as well coastlines vulnerable to the tsunami hazard. However, the list of events described above, just like the catalog and the maps, show that tsunamis are potentially destructive in this area of the Caribbean, where high-magnitude earthquakes (in 1690, 1751, 1831, 1843, 1867, 1969 and 1991) and volcanic eruptions (in 1718, 1880, 1902 and 1939) are frequent and can also result in landslides (as in 1690, 1718, 1876, 1880, 1902 and 1985). Tsunamis that can affect Martinique can be generated from diverse local as well as distant sources. Mainly tsunamis that can affect Martinique tend to be of local origin, thus there is not sufficient time to issue a tsunami warning. Earthquakes generate the majority of tsunamis, although many are caused by gravitational flank collapses as well as lahars and landslides. Although the sources of many tsunamis have been identified as located in many of the islands of the Caribbean arc, Martinique on its own, principally because of the re-awakening of the Mount Pelée volcano has generated over eight local tsunamis within a year (1902), of which two were registered as 'abnormal oscillations'.

From a spatial point of view, according to Figure 8, we can say that three towns are particularly vulnerable: Fort-de-France (the political and economical capital of the island), La Trinité and Saint-Pierre. Presently, a tsunami generated by a new eruption of Mount Pelée would potentially affect the towns of Le Précheur, Grand-Rivière, Macouba, and Saint-Pierre, which have a total population of 8,360 inhabitants (plus the tourists), i.e. 2% of the population of the island (INSEE, 2009). On the contrary, a tsunami like that of 1755 would affect the towns of Fort-de-France, Le Lamentin, La Trinité and Le François, i.e., where over 40% of the population (162,131 inhabitants) are located (INSEE, 2009). Relatively, only the southern and the west coasts of the island seems to be protected from tsunamis because of the presence of natural and residual coral reef barriers.

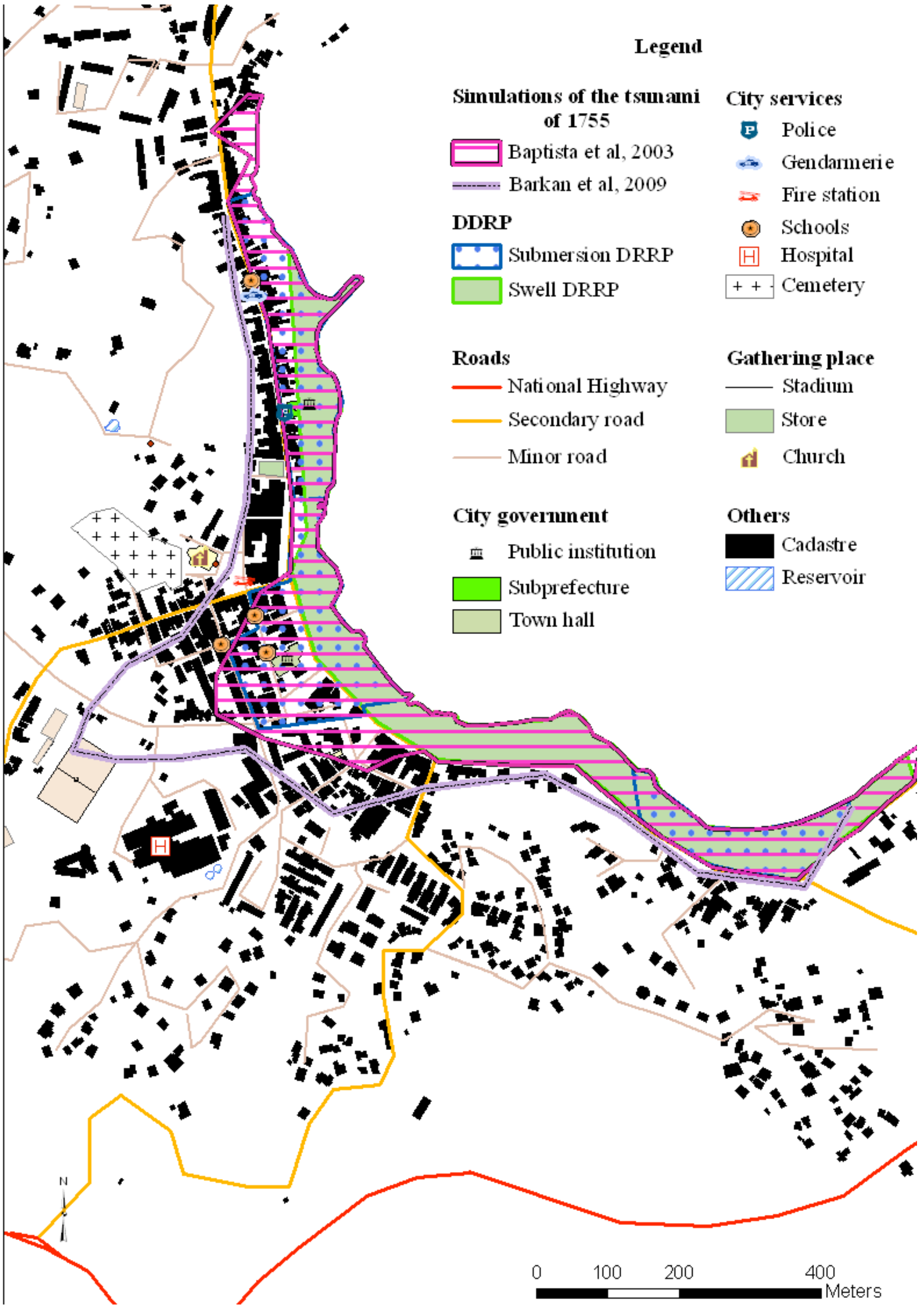

Fig. 8: Vulnerability of La Trinité: local submersion hazard limit and proposition of extension according to tsunami simulation. All the strategic sites and roads are indicated.

3.2.1 Uncertain Tsunamis

The detailed catalog (chart) also lists tsunamis, which cannot be documented with certainty. The following is a discussion of seven such events.

The first is a set of two tsunamis that appear in all written testimonies with only date, time and origin. Archived exactly one year apart, respectively on 30 November 1823 and 30 November1824, both of these events purportedly caused 'damages in the harbour' on those two dates - seemingly the Saint-Pierre harbour. Moreover, both events appear to have occurred following periods of high temperatures that were accompanied by torrential rains (Mallet, 1852, 1853, 1854). These similarities lead to two distinct hypotheses. It is entirely possible that these two purported tsunamis were in fact one single event, wrongly reported as separate events due to transcription of calendar mistakes. Alternatively, it is somewhat possible that the two events resulted from earthquakes that occurred exactly one-year apart. However it is highly unlikely that such coincidence in the day and month actually occurred. Finally, it is also entirely possible that the reported tsunamis were storm surges generated by hurricanes.

The tsunami of 8 November 1876 is reported in a letter that is referred in Lambolez (1905). This letter recollects 'waves' and 'bellowing swell' between the Presqu'isle of the Caravelle and Sainte Marie, stating that 'often to occur here'. This purported tsunami seems to have originated from a submarine landslide if we take its description into account. However, there is a significant margin of error when dealing with historical sources that contain vague descriptions. Significantly, this event is not listed in any of the other reference sources.

Finally, insufficient information is provided regarding the remaining uncertain tsunamis as to their geographic origin location, so that these cannot be really considered as real events by the present study. In fact, many of these events are referred to in an unspecific way and may have been induced by landslides, earthquakes, and storms - as was the case for the 3 June 1718 or 2 August 1837 events. Other tsunami events listed as 'abnormal oscillations' (i.e. the 1657 event) make it even harder to assess the validity of their tsunamigenic nature. All of these tsunami events, because of vagueness of the information, are associated with a degree of validity (see Table 1) that allows us to visualise them quickly and dissociate them from those that are better documented as certain.

Overall, only the tsunamis that caused serious and significant damages, both in material and in human lives, are verifiable with any kind of factual certainty in assessing Martinique's potential tsunami hazard. These major events have become the subject of numerous studies, which further permit the assessment of tsunami risk for other coastal areas of the island. Unfortunately some tsunamis, although destructive, are harder to document adequately because of lack of interest. For example the 1761 tele-tsunami, associated through its origin with the Lisbon earthquake of 1761, illustrates the difficulties in the compiling of historical catalogs, since good registration of events depends on the validity of historical reports and of various documents. In the case of 1761, only a few specialists (Zahibo and Pelinovski, 2001; Baptista et al, 2006) have studied this tele-tsunami, and the results do not allow us to integrate this event in the study of tsunamis in Martinique, due to the lack of proper historical accounts, regarding the impact on the island.

3.2.2 Uncertainty of Sources

In view of the above listed uncertainties, the results need to be evaluated critically, since they rely partly on sources that may depend on author's subjectivity.

Historical sources must be used with caution as they may introduce erroneous data, due to inadequate understanding by the reporting past scientists and observers. Thus, of the many recorded 'raz-de-marées' (common French for tsunami), only a few are actually tsunamis. Let us note that the observation and localisation of tsunamis depends mainly on human presence along impacted areas and that at coastal areas with low population density significant tsunami impact may not have been properly reported. Furthermore many of the names of localities on the island have changed through centuries, so it is not always easy to locate precisely the extent of the flooded zones (i.e. 'as far as the stone bridge on river Roxelane', (Lambolez, 1905)). The use of secondary sources is also a factor of uncertainty, as the problem raised by O'Loughlin and Lander (2003) shows, when they explain the existence of different dates for a single event due to calendar mistakes. Finally, the absence of information in the archives does not necessarily mean an absence of an actual tsunami, since literate men – who were scarce in this colonial island, only transcribed these events.

Additionally, the results of tsunami modelling depend on the data gathered by the research specialists; therefore, as with any other scientific endeavour, they come with a margin of error or uncertainty. These models can overestimate or underestimate tsunami amplitudes. Only a study of sedimentary deposits (as in Morton et al, 2006) can confirm whether the listed tsunamis actually occurred. However, subsequent development of the heavily populated coastal areas makes such investigations almost impossible, unless construction works expose accidentally tsunami deposits (Nicolae-Lerma, pers. comm., 2010).

Lastly, the data gathered by the mareographs of SHOM may have been useful, but no access was possible. Moreover, most of the mareographic equipment has only been installed recently (October 2005) on Martinique (Créach, pers. Comm., 2010).

Up to now the present study concentrated on the tsunami hazard in Martinique but without including a social-economic dimension: the vulnerability. Only the coastal town of La Trinité was chosen for further assessment of the tsunami hazard.

3.2.3 Vulnerability of La Trinité

The town of La Trinité is located on the Atlantic coast of the island. It has a population of 13,582, distributed over an area of 45.8 km². Although the town concentrates only 3.5% of the Martinique's total population, it is the designated local administrative centre ('sous-préfecture' - district level) and is host to the only hospital on this part of the coast. Moreover, La Trinité has been affected in the past by eight tsunamis of various origins (seismic, volcanic, landslides) and generating sources (Lisbon, Saint-Vincent, Martinique). Of those recorded in La Trinité, which seem to be the largest, only the 1755 tsunami provides sufficient data to conduct a vulnerability study of the town nowadays. Moreover, La Trinité is located at very low elevation (< 5 m) and concentrates its public offices in a narrow area very close to the sea, which increases the town's tsunami vulnerability. Thus, Figure 8 shows the strategic sites of the town (schools, administrative centres, firehouses, hospitals, etc.) as well as the simulation results that were produced using the source of Barkan et al. (2009), maximising a scenario for the Caribbean, located in the Iberian peninsula but not based on existing submarine or geological structures (Roger et al, 2010a). The results of modelling, however, have not been yet published for Martinique.

As a matter of fact, no Disaster Risk Reduction Plan (DRRP) seems to be interested in indexing the vulnerability of the coastal areas with regards to the tsunami risk, whereas the Swell and Submersion DRRP are already taken into account in urbanization planning. The use of maximising the scenarios with tsunamis generated either by earthquakes affecting the Caribbean and/or based on already-existing geological structures (Baptista et al, 1998; Baptista et al, 2003; Barkan et al., 2009; Roger et al, 2010a,b) on the locality of La Trinité, allowed the present study to compare the modelled inundation of the 1755 event (the models are consistent with the historical accounts and observations, Roger et al., 2010a,b) with those modelled by the two DRRP. The studies indicate that the tsunami inundation similar to that of 1755 would flood the town and all its strategic sites (district offices, mayor's house, schools, police stations, firehouse and emergency centres, etc.), with a maximum flow depth much more significant than that indicated by DRPP, and that serious material and human damage is possible, if prevention measures are not properly implemented (education, works, buildings displacements, etc.) (Leone et al., 2010). Moreover, the present study indicates that the road network will be directly impacted by a potential sea-level rise associated with a similar tsunami. For example, the main coastal road, which separates the town from the sea, would be inundated, thus causing serious problems with the evacuation of people and the transportation of supplies. Additionally, all the buildings within the first 200 m from the coastline will be inundated according to the simulation of the maximum potential scenario for the Caribbean (Barkan et al., 2009). Of all the buildings in La Trinité, only the hospital s is located outside this inundation zone. It should also be noted that the 1755 tele-tsunami flooded the bay of Fort-de-France and of Lamentin, which nowadays is the center of the island's political and economic activity and of the island's main airport and harbor (Lamentin) as mentioned by Roger et al. (2010b).

The DEM (Digital Elevation model) used for tsunami simulations (propagation and inundation) in La Trinité Bay has been constructed using high resolution bathymetry (obtained from high resolution multi-beam and re-sampled bathymetric data of the French Hydrographic Service, SHOM; Roger et al. 2010b) and from topographic data (IGN, 2006); The model reproduces submarine features, coastal configuration and the aerial landscape.

4. CONCLUSION

The compilation of the present tsunami catalog for Martinique Island leads to the following conclusions:

After an accurate comparison of the different available historical catalogs, only twenty-eight events have been classified as tsunamis that reached Martinique since its discovery. Among them, twenty-three tsunamis – corresponding to 50% of the total - have been generated by earthquakes, directly or indirectly (induced landslides). For the majority of cases it was not possible to discriminate between a direct or indirect cause due to the lack of adequate historical data. In the same way, 28% of those tsunami events have occurred following volcanic eruptions but again, it is very difficult to make the distinction between a direct origin associated with a lahar entering the sea, or a volcano's flank instability, or else a combination of an earthquake and an eruption. 49% of the events (16/33) have had a local impact.

The present study allowed the conduct of a preliminary vulnerability study of the tsunami hazard. In fact, tsunamis have affected several localities along the coast of Martinique, but some of them, due mainly to the geographical location, coastal configuration and mainly because of lack of proper observations, may show a lack of impact. Thus, the town of La Trinité was the perfect example for this study of tsunami risk and vulnerability, since this is the area of increased tourist activity and coastal urbanization, indicative of similarly exponential vulnerability of other coastal towns. The choice of the 1755 Lisbon tsunami as the worse possible scenario for tsunami impact on Martinique highlights the need to improve the current anti-flood DRR plan for the island.

ACKNOWLEDGEMENTS

The present research was funded by the MAREMOTI project from the French ANR (Agence Nationale de la Recherche) under contract ANR-08-RISKNAT-05-01c and by the LRC Yves Rocard (Laboratoire de Recherche Conventionné CEA-ENS). We are grateful to Alain Rabaute (GeoSubSight company) and Pierpaolo Dubernet (ENS Paris) for their technical support, as well as to Irina Nikolkina (LaRGe, Université Antilles-Guyane), Yanni Gunnell (CNRS, Université Lumière-Lyon 2) and Pascal Saffache (CEREGMIA, Université Antilles-Guyane) for constructive discussions about tsunamis in the Caribbean, and to Manuel Pubellier (ENS Paris) for discussions concerning the geodynamic context in the Antilles and surrounding areas. We also thank Lola Wilhelm for improving the English version of the manuscript and George Pararas-Carayannis for his help in improving the quality of the paper and for editing it.

REFERENCES

Alasset P.J, H. Hébert, S. Maouche, V. Calbini, M. Meghraoui (2006). The tsunami induced by the 2003 Zemmouri earthquake (MW = 6.9, Algeria): modelling and results, Geophys. J. Int, 166**,** 213–226.

Baptista M. A., S. Heitor and L. Mendes Victor (1998). The 1755 Lisbon tsunami; Evaluation of the tsunami parameters, J. of Geodynamics, 25(2), 143–157.

Baptista M.A., J. M. Miranda, F. Chierici and N. Zitellini (2003). New study of the 1755 earthquake source based on multi-channel seismic survey data and tsunami modeling, Natural Hazards and Earth System Sciences, 3, 333–340.

Baptista M.A., J.M. Miranda and J.F. Luis (2006). In Search of the 31 March 1761 Earthquake and Tsunami Source, Bulletin of the Seismological Society of America, 96(2), 713–721.

Barkan R, U. Brink, J. Lin (2009). Far field tsunami simulations of the 1755 Lisbon earthquake: Implications for tsunami hazard to the U.S. East Coast and the Caribbean, Marine Geology, n°264, 109–122.

Boyer-Peyreleau, E.E. (1823). Les Antilles Françaises, particulièrement la Guadeloupe, depuis leur découverte jusqu'au 1er Novembre 1823, 3 volumes, Brissot-Thivars, Paris.

Calmont A. and C. De Vassoigne (1999). Guadeloupe, Martinique, Guyane: Des espaces tropicaux entre insularité et continentalité, Mappemonde n°54 (1999.2).

Charbit Y. (2006). Les colonies françaises au xviie siècle : mercantilisme et enjeux impérialistes européens, Revue européenne des migrations internationales.

Chauleau Y. (1993). Dans les iles du vent, la Martinique XVIIe-XIXe siècle, l'Harmattan.

Chester D-K. (2001). The 1755 Lisbon earthquake, Progress in Physical Geography, 25, 363–383.

Choi B. H., E. Pelinovski, K.O. Kim and K.O. Lee (2003). Simulation of the trans-oceanic tsunami propagation due to the 1883 Krakatau volcanic eruption, Natural Hazards and Earth System Sciences,3, 321–332.

Clément A. (2009). "Du bon et du mauvais usage des colonies" : politique coloniale et pensée économique française au XVIIIe siècle, Cahiers d'économie politique, N°56, pp. 101-127.

Du Tertre J.-B. (1668-1671). Histoire générale des Antilles habitées par les Français.

Feuillard M., C.J. Allegre, G. Brandeis, R.Gaulon, J.L. Le Mouel, J.C. Mercier, J.P .Pozzi and M.P. Semet (1983). The 1975–1977 crisis of la Soufriere de Guadeloupe (F.W.I): A still-born magmatic eruption, Journal of Volcanology and Geothermal Research, 16(3-4), 317-334.

Germa A. (2008). Evolution volcano-tectonique de l'île de la Martinique (Arc insulaire des petites Antilles): Nouvelles contraintes géochronologiques et géomorphologiques, Thèse de Doctorat, Université d'Orsay.

Goiffon M. (2003). Pression foncière et littoralisation à la Martinique: Pression anthropique et environnement en Amérique latine, Les Cahiers d'Outre-Mer, N° 223.

Grindlay N. R., M. Hearne and P. Mann (2005). High Risk of Tsunami in the Northern Caribbean, Eos, 86,(12).

Herd R.A., M. Edmonds, V-A Bass (2005). Catastrophic lava dome failure at Soufriere Hills Volcano, Montserrat, 12–13 July 2003, Journal of Volcanology and Geothermal Research, 148, 234– 252.

Hess J. (1902). La Catastrophe de la Martinique, Note d'un reporter, Ed. Eugène Fasquelle, Paris.

Institut Géographique National (2006). Le Lamentin, presqu'île de la Caravelle, PNR de la Martinique. Carte de Randonnée, 4502 MT, édition 2, 1 : 25000.

INSEE (2009). Enquête de recensement sur la population en Martinique, le 1er Janvier 2006, INSEE Antilles-Guyane, N°39, Janvier 2009.

Kathiresan K. and N Rajendran (2005). Coastal mangrove forests mitigated tsunami, Estuarine, Coastal and Shelf Science, 65, 601-606.

Kunkel C.M., R.W. Hallberg and M. Oppenheimer (2006). Coral reefs reduce tsunami impact in model simulations, Geophysical Research letters, 33, L23612, doi:10.1029/2006GL027892.

Lacroix A. (1904). La Montagne Pelée et ses éruptions, Editions Masson. 663 pp.

Lambolez C.L. (1905). Saint-Pierre – Martinique, Annales des Antilles françaises, Journal et album de la Martinique : Naissance, vie et mort de la cité créole (1635 – 1902), Livre d'or de la Charité, Ed : Berger-Levrault et Cie, Paris.

Lander F. (1997). Caribbean tsunami, an Initial History, Naturals Hazards and Hazards Management in the Greater Caribbean and Latin America, 3, 1–18.

Lander F., L.S. Whiteside and P.A. Lockridge (2002). A Brief history of tsunamis in the Caribbean Sea, The International Journal of The Tsunami Society, 20(2), 57–94.

Lander F., L.S. Whiteside and P.A. Lockridge (2003). Two Decades of global tsunamis (1982-2002), Science of Tsunami Hazards, 21(1), 3-88.

Lalung H. (1948). Les Caraïbes, peuple étrange, aujourd'hui disparu, Bourrelier et Cie, Paris.

Le Friant A., G. Boudon, A. Arnulf, R. Robertson (2009). Debris avalanche deposits offshore St. Vincent (West Indies): Impact of flank-collapse events on the morphological evolution of the island, Journal of Volcanology and Geothermal Research, 179, 1–10.

Leone F. and T. Lesales (2008). L'évaluation intégrée du risque volcanique. Application à la montagne Pelée (Martinique), in Pagney Benito-Espinal (Ed) - Les interfaces ruptures, transitions et mutations, coll. Espaces tropicaux. Presses Universitaires de Bordeaux.

Leone F., F. Lavigne, R. Paris, J-C Denain and F. Vinet (2010). A spatial analysis of the December 26th, 2004 tsunami-induced damages: Lessons learned for a better risk assessment integrating buildings vulnerability, Applied Geography, in press.

Macdonald R., C.J. Hawkesworth, E. Heath (2000). The Lesser Antilles volcanic chain: a study in arc magmatism, Earth-Science Reviews,49, 1–76.

Mallet, R. (1853). Catalogue of Recorded Earthquakes from 1606 B.C. to A.D. 1850, Part I, 1606 B.C. to 1755 A.D. Report of the 22nd Meeting of the British Association for the Advancement of Science, held in Belfast, Sept. 1852, John Murray, London, 177 pp.

Mallet R. (1854). Catalogue of Recorded Earthquakes from 1606 B.C. to A.D. 1850, Part II, 1755 A.D. to 1784 A.D., Report of the 23Td meeting of the British Association for the Advancement of Science, held in Hull, Sept. 1853, John Murray, London, 118-212.

Mallet R. (1855). Catalogue of Recorded Earthquakes from 1606 B.C. to A.D. 1850, Part III, 1784 A.D. to 1842 A.D., Report of the 24" Meeting of the British Association for the Advancement of Science, John Murray, London, 326 pp.

Morton R., B. Richmond, B. Jaffe, G. Gelfenbaum (2006). Reconnaissance Investigation of Caribbean extreme wave deposits – preliminary observations, interpretations, and research directions, Open-File Report 2006-1293, USGS.

O'Loughlin K. and F. Lander (2003). Caribbean Tsunamis, A 500 year History from 1498 – 1998, Kluwer Academic Publishers.

Pararas-Carayannis, G., 2003. Near and Far-Field Effects of Tsunamis Generated by the Paroxysmal Eruptions, Explosions, Caldera Collapses and Slope Failures of the Krakatau Volcano in Indonesia, on August 26-27, 1883, Presentation for the International Seminar/Workshop on Tsunami "In Memoriam 120 Years Of Krakatau Eruption Tsunami And Lesson Learned From Large Tsunami" August 26th 29th 2003, Jakarta and Anyer, Indonesia. Also published in the Journal of Tsunami Hazards, Volume 21, Number 4. 2003

Pararas-Carayannis, G., 2006. Risk Assessment of Tsunami Generation from Active Volcanic Sources in the Eastern Caribbean Region - In "CARIBBEAN TSUNAMI HAZARDS"- Proceedings of National Science Foundation Caribbean Tsunami Workshop, March 30-31, 2004, Puerto Rico, Aurelio Mercado-Irizarry - Philip Liu, Editors. ISBN 981-256-545-3, 341 pp. 2006, Hard Cover Book. World Scientific Publishing Co. Pte.Ltd., Singapore.

Pararas-Carayannis G., (2010). Assessment of Tsunamigenic Potential along the Northern Caribbean Margin – Case Study: Earthquake and Tsunamis of 12 January 2010 in Haiti. Science of Tsunami Hazards, Vol 29, No. 3 (Review of draft report).

Revert E. (1949). La Martinique : Etude géographique et humaine, Paris : Nouvelles Éditions latines, 559 pp. Collection : Bibliothèque de l'Union française.

Roger J. and M.A. Baptista (2009). Synthèse des informations historiques relatives au tsunami associé au séisme de Lisbonne de 1755 dans les Antilles, Programme ANR RISKNAT, projet MAREMOTI, Rapport d'activité n°2.1

Roger J., M-A Baptista, A. Sahal, F. Accary, S. Allgeyer, H. Hébert (2010b). The transoceanic 1755 Lisbon tsunami in Martinique, Pure and Applied Geophysics, proceedings of the International Tsunami Symposium, Novosibirsk, Russia. (in press).

Roger, J., S. Allgeyer, H. Hébert, M.A. Baptista, A. Loevenbruck, F. Schindelé (2010a). The 1755 Lisbon tsunami in Guadeloupe Archipelago : sourve sensitivity and investigation of resonance effects, The Open Oceanography Journal, 4, 58-70.

Roger, J., M.A. Baptista, D. Mosher, H. Hébert, A. Sahal (2010c). Tsunami impact on Newfoundland, Canada, due to far-field generated tsunamis. Implications on hazard assessment. Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering, July 25-29, 2010, Toronto, Canada, n°1837.

Saffache P. (2005a). Petit manuel de géographie de la mer et des littoraux : essai de compréhension du milieu littoral martiniquais, Matoury : Ibis Rouge Editions, Presses Universitaires Créoles, Collection Géographie & Aménagement des Espaces Insulaires, 53 pp.

Saffache P. (2005b). The vulnerability of the island of Martinique to the risk of a tsunami, Études caribéennes, n°3. http://etudescaribeennes.revues.org/653

Saffache P., J.V Marc, J. Mavoungo, V. Huyghues-Belrose , O. Cospar (2003), Tremblements de terre et raz de marée dans les Départements Français d'Amérique (1643-2002) : éléments pour un aménagement raisonné et une prise de conscience de la vulnérabilité du milieu. Éditions Publibook Université, Collection Sciences Humaines et Sociales, Série Géographie, Paris.

Sahal A., J. Roger, S. Allgeyer, B. Lemaire, H. Hébert, F. Schindelée, F. Lavigne (2009). The tsunami triggered by the 21 May 2003 Boumerdès-Zemmouri (Algeria) earthquake: field investigations on the French Mediterranean coast and tsunami modeling, Natural Hazards and Earth System Sciences,9, 1823–1834.

Schleupner C. (2007). Spatial assessment of sea level rise on Martinique's coastal zone and analysis of planning frameworks for adaptation, J Coast Conserv, 11, 91–103.

Smith M. and J. Shepherd (1993). Preliminary Investigations of the Tsunami Hazard of Kick'em Jenny Submarine Volcano, Natural Hazards, 7, 257-277.

Yeh, H., Liu, P., Briggs, M., Synolakis, C. (1994). Propagation and amplification of tsunamis at coastal boundaries. Nature, 372, 353-355.

Westercamp D. and H. Tazieff (1980). Martinique, Guadeloupe Saint-Martin, La Désirade, Guides Géologiques Régionaux, Masson, Paris.

Zahibo N. and E. Pelinovsky (2001). Evaluation of tsunami risk in the Lesser Antilles, Natural Hazards and Earth System Sciences, 1, 221–231.

Zahibo N., E. Pelinovsky, A. Yalciner, A. Kurkin, A. Koselkov, A. Zaitsev (2003). Le tsunami de 1867 aux ÎlesVierges : observations et modélisation, Oceanologica Acta, 26, 609–621.

Zahibo N., E. Pelinovski, E. Okal, A.Yalçiner, Ch.Kharif, T. Talipova, A. Kozelkov (2005). The earthquake and tsunami of november 21, 2004 at Les Saintes, Guadeloupe, Lesser Antilles. Science of Tsunami Hazards, 23(1), 25-39.

Table 1: Criterion of validity

Degree of validity	**Meaning**
1	‘Abnormal oscillations’
2 a	Tsunamis generated but not observed in Martinique
2 b	Known earthquake or landslides which did not lead to a tsunami, according to the available sources
3	Events sometimes recorded as tsunamis, but about which sources disagree and/or give contradictory accounts
4	Tsunamis regularly referred to by a significant proportion of sources
5	Tsunamis systematically and unanimously recorded as such

DATE				Localisation of tsunamis			Parameters							Validity coefficient	Consequences	sources	Additional information
Year	Month	Day	Hours	Origin of the tsunami		Affected towns and rivers in Martinique	Type	Cause (Intensity, Magnitude)	Period	Range	run-up	Nb waves	Withdrawal		Damages		
1657				Martinique	Martinique		Abnormal sea oscillations	S						1	Houses (seism)	Lambolez, 1905	First earthquake since 1635
1690	April	6	16h LT	Antigua and Guadeloupe (S) + Redonda (L)	Charlestown, Charlotte-Amalie, Guadeloupe, Martinique, Barbade/Barbuda (?), Ste Lucie, Montserrat, Antigua, St Christopher		Regional tsunami	S (XI, 8,1), L					201 m (Charlestown), 16,5 to 18,5 m à St Thomas	4		Lander, 1997 ; Lander et al, 2002 ; O'Loughlin and Lander, 2003	Similar event in 1843, 1985, 2004
1702	September			Martinique, Guadeloupe	Martinique, Guadeloupe, Antigua		Regional tsunami	S (VIII, 6,5)						2 a	-	Saffache et al, 2003 ; O'Loughlin and Lander, 2003	Excited animals
1718	March	6	night	Martinique, St Vincent	Martinique, St Vincent		Local tsunami	S + L (Mart) + V (St-Vincent)						4		Lambolez, 1905 ; O'Loughlin and Lander, 2003	
1751	November	21	7h50 LT	Hispaniola	Antilles (including Martinique)		Regional tsunami	S (XI, 8)						3		O'Loughlin and Lander, 2003 ; [www.tsun.sscc.ru]	
1755	November	1st	2h à 6 h	Lisbonne	Martinique	Trinité, Galion, Fort-Royal, Lamentin, Cul-de-sac François	Télétsunami	S (Ms : XII, 8,75 - 9)	15 min (Trinité)		12 pieds (Trinité)	3	200 "pas" (= 124 m)	5	Damaged houses, docks, shops, and boats	Lambolez, 1905 ; Saffache et al, 2003	No tsunami referenced in Ste Marie and Le Robert. No awareness of tsunami event by slaves (slaves collected fishes on the beach during the sea withdrawal caused by the tsunami).
				Lisbonne	Martinique	Epinette River (Trinité), Lamentin River and Fort-Royal River	Télétsunami	S (Ms : XII, 8,75 - 9)			3 pieds (Lam)	3		5	Damaged houses, docks, shops, and boats	Lambolez, 1905 ; Saffache et al, 2003	
				Lisbonne	Martinique		Télétsunami	S (Ms : XII, 8,75 - 9)		4,6 (VII) to 1,8 m		3	1,6 km	5	Damaged houses, docks, shops, and boats	Zahibo and Pelinovski, 2001 ; O'Loughlin and Lander, 2003	
1767	April	24	6h30 LT	Surinam	Martinique, Barbade		Regional tsunami	S						4		O'Loughlin and Lander, 2003	
1823	November	30	3h10 LT	Martinique	Martinique	St Pierre (Harbour)	Local tsunami	S (4,8)						4	Damaged boats	O'Loughlin and Lander, 2003 ; Saffache et al, 2003	Similar events on a 1 year interval

1824	November	30	3h30 LT	Martinique	Martinique	St Pierre (Harbour)	Local tsunami	S (4,8)						4	Damaged boats	O'Loughlin and Lander, 2003 ; Saffache et al, 2003	
1827	November	30	3h LT	Martinique, Guadeloupe, Antigua			Regional tsunami	S (VIII, 6,5)						2 a		O'Loughlin and Lander, 2003	
1829	October	26		Martinique	Martinique		Local tsunami	S ou Storm						4		O'Loughlin and Lander, 2003	
1831	December	3	19h40LT	Grenada	St Kitts, St Vincent, Guyana, Trinidad		Regional tsunami	S (IX, 7)						2ab		O'Loughlin and Lander, 2003	Effect of the tsunami reported at St Kitts and Trinidad
1837	July	26	12h51 UT	Martinique	Martinique		Local tsunami	S ou Storm						2ab	Numerous casualties	Lander, 1997 ; Lander et al, 2002 ; O'Loughlin and Lander, 2003	
1839	January	11	6h LT	Martinique	Martinique	harbour	Local tsunami	S (IX, 6,9) : id Seaquakes						4	Boats damaged by the tsunami, 400 houses destroyed in Fort Royal (S), 400 deads	Lambolez, 1905 ; O'Loughlin and Lander, 2003	
1843	February	8	10h35 LT	Guadeloupe	Antilles (including Martinique)		Regional tsunami	S (XII, 8,3)		1,2 m				2 b		Lander, 1997 ; Lander et al, 2002 ; O'Loughlin and Lander, 2003	Similar event in 1690, 1985, 2004
1867	November	18	14h50 LT	Iles Vierges	Antilles (including Martinique)	Fort-de-France	Regional tsunami	S (X, 7,3)		0,7 m				5		Zahibo and Pelinovski, 2001; Zahibo et al, 2003 ;; O'Loughlin and Lander, 2003	
1874	March	11	4H30 LT	Dominique and St Thomas	Dominique and St Thomas		Regional tsunami	L						1		O'Loughlin and Lander, 2003	
1876	November	8	15h	Martinique	Martinique	between Ste Marie and the Presqu'île de la Caravelle (Trinité)	Local tsunami	L ?						4	No damages	Lambolez, 1905	
1880	January	4	11 h LT	Dominique	Dominique		Local tsunami	V + L						2 b		O'Loughlin and Lander, 2003	River level rised by 3,7 m (Roseau)
1901				Martinique	Martinique	Rade de St Pierre	Abnormal sea oscillations, violent currents	V				3 or 4		4	No damages	Saffache et al, 2003	
1902	February-March			Martinique	Martinique	North of the island : Macouba - Le Prêcheur	Abnormal sea oscillations, violent currents	V						4	No damages	Saffache et al, 2003	

1902	May	5	13h LT	Martinique (Factory Guerin)	Martinique	La Guérite - Bellevue (between Fort de France and the Pointe des nègres)	Local tsunami	V (3rd lahar)					100 m	5	Flooded houses and roads (Fonds Core). Flooded shops, boats moved towards coast, destroyed docks	Hess, 1902 ; Lambolez, 1905 ; Saffache et al, 2003	
			13h LT	Martinique (Factory Guerin)	Martinique	Blanche River, Roxelane River(St Pierre)	Rising of rivers level	V (3rd lahar)	2 min (Blanche)	8 mètres (Rox)	"Pont de Pierre" (Rox)	1	10 m to 300 feet (Blanche)	5		Hess, 1902 ; Lambolez, 1905 ; Saffache et al, 2003	
			13h LT	Martinique (Factory Guerin)	Martinique	St Pierre (Port :Company Girard, Square Bertin, Fonds-Coré, le Mouillage) + Carbet	Local tsunami	V (3rd lahar)	1 to 2 min	3 to 4 m for the first wave to 20 m	20 m (with the fontain of the square Bertin)	2 to 15 vagues	From 60 to 70 m (Mr Sully) and to 1m20 (person resqued). About 20 to 30 m	5		Hess, 1902 ; Lambolez, 1905 ; Saffache et al, 2003	
			13h LT	Martinique (Factory Guerin)	Martinique	Trinité	Local tsunami	V (3rd lahar)		80 cm		3		5		Hess, 1902 ; Lambolez, 1905 ; Saffache et al, 2003	
1902	May	7	19h LT	St Vincent	Martinique	Trinité	Local tsunami	V				3	80 cm	5		Lander, 1997 ; Lander et al, 2002 ; O'Loughlin and Lander, 2003	
1902	May	7	14 - 15h LT	St Vincent	Martinique	Madame River (Fort de France), Des Pères River (St Pierre)	Local tsunami	V			25 cm			5		Saffache et al, 2003	
1902	May	8	19H - 20h LT	Martinique (Mount Pelée)	Martinique	St Pierre, le Prêcheur, Carbet, Trinité, Fort-de-France	Local tsunami	V (Nuées ardentes)		3 m (St Pierre), 2m (Carbet)	40 cm (Fort). 200 m (Carbet)	3	1,50 to 2 m (Fort de France)	5	Destruction of all boats in the harbour, except Roddam. 52 km2 destroyed, 38,000 deads, 1 survivor (prisonnier)	O'Loughlin and Lander, 2003	
1902	May	9		Martinique, Ste Lucie	Martinique		Anormal perturbations	V (vent volcanique)						5		O'Loughlin and Lander, 2003	
1902	May	20		Martinique (Mount Pelée, Souffrière St Vincent)	Martinique	Saint Pierre, Carbet, Petite Anse to St Pierre, Fort de France, Trinité	Local tsunami	V		3,50 m (wave hight) : Carbet	50 m at the Petite Anse, 40 cm to St Pierre Fortification			5	Destroyed houses, boats, docks	Saffache et al, 2003	

1902	August	30	21h25 LT	Martinique (Mount Pelée)	Martinique	Saint Pierre, Carbet, Fort de France, Schoelcher, Case Pilote, Trinité	Local tsunami	V		3 m (St Pierre), 1 m at Fort-de-France and Trinité	100 m at Case Pilote, 30 m at Schloecher			5	Flooded docks in Fort de France, including La Savanne square	Saffache et al, 2003 ; O'Loughlin and Lander, 2003	
1906	February	16	1h25 LT	Ste Lucie	Martinique, St Vincent, Guadeloupe, Grenade, Dominique, Barbade		Local tsunami	S (VIII)						2 a		Lander et al, 2002	Tsunamigenic seism reported the same year, Dec. 31, in Venezuela.
1939	July	24	12h LT	Kick'em Jenny	Antilles (including Martinique)	Fort-de-France, Le Vauclin	Regional tsunami	V (VEI: 1)						4		Smith and Shepherd, 1993 ; O'Loughlin and Lander, 2003	
1969	December	25		Guadeloupe	Antilles (including Martinique)		Regional tsunami	S (X - XI, 7,7)						2 b		O'Loughlin and Lander, 2003 ; Zahibo et al, 2005	Barbade, Antigua, Dominique
1985	March	16	14h54 UT	Guadeloupe	Guadeloupe		Local tsunami	S (VI, 6,3) + L						2 b		O'Loughlin and Lander, 2003	Similar event in 1690, 1843, 2004
1991	April	22	21h56 UT	Costa Rica	Antilles (including Martinique)	Fort-de-France Bay	Regional tsunami	S (X - XI; 7,6)						4		Lander et al, 2002 ; O'Loughlin and Lander, 2003	
2004	November	21	11h40 UT	Guadeloupe (Les Saintes)	Guadeloupe		Local tsunami	S (6,3)						2 b		Zahibo et al, 2005	Similar events in 1690, 1843, 1985