Issues 08

Issues in Risk Science

Tectonic Threats in the Caribbean

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Executive Summary

- The Eastern Caribbean, and in particular the Lesser Antilles, is a region of high tectonic hazard, with earthquakes, tsunamis and volcanic eruptions all presenting a significant threat.
- Most tectonic hazards result ultimately from the subduction of the American Plate beneath the much smaller Caribbean Plate, resulting in a chain of overlying volcanic islands and the occurrence of earthquakes both along the plate boundary in the subduction zone and in the deforming zone of the over-thrusting Caribbean Plate.
- Historical records of hazardous tectonic events extend back to the 16th Century, but for much of the area they are at best sketchy, until the late 18th Century, in particular for earthquakes.
- Instrumental recording networks were not well-established in the region until the 1950s so that records of small earthquakes, upon which extrapolations to predict recurrence of rare, large earthquakes are based in many estimates of seismic hazard, are very short indeed.
- The historical pattern of earthquakes reflects only about half of the observed movement of the Caribbean Plate relative to the American Plate, providing the possibility that the balance may be accommodated by rare, very large plate boundary earthquakes that are not represented in the short historical and instrumental earthquake records.
- The potential exists for great earthquakes (comparable to the 2004 Sumatra earthquake) of moment magnitude 8.5 – 9.0 rupturing the 1000 km length plate boundary between easternmost Hispaniola and Guadeloupe.
- The tsunami generated by such an event has the potential to seriously impact upon large populations including tourists, and affect coastal infrastructure and property.
- Although tsunami hazards in the Lesser Antilles are poorly constrained in terms of frequency of events, the variety and scale of potential sources indicates that there is a significant potential for events with tsunami intensity similar to that in the Indian Ocean tsunami of 2004, if not greater.
- The most damaging earthquakes are also felt over wide areas, causing multiple losses in different islands in the same event, so a process of risk aggregation is critical to understanding the insurance implications of seismic hazard in the Lesser Antilles.
- Discounting the submarine volcano, Kick ‘em Jenny, nine eruptions or episodes of minor activity occurred at five volcanoes during the 20th Century, giving a time-averaged return period of a little over 11 years.
- Eruptions of the 15 active volcanoes in the Lesser Antilles are generally small to moderate. There is also, however, geological evidence for very large explosive eruptions capable of affecting more than the host island.
- Analysis of repose-period patterns reveals the most hazardous Lesser Antilles volcanoes to be those already in repose for about 50 years and for 250 – 450 years. On this basis, the highest relative hazard is associated with Saba, Guadeloupe (La Soufrière), Dominica (Patates), Martinique (Mont Pelée) and St. Vincent (Soufriere).

1. Introduction

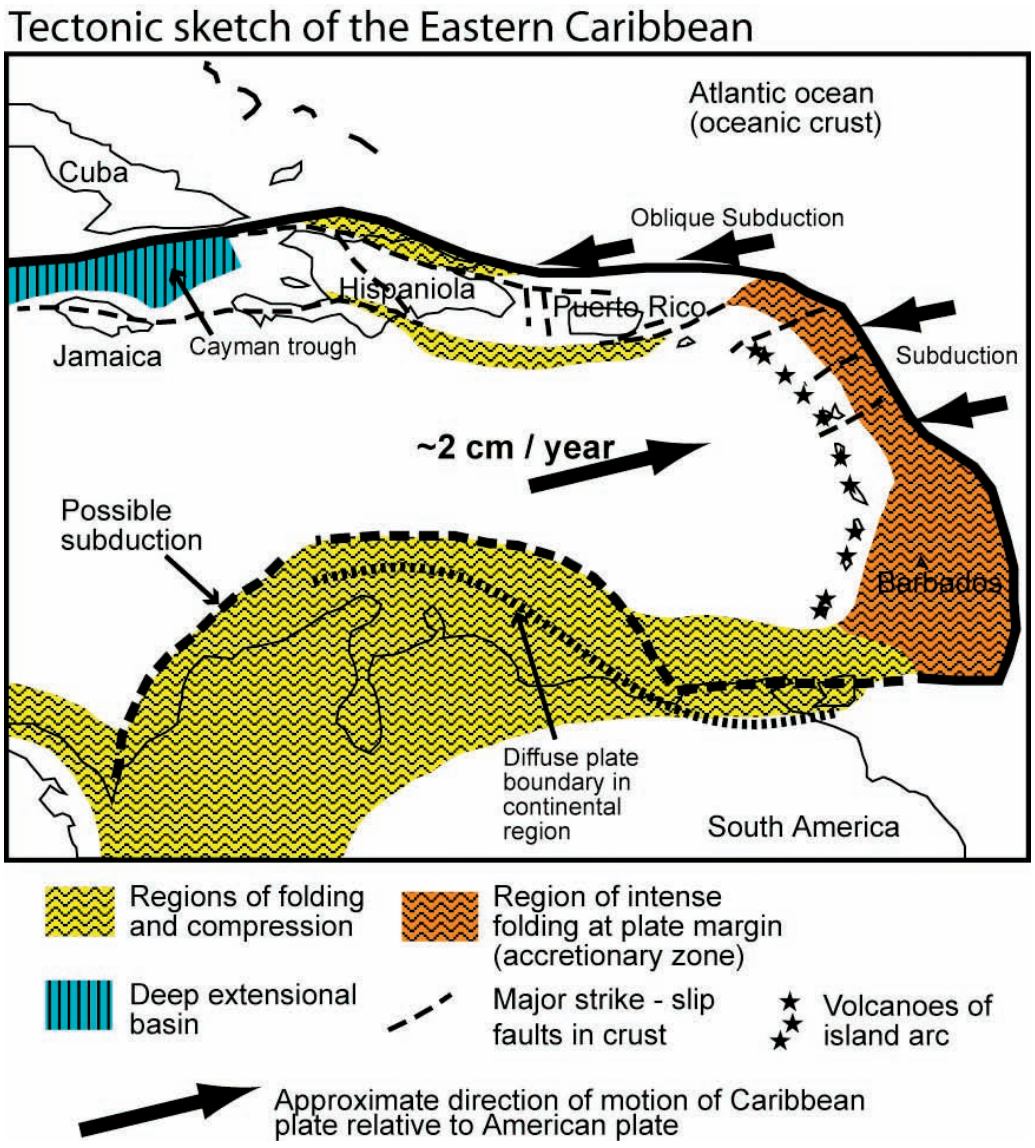
This Issues paper addresses earthquake, tsunami and volcanic hazards in the tectonically-active Lesser Antilles, taken here to comprise the chain of small islands stretching from Trinidad in the south-east to the American Virgin Islands in the north-west (**Figure 1**). Broadly-speaking, in cases of all but the largest – and rarest – eruptions, the hazards associated with a particular volcano are confined to the host island. In contrast, the impacts of earthquakes and tsunamis may be more wide-ranging, and events towards the upper end of the magnitude range for both types of event can encompass several adjacent islands, or even the entire region, and perhaps beyond. For this reason, this report also considers seismic and tsunami sources that lie outside the region of interest, most notably Puerto Rico and the adjacent submarine slopes and ocean trenches, which present a significant tsunami threat to the Lesser Antilles. We do not consider within-island variations in hazard, although these are clearly significant, particularly in relation to tsunamis, which only directly impinge upon the coastal zone.

Figure 1: Location map for the Lesser Antilles.

2. Setting the Scene

The Lesser Antilles island chain extends along the margins of a small tectonic plate, the Caribbean Plate. This is a fragment of oceanic crust – originally part of the Pacific Ocean group of plates – which has become wedged into the American Plate, but is continuing to move eastwards relative to it at a rate of about 2 cm a year (Dixon et al. 1998). Over the historic period, about half of this movement has been accommodated by slip during the recorded earthquakes: the rest has either been accommodated by distributed deformation or fault creep that is not associated with earthquakes, or is accumulating stress at the submarine plate boundary where it may be released in great earthquakes. The geological hazards in the region result from this motion and the forces that drive it. The nature of the hazards varies as a function of the means by which the motion is accommodated (**Figure 2(a)**).

2(a)



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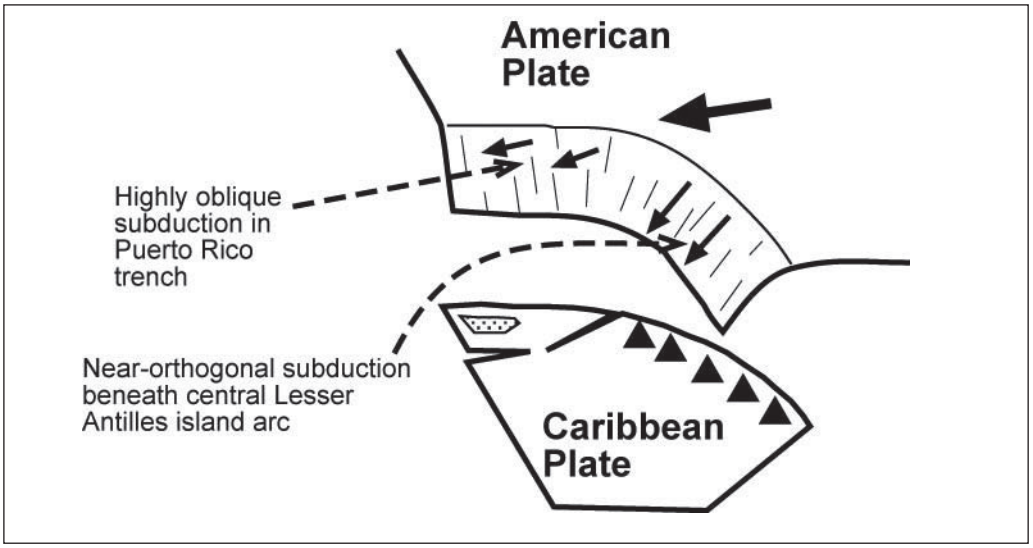

Figure 2: Tectonic map of the Lesser Antilles showing plate boundaries, rates of plate movement, active volcanoes, major faults and regions of strong deformation (a) and a perspective diagram showing the relationship between the Caribbean and American plates (b).

From the perspective of geological hazards, the margins of the plate, including broad deformation zones indicated in **Figure 2(a)**, can be divided into:

- The eastern Lesser Antilles Subduction Zone, the so-called 'accretionary prism' of deformed sediment scraped off the down-going plate, and the arc of volcanic islands.
- The northern plate margin from the Virgin Islands through the Greater Antilles, characterised by highly oblique, non-volcanic subduction under Puerto Rico that passes west into a zone of crustal compression and strike–slip faulting through Hispaniola to Cuba and Jamaica.
- The complex southern boundary along the north coast of South America, with strike-slip faulting, compression and possible incipient subduction.

This report deals primarily with the first of these zones and the eastern part of the second, the Virgin Islands and Puerto Rico, although the islands at the southern end of the Lesser Antilles, and especially Trinidad, are also affected by earthquakes generated along the southern boundary of the Caribbean Plate in Venezuela.

The plate boundaries in the north and south are particularly complex owing to geologically recent changes in plate motion. The most complex part of the southern margin in western Venezuela and Colombia is away from the area discussed in this report, but geological developments in the north between Western Hispaniola and the Virgin Islands are more relevant. In this area, slices of the Caribbean Plate in Hispaniola, referred to collectively as the Gonave microplate (Mann et al. 1995) are being broken off along east-west strike slip faults that extend with decreasing displacement rates as far east as Puerto Rico; Puerto Rico itself is still moving with the Caribbean Plate (Dixon et al. 1998). Despite this, the subduction zone plate boundary remains active to the north of Hispaniola, as evidenced by the major thrust earthquake

of 1946 (Russo & Villasenor, 1995) and it is therefore likely that the deep Puerto Rico trench represents the surface trace of a still-active subduction zone, albeit one with a large oblique component of slip (Figure 2(b)). The potential of this subduction zone to generate giant earthquakes is discussed further in Section 3.

Major geological hazards in the Lesser Antilles include both seismic and volcanic hazards, as well as tsunami hazards resulting from earthquakes, volcanic eruptions and landslides. These result ultimately from the subduction of the American Plate, which produces earthquakes both along the plate boundary in the subduction zone and in the deforming zone of the upper, Caribbean Plate, which extends from the toe of the accretionary prism in around 5 km water depth offshore, through the volcanic island arc to the steep Grenada Escarpment, west of the volcanic islands themselves. The accretionary prism is almost entirely underwater: it is composed of sediment discharged from the Orinoco River in Venezuela and accordingly thins markedly from south to north. Deformation within the accretionary prism is intense: the island of Barbados, located on top of the prism, for example, is being uplifted at a long-term rate of about 0.5 cm/year (Speed & Cheng, 2004). Earthquakes in the upper plate, close to the islands of the volcanic arc, represent a disproportionate part of the seismic hazard in those islands because their epicentres are close to the islands. However, the historical pattern of earthquakes reflects only about half of the 2 cm/year movement of the Caribbean Plate relative to the American Plate across the subduction zone and the resulting 0.5 cm/year uplift of the accretionary prism. The other half may be accommodated by distributed deformation or creep that is not associated with earthquakes, but may instead be accommodated by rare, very large plate boundary earthquakes that are not represented in the short historical and instrumental earthquake records. This represents a major source of uncertainty in seismic and tsunami hazard in the region that is discussed further below.

The volcanic hazards in the Lesser Antilles, as in other island arcs, result from the subduction of water bound in the hydrous minerals of the altered oceanic crust in the down-going plate. Release of this water as the descending rocks are heated leads to melting of the overlying hot mantle to produce hydrous basaltic magmas with as much as 5% water by weight. As the magmas rise to the surface, especially if partial crystallisation en route leads to concentration of dissolved water in the remaining, more viscous magma, the water tends to come out of solution, driving explosive expansion of the magma and leading to highly dangerous, explosive volcanic eruptions. The active volcanic islands can be subdivided according to their time-averaged rates of eruption and other characteristics of their volcanic activity. The northern (Saba, St. Eustatius, St. Kitts, Nevis and Montserrat) and southern (Grenada, Grenadines and St. Vincent) groups are characterised by relatively low magma production rates and relatively frequent and small-volume eruptions. A central group (Guadeloupe, Dominica, Martinique and St. Lucia) are characterised by a higher magma production rate. While some of this is expressed in frequent, relatively small, eruptions (especially in Martinique in the geologically recent past) an important qualitative difference between these islands and those to the north and south is that they also experience infrequent, highly explosive eruptions, with erupted volumes of magma as high as tens of cubic kilometres. For comparison, this is in the same range as the volumes of the largest historic eruptions such as the 1883 eruption of Krakatoa (c. 20 km^3).

In contrast, along the northern and southern boundaries of the Caribbean Plate, the dominant geological hazards result from faulting. The major faults at the surface are of the strike-slip type, analogous to the well known San Andreas Fault system of California, but as in that region a component of plate convergence and, more importantly, irregularities along the plate boundaries result in local extension and compression. The islands from Anguilla through the Virgin Islands to Puerto Rico lie in a transitional region characterised by highly oblique subduction of the Atlantic Plate beneath Puerto Rico, producing the Puerto Rico Trench; compression and possibly incipient subduction of the Caribbean Plate to the south of Puerto Rico, producing the Muertos Trough; and major strike-slip faulting and extensional basin formation in the intervening ridge (**Figure 2**; also **Figure 4**). Although volcanic activity in this region is presently very minor and diminishing through geological time, the complexity of the deformation and the resulting steep submarine slopes give rise to major seismic and tsunami hazards (see Sections 3 and 4). As with the Lesser Antilles Arc, the pattern of historical earthquakes reflects only about half of the relative plate movement of 2 cm/year and so there is potential for rare, very large earthquakes, particularly along the Puerto Rico trench.

3. Earthquakes and Earthquake Hazards

Although less notorious than the volcanic disasters that have occurred in the Lesser Antilles, earthquakes have caused the second and third most destructive geological disasters in the Caribbean as a whole: the 1692 earthquake and tsunami which destroyed Port Royal in Jamaica (where more than half the inhabitants died in the event itself or later of disease) and the 1843 earthquake which severely damaged Guadeloupe and adjacent islands. Both of these events claimed several thousand lives, directly and indirectly, amongst populations much smaller than at present.

3.1 The size and frequency of earthquakes

The cumulative co-seismic displacements built up over geological time are perhaps the dominant control on the non-volcanic geology of this area as well as other active tectonic zones. Thus a general pattern of earthquake distribution can be deduced from the distribution of the zones of deformation (Section 2) around the Caribbean Plate boundary as well as from seismic monitoring. Geological evidence for the sizes and size – frequency distributions of individual earthquakes, however, is in general indirect. This is especially the case in the Lesser Antilles where the surface traces of many of the most important fault zones are below sea level.

In such cases considerable reliance has to be placed on historical records of earthquakes and their resulting damage, in addition to instrumentally-recorded earthquakes. Unfortunately, although the historical records extend back to the 16th Century in some places, such as Puerto Rico and Trinidad, they are at best sketchy in much of the area until the late 18th Century. Analysis of the standard earthquake catalogues for the Lesser Antilles (Robson, 1964; Tanner et al. 1997) indicates the presence of significant biases in reporting of earthquakes (such as under-reporting of seismic shaking in islands away from centres of colonial government and the home towns of regional newspapers) until the early 20th Century. Instrumental recording

networks were not well-established in the region until the 1950s and so the records of small earthquakes, upon which extrapolations to predict recurrence of rare large earthquakes are based in many estimates of seismic hazard, are very short indeed.

Although there are significant problems with the completeness of the historical catalogues of earthquakes (perhaps better considered as a catalogues of seismic shaking events since it is organised on the basis of separate reports from different islands, so the larger earthquakes in particular appear in multiple reports from different islands), some general indicators of seismic hazard can be drawn from the catalogues. It is however important to bear in mind the incompleteness and age bias in the catalogues. This is illustrated in Figure 3 which is based on the Robson (1964) catalogue (while there are differences between the two catalogues and also with the overlapping catalogue of McCann et al. 2004, the essential patterns remain the same).

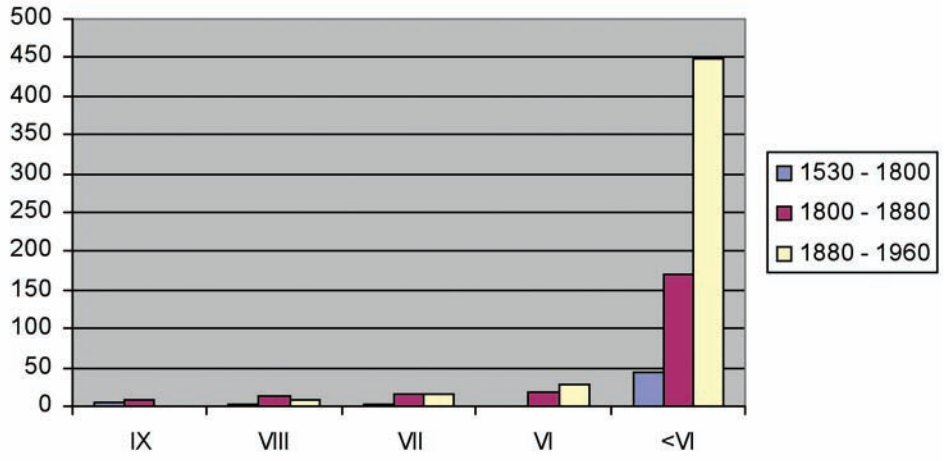

Figure 3: Frequency–time distribution of seismic–shaking events, classified by estimated Modified Mercalli seismic intensity: events "<VI" include all felt events without specifically–noted damage. Note that this is NOT an earthquake frequency plot, since the largest earthquakes are felt in a number of islands and thus produce multiple seismic–shaking events.

It is notable that the most damaging earthquakes are also felt over wide areas, and so cause multiple losses in different islands in the same event, so a process of risk aggregation is critical to understanding the insurance implications of seismic hazard in the Lesser Antilles. This is exemplified by the 1843 earthquake, whose worst effects were felt in Guadeloupe but which also caused more damage than any more local event in several adjacent islands. Thus taking the Robson catalogue as an example, the 13 records of felt seismic intensity of IX in this catalogue are in fact associated with only three earthquakes, those of 1690, 1843 and 1897: the latter is the only one of the three to have produced a felt seismic intensity of IX in only one island (Martinique).

One caveat to the application of the Robson and Tanner et al. catalogues in this regard is that large earthquakes in adjacent areas are likely to affect the northern and southern Lesser Antilles in particular. Major earthquakes in Puerto Rico and the Virgin Islands that affected the northern Lesser Antilles include events in c. 1520, 1787 (the largest recorded in the region, possibly excepting the 1843 Guadeloupe earthquake), 1867, 1918 and 1943: most of these were also significantly tsunamigenic events.

Smaller destructive earthquakes, occurring perhaps once in every two or three decades and whose main effects are felt in only one island, also tend to produce less damage in that island: maximum seismic intensities in such earthquakes are usually recorded as VIII in the seismic catalogue. Such events are exemplified by the largest damaging earthquake to have occurred in the Lesser Antilles since 1960, that of October 8th, 1974. This was a relatively shallow event, with an instrumentally-located focus at 27 km depth located 35 km NW of St. John's, Antigua. Damage at an estimated Mercalli Intensity of VIII occurred in Antigua (mainly affecting masonry buildings and oil refinery and harbour installations, both of the latter built on water-saturated alluvium); intensity VII damage occurred in the adjacent islands of Barbuda, St. Kitts and Montserrat. The epicentre of the earthquake was in fact closer to Barbuda than to Antigua: the disparity in damage may have been due to differences in local substrate conditions, with more buildings in Antigua being subjected to seismic waves amplified in soft substrates. As noted above, it is therefore likely that the bulk of earthquake damage that occurs in any one island will occur in events that are simultaneous with the most damaging events in adjacent islands. In contrast to the Antigua earthquake, the widely felt 2007 Martinique earthquake was a deep (~90 km focal depth) event on the subduction zone north of Martinique, perhaps comparable to (but much smaller than) the 1843 Guadeloupe earthquake.

Seismicity in the period of instrumental recording within the region, since the early 1950s, has broadly followed the pattern of historical earthquakes. Accurate location of earthquake foci, and determination of focal mechanisms, made possible by analysis of the instrumental data, has highlighted the diverse sources of earthquakes in the region and in particular the division between (i) deep and far offshore earthquakes on the Lesser Antilles subduction zone and (ii) shallow earthquakes close to the islands in the upper crust of the overriding Caribbean Plate and on the strike-slip fault zones on the northern and southern sides of the plate. The major fault zones of this type are indicated in **Figure 4**. As noted above, the upper plate earthquakes in particular tend to be the smaller, locally damaging events, whereas the major earthquakes of 1843 and perhaps 1787 likely occurred on segments of the plate boundary itself, although this is not proven. There is a slight tendency for upper-plate earthquakes to be concentrated in the non-volcanic islands, perhaps because subsurface temperatures in the volcanic islands are higher allowing aseismic creeping deformation that relieves accumulating strain.

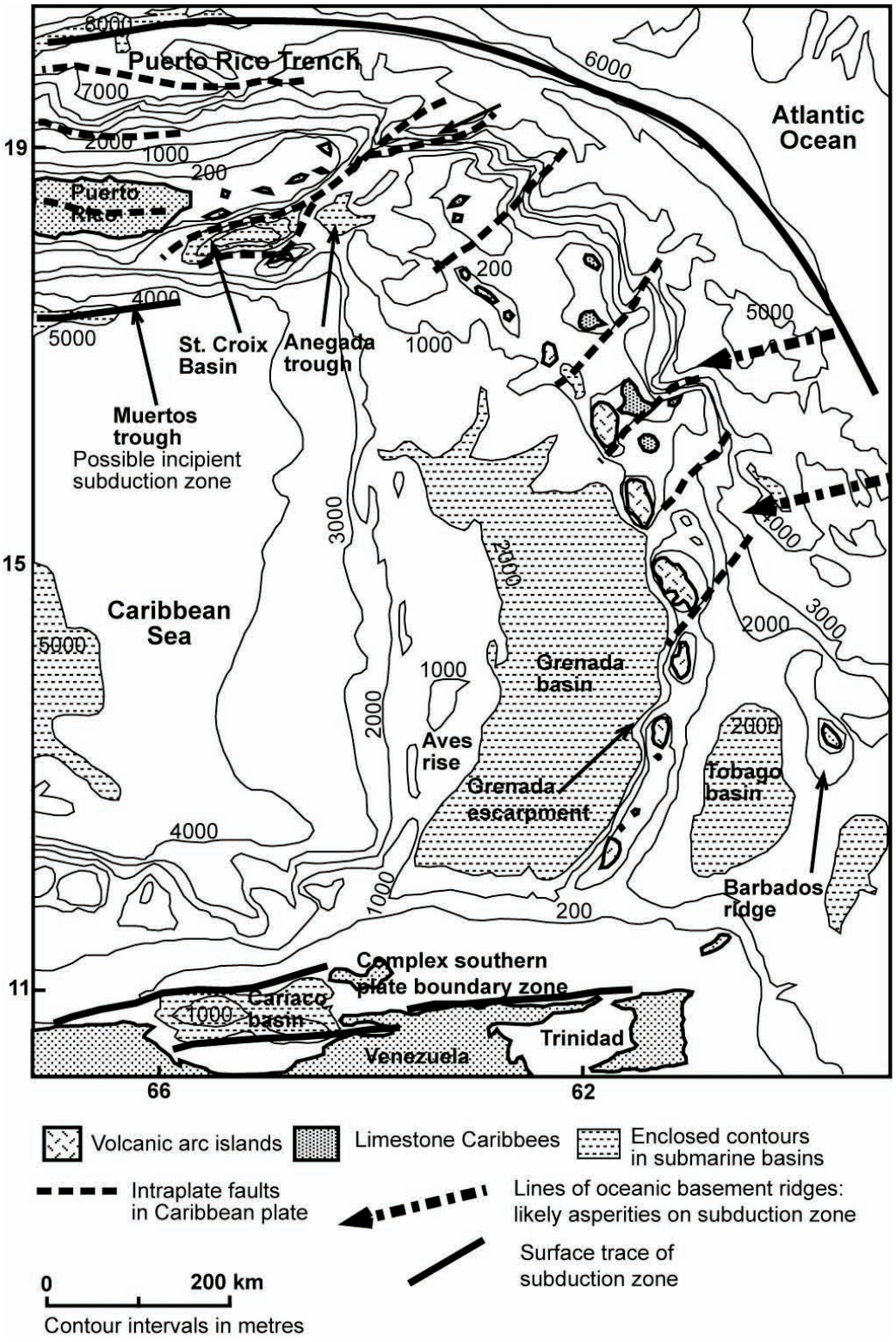

Figure 4: Structural and topographic map of the Lesser Antilles showing the location of the subduction zone, the positions of volcanic islands and faults, submarine contours and other structural and topographical information.

3.2 Great earthquakes in the Lesser Antilles region

Critically, few segments of the subduction zone plate boundary along the Puerto Rico trench and the Lesser Antilles arc appear to have experienced large earthquakes in the historical period. The two segments with large historical plate boundary earthquakes are in fact the westernmost, north of easternmost Hispaniola, and the short segment under Martinique and Guadeloupe between the oceanic basement ridges indicated in Figure 4 (these events including the 1946 Hispaniola earthquake and the 1843 and 2007 earthquakes affecting Guadeloupe and Martinique respectively. The 1787 earthquake affecting Puerto Rico and the Virgin Islands could have been a plate boundary earthquake (McCann et al., 2004) but the lack of a tsunami associated with it suggests that it was instead a strike-slip earthquake along the faults cutting the slope north of Puerto Rico (**Figure 4**). As noted in section 2, there is a notable apparent slip deficit along the rest of the plate boundary with only about half of the 2 cm/year relative plate motion being accommodated by the historical earthquakes. The remaining 1 cm/year has to be accommodated either by aseismic creep or by rare, very large or great earthquakes with moment magnitudes of 8.5 or greater. The geometry of the deep Puerto Rico trench and forearc and the exceptionally large gravity anomaly associated with it (Ten Brink, 2005) suggest that the plate boundary is strongly coupled rather than creeping, and if so the great earthquake interpretation seems more likely. As the 2004 Sumatra earthquake and Indian Ocean tsunami showed, such events can produce catastrophic damage, in particular where immigrant or transient/tourist coastal populations are unaware that such events are possible.

Geological evidence provides some constraints on whether great earthquakes are possible on the Caribbean/North American Plate boundary. Such earthquakes rupture large lengths of the plate boundary, in the order of 1000 km. Such extended ruptures only occur where the plate boundary is not broken up by asperities (irregularities or discontinuities), such as transform faults or ridges in the downgoing plate, but may be especially common where large amounts of sediment are subducted that smooth out the plate interface. As shown in **Figure 4**, two ridges to the east of the central Lesser Antilles islands of Guadeloupe and Martinique break the plate boundary into southern and northern segments, with the thickest part of the Barbados accretionary prism to the south, and the deep Puerto Rico trench to the north.

The southern Barbados section has been extensively researched for scientific purposes, particularly by the Ocean Drilling Program in its investigations of the accretionary prism. This comprises sediment that is scraped off and piled up on the overriding plate rather than being subducted, leaving the underlying oceanic crust and its asperities in direct contact with the overriding plate. It is also characterised by very high pore-fluid pressures on the plate boundary and in the overriding accretionary prism, and such pressures tend to promote aseismic creep as opposed to earthquake ruptures. The excess 1 cm/year of motion may therefore be accommodated by such creep and if so the Barbados section may have relatively low probability of producing giant earthquakes. However, the thick sedimentary sequence of the accretionary prism may make it susceptible to so-called “quiet” or tsunami earthquakes, in which large slips in weak sediments are only inefficient sources of seismic shaking but do produce damaging tsunamis (Section 4).

In contrast, the Puerto Rico trench section has features that support a higher potential for a giant earthquake. Geological data indicate strong subsidence of the trench slope up to Puerto Rico during the past few million years (Ten Brink, 2005), associated with so-called tectonic erosion of the overriding plate that involves subduction of sediment and other rocks down the subduction zone. This suggests that there is the potential for great earthquakes of moment magnitude 8.5 – 9.0 rupturing the 1000 km length plate boundary between easternmost Hispaniola and Guadeloupe. Given that only about 1 cm/year of motion is available to drive the occurrence of great earthquakes, these events (with slips of order 20 m at the plate interface) may only occur at the Puerto Rico trench at intervals of order 2000 years. As noted above, since the 1787 earthquake north of Puerto Rico did not produce a tsunami, it was most likely on one of the major strike-slip faults that cut the trench slope (**Figure 4**). Except in the far west north of Hispaniola, there is in fact little evidence for a major earthquake rupture of the subduction zone itself along the Puerto Rico trench in the historic period. However, and although the ruptures will likely be mainly far offshore and produce only moderate levels of seismic shaking onshore as in Sumatra in 2004, such an earthquake in the future would produce high levels of tsunami damage affecting the large populations and infrastructure in coastal areas, again as in the Indian Ocean event.

Earthquake and tsunami events on the scale of Sumatra 2004 produce significant traces in the geological record and are therefore susceptible to palaeoseismic investigations such as dating of coseismic uplift and of tsunami deposits. In the case of the Puerto Rico Trench and Lesser Antilles system, however, evidence of co-seismic uplift is absent, while tsunami deposits may be both poorly preserved (because of the tropical climate and coastal erosion) and difficult to distinguish from storm deposits emplaced in the much more frequent hurricanes. No such onshore evidence for giant earthquakes on the Puerto Rico Trench has been clearly identified to date. Some evidence may exist, however, in the offshore deep marine sediments. Giant earthquakes are associated in Cascadia (Pacific coast of Oregon, Washington and British Colombia) and elsewhere with widespread submarine landsliding and emplacement of thick, widespread, sediment beds (known as turbidites) on the ocean floor. Investigations of deep ocean sediments in the Puerto Rico Trench and Grenada Basin, and smaller basins within the arc (**Figure 4**), indicate the presence of numerous thick, laterally extensive, turbidite beds known as mega-turbidites, especially in the Puerto Rico Trench (Pilkey, 1988). While at least some of the Grenada Basin turbidites, in particular, may be products of volcano collapse landslides, the occurrence of these units in the Puerto Rico Trench provides indirect evidence of great earthquakes on the plate boundary. The frequency of these turbidite events has been argued to be at least 1-in-20 000 years (Pilkey, 1988), but individual events have not been dated.

4. Tsunamis and Tsunami Hazards

In the Lesser Antilles and adjacent areas, as in other islands in tectonically- active zones at ocean margins, several sources of tsunami hazard exist, which vary widely in their nature and frequency-magnitude distributions:

- Sub-seafloor earthquakes producing co-seismic seafloor displacements.
- Submarine landslides (often triggered by earthquakes): rapid downslope movement of the material involved, as coherent sliding blocks, fragmented debris avalanches, dense turbidity currents or a combination of all three.
- Submarine volcanic activity, including shallow-water explosions, crater-floor subsidence events, and submarine landslides.
- Sub-aerial volcanic activity producing flows (mudflows and dense pyroclastic flows) and landslides which enter the sea. The largest events of this type involve volcano lateral collapses that are partly sub-aerial and partly submarine.

The largest tsunamis are capable of propagating over distances of thousands of kilometres through the deep ocean basins and still having significant effects: thus it is necessary to consider both local (within the Caribbean) and remote sources. Conversely, local effects as the tsunami waves approach the shore produce wide local variations in tsunami runup, typically from half the average runup to twice the average as measured along coastal sections on order 100 km long. The following discussion is therefore limited to a general consideration of the location of tsunami sources both inside and outside the region.

Table 1 shows the historically-recorded damaging tsunamis (Lander et al, 2002) that have affected the Eastern Caribbean. In view of the great distances over which tsunamis can propagate, it is worth noting that a number of other earthquakes in the Caribbean region have been associated with tsunamis: those of 1856 off Central America, 1751 and 1946 off Hispaniola, and above all the 1692 earthquake which destroyed Port Royal in Jamaica, by a combination of seismic shaking, tsunami and permanent subsidence, and also caused extensive tsunami damage at St. Ann's on the north coast of Jamaica. The majority of the historically-recorded tsunami events in the Eastern Caribbean have been associated with local earthquakes, but three events in **Table 1** are of note: the 1755 earthquake, with a source close to the coast of Iberia, which generated a major tsunami that destroyed much of Lisbon and Cadiz, but also resulted in a significant wave on the far side of the Atlantic Ocean; and small, but in one case fatal, tsunamis associated with the entry into the sea of volcanic flows during subaerial volcanic eruptions.

DATE	ISLANDS/ AREAS AFFECTED	RECORDED EFFECTS	MAXIMUM RUNUP	ESTIMATED MAGNITUDE	CAUSE AND SOURCE
1.9.1530	NE Venezuela (Paria)	Rise in sea level, followed by fall	8 m (four fathoms) ?	3	Local earthquake
5.4.1690	Nevis	Sea withdrew “a furlong”, then returned	Unknown		Local earthquake
1.11.1755	Martinique Barbados Saba St. Martin Antigua Dominica	Martinique: wave up to 1 storey high in town, causing damage Saba: flooding of waterfront buildings	Barbados: 1.5 – 2 m Saba: 7 m St. Martin 4.5 m; Antigua, Dominca c. 3.6 m	1-3 (in Caribbean; 4 to 5 along Iberian coasts)	Earthquake in Gibraltar – Azores transfer fault zone, S. of Portugal (Great Lisbon Earthquake and tsunami)
31.3.1761	Barbados	“Remarkable ebbing and flowing of the tide”	Unknown		Locally – felt (small?) earthquake
24.4.1767	Martinique, Barbados	Ebbing and flowing of the sea	Unknown		Earthquake, felt in Martinique, Barbados and British Guiana (large event far offshore?)
30.11.1823	Martinique	Some damage in harbour	Unknown		Local earthquake, strongly felt but not causing directly recorded damage
8.2.1843	Antigua	Sea rose but fell again immediately, remaining calm (slow tsunami)	1 m	0	Great Guadeloupe earthquake
18.11.1867	St. Thomas Puerto Rico Guadeloupe Grenada	Damage to harbour buildings, houses and boats	Several metres in St. Thomas; 1.5 min Grenada	3	St. Croix earthquake
6.5.1902	St. Pierre, Martinique	Yacht “Precheur” capsized with loss of several lives; damage to waterfront in St. Pierre	1 – 2 m (local)	N/A	Entry into sea of mudflow associated with initial stages of volcanic eruption
11.10.1918	Puerto Rico	30 deaths and much damage in Aguadilla (north - western Puerto Rico)	Unknown	3+ ?	Earthquake in Mona Passage (west of Puerto Rico)
17.1.1929	Venezuela	Much damage in Cumana	Unknown	3 ?	Earthquake
26.12.1997	Montserrat	Old Town bay area; little damage	3 m (local)	1	Entry into sea of debris avalanche generated by lava dome collapse

Table 1: Historically – recorded tsunami in the Eastern Caribbean (summarized from Lander et al. 2002). Tsunami magnitude scale depends on maximum observed runup (0: 1 – 1.5 m; 1: 1.5 – 2 m; 2: 4 – 6 m; 3: 8 – 12 m; 4: 16 – 24 m; 5: > 32 m).

The most damaging historic tsunamis in the Eastern Caribbean were, however, produced by relatively small (although significant) earthquakes in the Puerto Rico Virgin Islands region. These events were most probably shallow, within-plate, earthquakes (Section 3). Other minor earthquakes, that produced disproportionately large earthquakes, occurred in 1761 and 1823. In contrast, the great 1843 Guadeloupe earthquake generated only a relatively trivial sea wave. This may in part be accounted for by the relatively deep source of this event, which from the onshore damage appears to have been on the subduction zone close to or underneath Guadeloupe itself.

The historical data summarised in **Table 1**, while useful, do not represent the full level of tsunami hazard in the region (while including transoceanic sources from elsewhere in the Atlantic, such as the 1755 Lisbon earthquake) because of the potential for major tsunamis from sources that are not represented in the historical record. Geological data and results of tsunami models indicate that these rare but potentially catastrophic events include:

- Very large or great earthquakes on the northern part of the plate boundary along the Puerto Rico Trench. As discussed in Section 3, such events could be comparable in scale to the Sumatra 2004 earthquake tsunami and might occur at intervals in the order of 2000 years.
- Quiet or tsunami earthquakes in the Barbados accretionary prism, with minimal seismic shaking but producing potentially very damaging tsunami in the southern part of the Lesser Antilles. The limited felt seismic shaking and problems with rapid interpretation of the seismic records of such events means that they often produce high mortality rates in the impact zones. The frequency of such events in the Lesser Antilles is unknown.
- Volcano eruption and volcano collapse-generated tsunamis, particularly from the large volcanoes in the central part of the Lesser Antilles arc. Comparison with tsunamis produced by relatively small island arc volcano collapses elsewhere, such as Ritter Island (Papua New Guinea) in 1888 and by major explosive eruptions, such as Krakatau in 1883, indicates that such events could be regionally damaging. The frequency of such events in the Lesser Antilles and adjacent areas is not well constrained, but they are not uncommon in the geological record.
- Landslide-generated tsunamis, from the many steep submarine escarpments in the region such as the North Puerto Rico Trench slope and the Grenada Escarpment. Some of the historical events may have been generated by small landslides of this type as noted in **Table 1**. Scars left by larger, prehistoric, submarine landslides are present in various parts of the region, especially on the slope of the Puerto Rico Trench (Schwab et al, 1990), although a feature on the Puerto Rico slope thought to be the scar of a giant landslide has since been reinterpreted as the product of multiple small landslides over a long period (Ten Brink et al, 2006).
- Collapse-generated tsunamis produced by large, rare volcano collapses at oceanic island volcanoes elsewhere in the Atlantic Ocean, such as Cumbre Vieja (La Palma, Canary Islands) and Fogo (Cape Verde Islands). Indications that these two volcanoes are showing signs of incipient instability suggest that the potential for such collapses may be increasing. Modelling results from different groups indicate that such collapses may provide the potential for major to catastrophic tsunami damage on coasts all around the North and Central Atlantic, including the Eastern Caribbean.

5. Volcanic Activity and Volcanic Hazards

The Lesser Antilles volcanic arc hosts 21 volcanoes that show more or less convincing evidence of activity during the Holocene (the last 10,000 years), and seven of which have been active in historic times (post-early 16th Century) (**Figure 5**). Discounting the submarine volcano, Kick 'em Jenny, nine eruptions or episodes of minor activity occurred at five volcanoes during the 20th Century, giving a time-averaged return period of a little over 11 years. For reasons of space we do not review local hazard zonations at individual volcanoes (for example at Montserrat; see papers in Druitt & Kokelaar 2002) but rather consider the overall distribution and style of activity to compare levels of volcanic hazard at the different volcanoes.

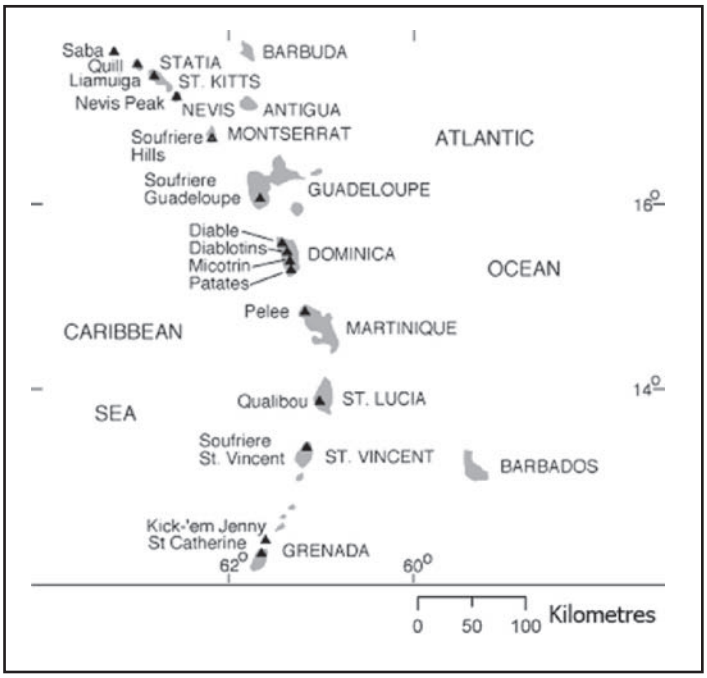

Figure 5: Location map for the Lesser Antilles volcanoes.

Reliable observations in the region began only in the late 17th Century and involve just 34 eruptions from seven volcanoes (**Table 2**). The ages of some earlier volcanic deposits have been estimated using various dating techniques, increasing the number of eruptions to 127 from 15 volcanoes, and extending the eruption record for a few islands by as much as 7,000 years. The most complete eruption records are those for Mt. Pelée (Martinique) La Soufrière (Guadeloupe), and Soufrière (St Vincent), which, taken together, provide the key information for assessing volcanic hazard in the region.

Island (volcano)	Last eruption	Known Holocene (<10,000 years) eruptions
Saba	Early 1600s	At least 1
St. Eustatius (The Quill)	About 400 AD	4
St. Kitts (Liamuiga)	1843	3
Nevis (Nevis Peak)	Holocene	At least 1
Montserrat (Soufrière Hills)	1995 - continuing	2
Guadeloupe (La Soufrière)	1976	22
Dominica (Diable)	Holocene	At least 1
Dominica (Diablotins)	Holocene	At least 1
Dominica (Micotrin)	1880	At least 1
Dominica (Patates)	About 1500	At least 1
Martinique (Mont Pelée)	1929	53
St Lucia (Qualibou)	1766	At least 1
St. Vincent (Soufrière)	1979	22
Kick 'em Jenny	2001	At least 11
Grenada (St. Catherine)	Holocene	At least 1

Table 2: Active volcanic islands in the Caribbean (listed north to south).

5.1 Styles of eruption at Caribbean volcanoes

By virtue of their tectonic setting, Caribbean volcanoes are fed by viscous, gas-rich, magma. When the quantity of gas bubbles is small, magma oozes out to form a lava dome. At the other extreme, when the gas-bubble content is very high, magma erupts as an exploding froth, driving columns of ash towards the stratosphere that can travel significant distances downwind. The destructive range of an eruption depends upon its magnitude and style, in addition to local environmental factors, such as topography and prevailing wind direction.

Caribbean volcanoes are renowned for extruding huge domes of lava (**Figure 6**) that may grow to volumes of tens of millions of cubic metres. Such domes may be the only product of an eruption, or they may grow after an earlier phase of explosive activity. In either case, they are inherently unstable and prone to major collapses with volumes of millions of cubic metres. When not confined by topographic barriers, the debris from collapses can travel for several kilometres at speeds of up to 100 km/hour. On their way, large boulders spontaneously disintegrate into giant clouds of lava dust and air, forming one category of pyroclastic flow. At temperatures of 500°-800°C, such clouds annihilate upon contact.

Figure 6: Lava dome at Soufrière Hills volcano, Montserrat

The ongoing eruption of the Soufrière Hills volcano on Montserrat, now in its 14th year, is a classic example of continued dome growth and collapse. It has also shown how pressure can sometimes accumulate within or just below domes to provoke small explosive eruptions. Although modest volcanologically, such explosions can send showers of incandescent boulders to distances of 1-2 km, as well as spewing columns of ash and pumice several kilometres skywards. These columns are sustained because magmatic fragments heat up the surrounding air and are carried upwards due to buoyancy. As they rise, the columns slowly cool and become heavier. Occasionally, the outside of a column may become heavy enough to collapse from kilometre heights. On reaching the ground, the cloud of air and fragments, still at 500°C or more, can travel downhill at hurricane velocities, spreading out as another type of pyroclastic flow. On occasion, an explosion is directed sideways, sourcing an uncooled (~ 1000ºC) pyroclastic flow that sweeps rapidly downslope. This occurred in the 1902 eruption of Mont Pelée (Martinique), obliterating the town of St Pierre 7 km distant and causing 28,000 deaths.

The most violent Caribbean eruptions occur when magma is expelled as an exploding froth. These so-called Plinian eruptions send columns of ash, pumice and gas more than 20 km into the stratosphere. The margins of these columns can collapse from enormous heights, generating pyroclastic flows that may travel beyond 10 km. In addition, ash particles remaining aloft may be carried by winds for hundreds of kilometres before eventually settling out. Although such events have been historically rare in the Caribbean, diagnostic deposits have been found for several earlier eruptions, most notably on Martinique, St. Kitts, Guadeloupe and St. Eustatius.

Before magma can feed a new eruption, it has to force open a pathway to the surface. This process is helped as water percolating through the ground is heated by the magma and turned into steam. Vaporisation generates large pressures that can explosively discharge old rock ahead of the magma, so opening a new conduit. Such phreatic

eruptions, which involve only old rock, typically begin weeks or months before the start of magmatic activity, and occasionally are not followed by magmatic activity at all. Normally, they are also modest in size and affect only the immediate vicinity of the explosion. Sometimes, however, they can generate sustained columns of pulverised rock that can collapse to produce 'cold' (less than 100ºC) pyroclastic flows. A classic example was the 1976 activity of La Soufrière de Guadeloupe: when a series of phreatic eruptions expelled hundreds of thousands of cubic metres of old rock. Although not followed by magmatic activity, some 74,000 people were evacuated from around the volcano for 15 weeks, leading to a major collapse of the island's economy.

5.2 The sizes of Caribbean eruptions

The scale of an explosive eruption is measured by the Volcano Explosivity Index (VEI), which groups known eruptions into nine categories by size (**Table 3**). The two smallest (VEI 0 & 1) correspond to eruptions dominated by lava effusion or dome growth. The remaining categories (VEI 2–8) are dominated by explosive eruptions, whose volumes increase by a factor of ten from one category to the next. Thus VEI 2 events have volumes of 1–10 million cubic metres, VEI 3 events volumes of 10-100 million cubic metres, VEI 4 events volumes of 0.1–1.0 cubic kilometres, and so on until VEI 8 with volumes of 1000–10,000 cubic kilometres.

VEI	Volcano	Year
2	Soufriere Hills (Montserrat, Caribbean); individual explosions	1995 – present
3	Nevado del Ruiz (Colombia)	1985
4	Mont Pelée (Martinique, Caribbean)	1902
5	Mount St. Helens (USA)	1980
6	Pinatubo (Philippines)	1991

Table 3: VEI measures of selected eruptions in the Caribbean and elsewhere.

In the Caribbean, dated eruptions have achieved VEI 4, although the majority have been VEI 2 and 3, with typical erupted volumes of 10–100 million cubic metres. For these eruptions, there is no clear correlation between repose interval and the size of the next eruption. In other words, the fact that the most recent eruption at a volcano was VEI 4 does not mean that the next eruption is likely to be smaller. It is therefore assumed for all the islands that an impending eruption may have any magnitude up to VEI 4.

In addition, geological studies have identified at least two deposits (one on St. Lucia, the other on Dominica) less than 40,000 years old, with volumes of several tens of cubic kilometres, corresponding to eruptions of at least VEI 6. Such large eruptions tend to recur at intervals much greater than those between events of VEI 4 or less. Globally, one VEI 6 eruption occurs every century or so. Scaling this by the proportion of the world's volcanoes in the Caribbean yields a crude expectation for a Caribbean VEI 6 eruption about once every 10–20,000 years. The probability of such an event is not considered here, but must be regarded as not insignificant.

5.3 Hazards at Caribbean volcanoes

Pyroclastic flows (**Figure 7**) constitute the most common hazard at Caribbean volcanoes. Whether produced by the failure of lava domes or the collapse of eruption columns, their distribution is strongly influenced by local topography (hills providing barriers, valleys focusing motion and increasing the range of flows), but they may commonly reach 5–10 km from the volcano. Destruction is absolute, due either to direct impact or to fires started by the heat of a passing flow.

Figure 7: Pyroclastic flow generated by dome collapse at Soufriere Hills volcano, Montserrat; September 1996. Photo credit: Bill McGuire

The more violent eruptions (VEI 2-4) produce sustained columns of ash and/or pumice buoyed up by hot air. Ash can be carried to heights of 5-25 km, whereupon it spreads laterally until the surrounding air cools and allows the particles to rain over the surface. Notional distances affected by major ash falls (sufficient to affect crops and buildings) are 1–30 km, the greater distances being associated with higher altitudes of lateral spreading. Strong prevailing winds will foster greater travel distances, as well as focusing lateral motion along the downwind direction. Dust in quantities to damage 'high-tech' equipment, such as computers and other electronic hardware, may settle out two or three times further away.

Two important hazards associated with pyroclastic flows are atmospheric shock waves and tsunamis. Shock waves are zones of high pressure that may form ahead of large, rapidly-moving, pyroclastic flows. They can be sufficiently powerful to level trees and demolish buildings, and their destructive range may extend at least half as much again as the length of the source pyroclastic flow. Tsunamis may be triggered as the dense, lower part of a pyroclastic flow enters the sea, as occurred in the 1883 eruption of Krakatoa (Indonesia).

Associated with all styles of eruption is the hazard from lahars, or volcanic mudflows. Heavy rainfall can transform beds of loose ash and pyroclastic-flow material into torrents of mud which, channelled along valleys, can be highly destructive even tens of kilometres from their source, and may generate tsunamis if they arrive to the coast.

Though lahars typically constitute a secondary hazard during eruptions, they present a threat that can continue for years after volcanic activity has ceased.

The destructive range of phenomena associated with eruptions of VEI 4 or less is generally expected to be restricted to the island on which the volcano is located. Should a VEI 6 emption occur, however, the range may increase at least ten-fold, for which immediately adjacent islands will also be under threat.

5.4 Quantifying volcanic hazard in the Caribbean

Of the Caribbean's 15 recognised active volcanoes, only four have a record involving more than four confined events: Mt. Pelee, Martinique (53 eruptions), La Soufrière, Guadeloupe (22), Soufrière, St Vincent (22), and Kick 'em Jenny (11). The last of these is a submarine volcano for which little detailed information is available, so assessment of eruption frequency is strongly influenced by the behaviour of just three volcanoes.

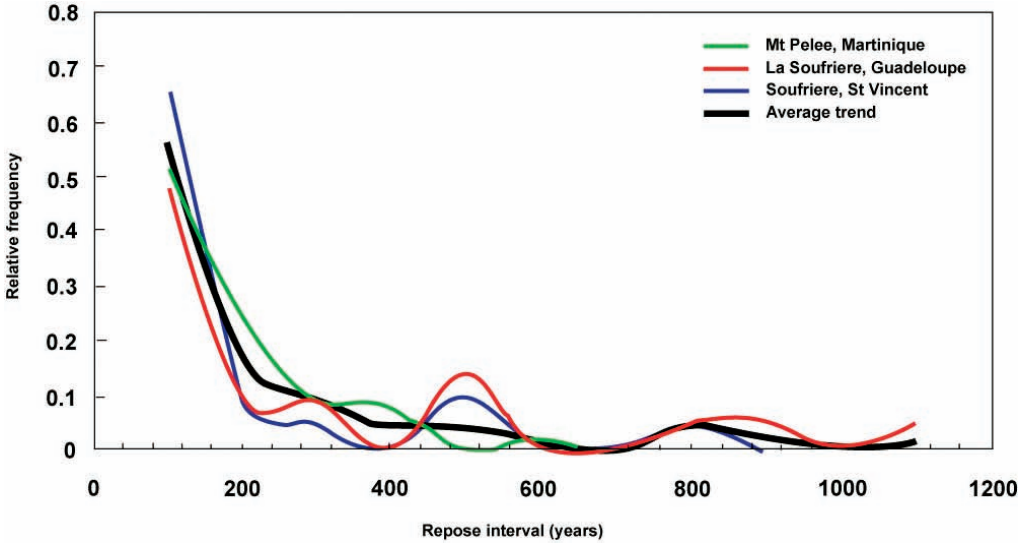

Figure 8: Distributions of repose intervals (the time between eruptions) for Mt Pelée (Martinique) La Soufrière (Guadeloupe) and Soufriere (St. Vincent).

Figure 8 shows the distributions of repose intervals (the time between eruptions) for Mt. Pelée, La Soufriere and Soufrière. Given the small number of events for each volcano, their distributions are remarkably similar. Without evidence to the contrary, therefore, it is assumed, as a first approximation, that (1) the distributions of repose interval are approximations to the same long-term distribution, shown by the 'Average Trend' and (2) the remaining sub-aerial (on-land) Caribbean volcanoes follow the same governing long-term behaviour. Figure 8 illustrates the probability of an eruption within a particular hundred year interval, assuming an eruption has just finished at the volcano of interest. Clearly, the probabilities are different when it is known that a volcano has already been in repose for a given time. As the current period of repose increases, the probability of renewed activity is calculated by (1) discarding the probabilities corresponding to times less than the current repose, and (2) renormalising the remaining probabilities. The results are summarized in **Table 4**. This shows, for example, that immediately after eruption, there is a 19 percent chance that the next eruption will occur within 50 years and a 40 percent chance that it will occur within

50–100 years, while for a volcano that has been in repose already for 100 years, the probability of renewed activity is 24 percent for 50 years and 15 percent for 50–100 years. As the actual repose increases beyond 350 years, the eruption probabilities become less reliable because (1) the actual number of eruptions upon which the table is based becomes very small (10 or less), and (2) in this particular case, an upper repose interval has been set at 500 years.

Current repose: Y (years)	**Probability (%) of an eruption within an interval of X years**									
	< 50	51-100	101-150	151-200	201-250	251-300	301-350	351-400	401-450	451-500
0	19	4	0	0	5	5	5	4	4	2
50	49	12	8	6	6	6	5	5	2	*
100	24	15	12	12	12	10	10	5	*	*
150	19	16	16	16	13	13	7	*	*	*
200	20	20	20	16	16	8	*	*	*	*
250	25	25	20	20	10	*	*	*	*	*
300	33	27	27	13	*	*	*	*	*	*
350	40	40	20	*	*	*	*	*	*	*
400	67	33	*	*	*	*	*	*	*	*
450	10	*	*	*	*	*	*	*	*	*

Table 4: Probability of an eruption within a time interval X after the current repose has achieved a period Y

On the basis of such a first-order analysis, it is unreasonable to distinguish volcanoes whose probabilities are within a few percent of each other. Accordingly, a five-point scale of relative hazard has been introduced to gather together comparably hazardous volcanoes. For an initial hazard grading, attention has been restricted to the probabilities of an eruption 'within the next 100 years', and a simplified scale established as follows. First, probabilities are grouped in ranges of 20 percent:

A: Probability 20% or less
B: Probability 21–40%
C: Probability 41–60%
D: Probability 61–80%
E: Probability 81–100%

Second, the groupings for intervals of 50 years or less and 50-100 years are combined in **Table 5**. For the hazard within 50 years, one point is assigned to A, 2 to B, until 5 for E. For the hazard between 50 and 100 years, a half-point is assigned to A until 2.5 points for E. The final ranking is the sum of the two points. Where the sum is equal, a more hazardous ranking is given to the combination with the greater hazard within 50 years (for example, BB is more hazardous than AD). The final combined ranking is then sorted into five groups, from 1 (least hazardous) to 5 (most hazardous).

Current repose (years)	Ranked probability of eruption within an interval of X years		Relative hazard	
0	A	B	2	
50	C	A	5	
100	B	A	3	
150	A	A	1	
200	A	A	1	
250	B	B	4	
300	B	B	4	
350	B	B	4	Reduced rank to adjust for long repose distortion
400	D	B	5	
450	E	*	5	

Table 5: Relative hazard rankings for new eruptions within 100 years.

The final ranking (**Table 5**) shows the most hazardous volcanoes to be those already in repose for about 50 years and for 250–450 years. These are followed in order of decreasing hazard by volcanoes in repose for (a) about 100 years, (b) a few years, and (c) about 150–250 years. **Table 6** lists the final rankings applied to Caribbean islands, which shows the highest values are associated with Saba, Guadeloupe (La Soufrière), Dominica (Patates), Martinique (Mont Pelée) and St. Vincent (Soufrière). To allow for distortions at large current reposes (which tend to exaggerate the hazard), the ranking for volcanoes already quiet for 250–450 years has been reduced by 1.5 points, but still remains at the most hazardous combined level.

The repose intervals in **Table 6** cover all but five volcanic centres: The Quill (St Eustasius), Morne Diablotins, Micotrin and Morne Patates on Dominica, and St. Catherine on Grenada, the last eruption for all of which may have been more than 1,600 years ago. These three centres have been allocated a nominal hazard rank of 3, since it is not known whether the long repose implies acute danger or that the volcano is at the end of its active lifetime.

The Repose-Interval trend in **Figure 8** is determined by eruptions occurring at intervals of decades or longer, for which eruption frequency is probably controlled by the ascent of new magma from depth. In contrast, eruptions after intervals of only a year or so may be hiccups in the expulsion of a single magma body and thus not subject to the same factors controlling the longer-term trend. Although rare, such short-term recurrence has occurred at least once in historical time at both La Soufrière and Mt Pelée. Accordingly, the hazard ranking for Soufrière Hills on Montserrat, the only Caribbean volcano currently in eruption, has been increased to 3 for a conservative estimate.

It should be emphasized that the final rankings in **Tables 5** and **6** are the results of a simplified analysis. The Repose-Interval trend is based solely on data for Mt. Pelée, La Soufrière de Guadeloupe and the Soufrière of St Vincent, so the final relative hazard will be best for these three volcanoes. The final rankings for other volcanoes are less confident because (1) they may follow trends in eruption frequency different from those

for the three volcanoes used, and (2) the behaviour of volcanoes already in repose for very long periods, especially those greater than about 1,000 years, may be affected by processes different from those operating at volcanoes that have been more recently in eruption. More detailed analyses of the hazard at each island will be required to test the reliability of the final hazard rankings.

Island (volcano)	Last eruption	Known Holocene (<10,000 years) eruptions	Relative hazard factor (1 – 5)
Saba	Early 1600s	At least 1	5
St. Eustatius (The Quill)	About 400 AD	4	3
St. Kitts (Liamuiga)	1843	3	1
Nevis (Nevis Peak)	Holocene	At least 1	3
Montserrat (Soufrière Hills)	1995 - continuing	2	2
Guadeloupe (La Soufrière)	1976	22	5
Dominica (Diable)	Holocene	At least 1	3
Dominica (Diablotins)	Holocene	At least 1	3
Dominica (Micotrin)	1880	At least 1	3
Dominica (Patates)	About 1500	At least 1	5
Martinique (Mont Pelée)	1929	53	5
St Lucia (Qualibou)	1766	At least 1	4
St. Vincent (Soufriere)	1979	22	5
Kick ‘em Jenny	2001	At least 11	2? (submarine)
Grenada (St. Catherine)	Holocene	At least 1	3

Table 6: Applying the relative hazard rankings to the Lesser Antilles volcanoes result in Saba, Guadeloupe (La Soufrière), Dominica (Patates), Martinique (Mont Pelée) and St. Vincent (Soufrière) achieving the highest relative hazard factors.

6. Sources and Further Reading

NB: This is not a complete list of sources consulted for this report, but rather a selection of papers and articles particularly critical to the discussion and arguments made therein, and others that will provide the reader with a broader perspective on the issues raised here.

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Appendix 1

A Note on Felt Seismic Shaking Intensity Scales and Earthquake Magnitude

Data on historical earthquakes and earthquake damage records are analysed in terms of Felt Seismic Shaking Intensity levels, which record the intensity of shaking felt at different locations within the overall zone of felt seismic shaking, partly in terms of eyewitness accounts of perceived shaking (especially at the lower end of the intensity scales), and partly in terms of the different levels of damage caused both to built structures and to the environment. The most widely used scale is the Modified Mercalli Intensity (MMI) scale but many historical records of damage in the Caribbean were made using the earlier Rossi-Forel scale. The two scales are as follows:

Rossi-Forel Scale (1883)

I. *Microseismic shock.* Felt by an experienced observer.

II. *Extremely feeble shock.* Felt by a small number of persons at rest.

III. *Very feeble shock.* Felt by several persons at rest. Strong enough for direction or duration to be appreciable.

IV. *Feeble shock.* Felt by persons in motion; disturbance of movable objects, doors, windows, crackling of ceilings.

V. *Shock of moderate intensity.* Felt generally by everyone; disturbance of furniture, beds, etc. ringing of some bells.

VI. *Fairly strong shock.* General awakening of those asleep; general ringing of bells; oscillation of chandeliers; stopping of clocks; visible agitation of trees and shrubs; some startled persons leaving their dwellings.

VII. *Strong shock.* Overthrow of movable objects; fall of plaster; ringing of church bells; general panic, without damage to buildings.

VIII. *Very strong shock.* Fall of chimneys; cracks in the walls of buildings.

IX. *Extremely strong shock.* Partial or total destruction of some buildings.

X. *Shock of extreme intensity.* Great disaster; ruins; disturbance of the strata, fissures in the ground, rocks falls from mountains.

Modified Mercalli Scale (1931, 1956)

I. Not felt.

II. Felt by persons at rest, on upper floors, or favorably placed.

III. Felt indoors. Hanging objects swing. Vibration like passing of light trucks. Duration estimated. May not be recognized as an earthquake.

IV. Hanging objects swing. Vibration like the passing of heavy trucks; or sensation of a jolt like a heavy ball striking the walls. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. In the upper ranges of IV wooden walls and frames creak.

V. Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters, pictures move. Pendulum clocks start, stop, change rate.

VI. Felt by all. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken. Knickknacks, books, etc. off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster and masonry cracked. Small bells ring (church, school). Trees, bushes shaken visibly, or heard to rustle.

VII. Difficult to stand. Noticed by drivers of motor cars. Hanging objects quiver. Furniture broken. Damage to masonry D, including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices, unbraced parapets and architectural ornaments. Some cracks in masonry C. Waves on ponds; water turbid with mud. Small slides and caving in along sand and gravel banks. Large bells ring. Concrete irrigation ditches damaged.

VIII. Steering of motorcars affected. Damage to masonry C; partial collapse. Some damage to masonry B; none to masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, and elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off.. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.

IX. General panic. Masonry D destroyed; masonry C heavily damaged some times with complete collapse; masonry B seriously damaged, general damage to foundations. Fame structures, if not bolted, shifted off foundations. Frames racked. Serious damage to reservoirs. Underground pipes broken.

X. Conspicuous cracks in ground. In alluviated areas, sand and mud ejected, earthquake fountains, sand craters.

XI. Most masonry and frame structures destroyed with their foundations. Some well built wooden structures and bridges destroyed. Serious damage to dams, dikes, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly.

XII. Rails bent greatly. Underground pipelines completely out of service.

XIII. Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air.

The two scales are broadly comparable except at the top end of the intensity scale where Rossi-Forel Intensity X is broadly equivalent to the entire range of MMI X to XIII.

The areas over which different intensity levels are felt broadly increase with earthquake magnitude, which allows approximate magnitudes of historical earthquakes to be estimated from these areas, with significant uncertainty resulting both from regional variations in seismic wave attenuation rates and also local effects resulting from seismic wave amplification in weak soils and sediments. However, earthquake magnitude is a fundamentally different concept, developed to quantify the size of the earthquake source rather than its effects if different places. Different Instrumental Earthquake Magnitude scales exist, based on relationships between earthquake size

and the records that they produce on seismometers of different design, but the fundamental physical scale is that of Earthquake Moment Magnitude Mw, related to estimates of the earthquake moment m0, itself related to the area of fault rupture in the earthquake, the average amount of slip (which broadly increases with area of fault rupture) and the elastic shear modulus of the rocks ruptured by the earthquake (broadly constant, but higher for mantle rocks than for crustal rocks). Where moment is measured in Newton-meters (the standard scientific units; engineers use dyne-cm and the constants in the equation are different) the equation relating the two is:

$$\mathbf{M_w = 2/3 \log_{10} m_0 - 6.0}$$

Critically, the broad relationship between area of rupture and amount of slip means that very large or giant (Mw = 8.5 to over 9) earthquakes only occur in subduction zone settings where earthquake fault ruptures around 1000 km long and 200 km wide can occur, as in the 2004 Sumatra earthquake. A key contemporary issue in assessment of earthquake hazards is whether all subduction zones can produce giant earthquakes at large time intervals (greater than the length of historical earthquake catalogues in most parts of the world), as turned out to be the case in Sumatra in contradiction of previous seismic hazard assessments, or whether they only occur in specific regions.

Notes

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