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# Rodrigues, Mauritius, and Réunion Islands Field Survey after the December 2004 Indian Ocean Tsunami

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The effects of the December 2004 Indian Ocean tsunami on the islands of Rodrigues, Mauritius, and Réunion were surveyed in March 2005. Runup and inundation were obtained at 35 sites. Measured runup ranges from 2.9 m on the southeastern coast of Rodrigues to negligible values further west on the same island, with most variations expressing the effect of differences in the structure of the coral reef. Most of the damage on Réunion was concentrated in harbors. At the main harbor of Le Port on Réunion, a 196-m vessel broke loose from its moorings and began drifting, inflicting damage on port infrastructure; this incident took place significantly later than the passage of the maximum-amplitude waves. There is a potential hazard to the Mascarene Islands from any future large earthquake in southern Sumatra. [DOI: 10.1193/1.2209190]

## INTRODUCTION AND BACKGROUND

This paper reports the findings of an International Tsunami Survey Team (ITST) that visited the Mascarene Islands of Rodrigues, Mauritius, and Réunion (Figure 1) in March 2005 to map the effect of the Indian Ocean tsunami of 26 December 2004 in the southwestern Indian Ocean. The Great Sumatra earthquake had the largest seismic moment in the last 40 years ($M_0 = 1.0 \times 10^{30}$ dyne-cm), surpassed only by the 1960 Chile earthquake, and possibly the 1964 Alaska earthquake (Stein and Okal 2005, Nettles et al. 2005). The resulting tsunami was the first one since the 1964 Alaska earthquake to reach catastrophic levels of destruction in the far field, i.e., thousands of kilometers away from its source (Synolakis et al. 2005). The human toll approached 250,000, most of which was due to the tsunami.

The devastation wrought by the tsunami occurred principally along the eastern shores of the Indian Ocean (Indonesia, Thailand, Sri Lanka, and India). However, Fritz and Borrero (2006, this issue) reported substantial damage and about 300 deaths in Somalia. Accordingly, it is important to investigate systematically the effects of the tsunami in the western Indian Ocean Basin, in order to document any local variations, and more generally to obtain a comprehensive and homogeneous database of runup and inundation values, to be used as benchmarks in future numerical simulations. In this context, surveys were carried out in March 2005 in Somalia (Fritz and Borrero 2006, this issue) and

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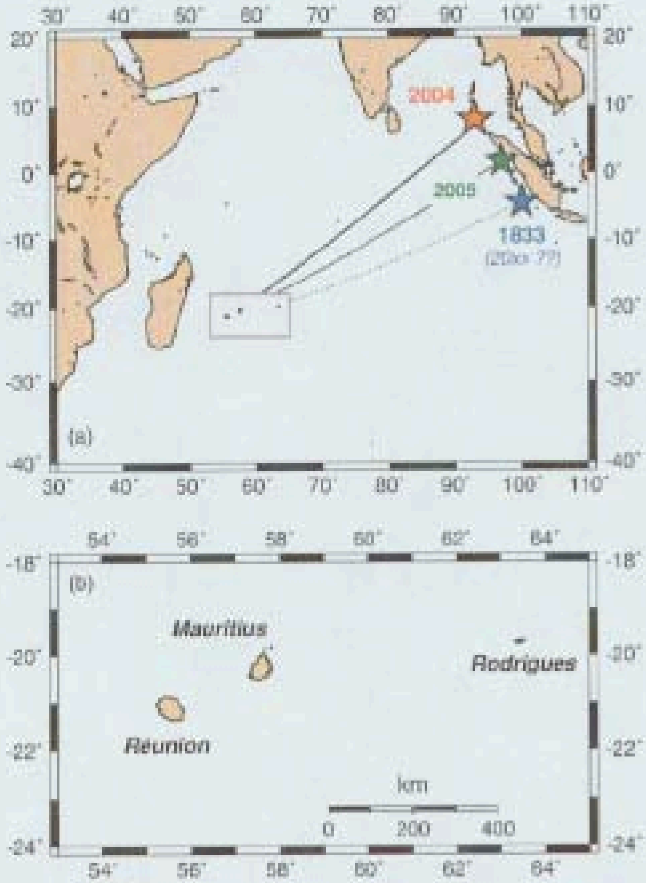



**Figure 1.** (a) The gray rectangle shows the field survey area in the Indian Ocean. The stars show, from north to south, the centroid of the 26 December 2004 Sumatra-Andaman earthquake, the centroid of the 28 March 2005 earthquake, and the epicenter of the 1833 mega-earthquake along the southern coast of Sumatra (Zachariasen et al. 1999), which could be a model for a future tsunamigenic earthquake threatening the Mascarene Islands. (b) The Mascarene islands of Réunion, Mauritius, and Rodrigues visited during the field survey; this area corresponds to the gray rectangle in (a).

in the Mascarene Islands, and in July–August 2005 in Madagascar and Oman. The present paper reports on the survey in the Mascarenes, and companion papers cover Madagascar and Oman (Okal et al. 2006a, this issue; Okal et al. 2006b, this issue).

An additional motivation for an in-depth study of the 2004 Indian Ocean tsunami in the Mascarenes is the probable future occurrence of a major earthquake along the southern coast of Sumatra, over a segment of subduction zone extending the rupture of the Sumatra-Andaman earthquake to the southeast (Figure 1), through a process of transfer of Coulomb stress (Harris 1998). As discussed in more detail in the Madagascar companion paper (Okal et al. 2006a, this issue), this process was most likely responsible for the occurrence of the second Sumatra earthquake, on 28 March 2005 (McCloskey et al. 2005), which, however, took place after the field survey in the Mascarenes. Despite its large moment ($1.1 \times 10^{29}$ dyne-cm), that event failed to generate a significant tsunami in the far field, because it occurred in a region of shallow bathymetry, even featuring several large islands (Kerr 2005). In turn, it is widely expected that the combined stress transfer from the December 2004 and March 2005 earthquakes could ripen the Sumatran subduction zone to the southeast, to the extent that a repeat of the 1833 mega-earthquake (Zachariasen et al. 1999) now looks likely in the next years or decades (Nalbant et al. 2005). The southwestern Indian Ocean, and in particular the Mascarene Islands, would lie only 10° away in azimuth from the direction perpendicular to the fault rupture, which Ben-Menahem and Rosenman (1972) have shown is that of constructive interference of the far-field tsunami wave generated by a propagating source. Thus, Réunion, Mauritius, and Rodrigues would be, relatively speaking, in greater danger from the expected tsunami than they were during the 2004 earthquake, whose rupture had a much more northerly orientation, due to the curvature of the Sumatra arc between its southern Sumatra and Andaman segments.

## LOGISTICS AND GEOLOGICAL BACKGROUND

The ITST, composed of the three authors of the present paper, visited Rodrigues during 4–7 March 2005 and visited Réunion during 7–11 March 2005. Because of logistical constraints, it was possible to spend only 7 hours on Mauritius, on 7 March, while in transit between Rodrigues and Réunion. At any rate, the tsunami had considerably lower amplitudes on Mauritius, presumably on account of the well-developed coral reef and wide lagoon fringing the island.

The island of Réunion, which constitutes an overseas department of France, is structurally comparable to the "Big" Island of Hawaii, but smaller, covering only 2,512 km$^2$ (Figure 2a). It is generally interpreted as the surficial expression of a mantle plume continuously traceable to the Dekkan Traps in India (Morgan 1981). As on the Big Island, its highest peak, Piton des Neiges, is an inactive shield volcano, now strongly eroded, whereas eruptions are essentially continuous at Piton de la Fournaise, on the southeastern flank of the island. Réunion also lacks a continuous coral barrier and a wide lagoon, although reef segments are present, especially on its western shores, where they can be occasionally submerged, as occurs offshore of Oahu in Hawaii. This and the general similarity in emerged and underwater morphology make the coastal environment of Réunion comparable to that of the main Hawaiian Islands. In this respect, the effects of the 2004 Indian Ocean tsunami on Réunion have direct relevance to Hawaii, as they constitute the first modern occurrence of significant far-field flooding on an island with a shield volcano structure, in particular since the beginning of systematic international tsunami surveys in the early 1990s (Synolakis and Okal 2005).

Mauritius, located about 200 km east-northeast of Réunion, is the next member of the island chain, with shield building dated 6.8–7.8 Ma, followed by significant erosion and some degree of localized post-erosional activity (McDougall and Chamalaun 1969). As a result, the strongly eroded island is somewhat smaller than Réunion (1,940 km$^2$,

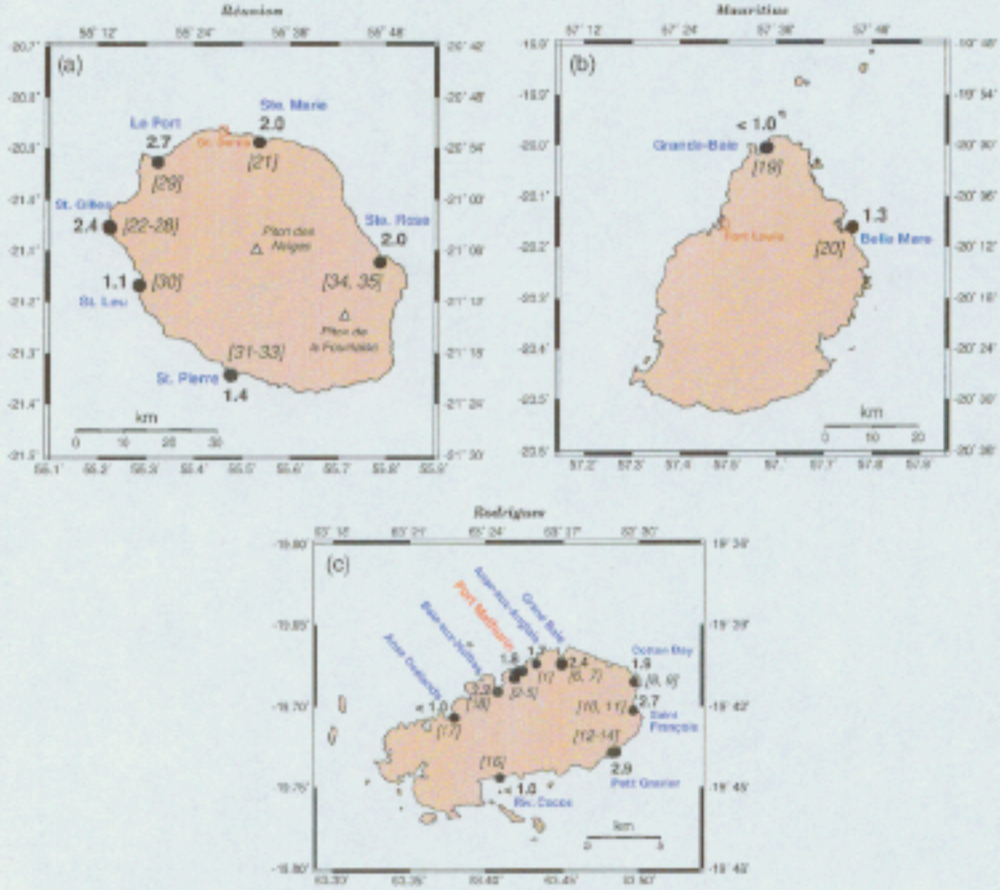



**Figure 2.** (a) Réunion Island, showing the data set gathered during the survey. The solid dots identify all entries that appear in Table 1, and the bold numerals indicate the largest value of runup or flow depth (in meters) recovered at each locality. Bracketed numbers in italics correspond to the site numbers in Table 1. The triangles identify the shield volcanoes composing the island, and the square identifies the capital city of Saint Denis. (b) Mauritius: the meanings of the symbols are the same as in (a). (c) Rodrigues Island: the meanings of the symbols are the same as in (a). The splash data point at Site 15 has been eliminated.

Figure 2b) and features a coral reef, fringing the island almost continuously, especially along its northern and eastern shores, where the resulting lagoon can reach a width of 2 km. Such a structure is expected to dissipate a significant fraction of the energy of a tsunami in the far field.

To the east, the much smaller island of Rodrigues (108 $km^2$) is part of the country of Mauritius, from which it is separated by 600 km (Figures 1 and 2c). Despite its volcanic character, it is not a genuine member of the Réunion hotspot chain, as it is both younger than Mauritius (1.5 Ma) and at a more southerly bearing than the chain (N 87° E, rather than N 56° E). Indeed, Morgan (1978) has used Rodrigues as a charter member of his proposed second type of hotspot island, whose properties would result from a lateral "plumbing leak" of the hotspot material into a nearby mid-ocean ridge system. However, recent investigations of Rodrigues and nearby structures have suggested a more rapid emplacement of its volcanics, at some distance from the ridge, while confirming the influence of a ridge-hotspot interaction (Dyment et al. 2001, Nauret et al. 2002).

Rodrigues is surrounded by a well-developed reef system, particularly in the northwest and southwest, where it extends over widths of 6 km. However, in the east, its width shrinks to 1 km or less. The main city and administrative capital of the island, Port Mathurin (population 6,000), is on the northern shore of the island, in front of a pass into the 2-km-wide reef.

## METHODOLOGY

Surveying in the Mascarenes relied on traditional methods, developed and used successfully by ITSTs over the past 13 years (Synolakis and Okal 2005). After identifying eyewitnesses, interviewing them, and recording their testimony, we conducted in situ visits at the relevant sites, followed by topographic measurements of the penetration of the tsunami waves. In Rodrigues, the eyewitnesses often led us to sites bearing preserved marks of the tsunami action (watermarks), such as water lines on buildings (Site 2) or displaced structures (Site 1).

In this context, we recall the following definitions:

- Inundation is the measure of the maximum extent of horizontal penetration of the wave.
- Flow depth is the measure of the altitude, relative to unperturbed sea level, of the crest of the wave at a location close to the beach.
- Runup is the measure of the altitude, relative to unperturbed sea level, of the point of maximum inland penetration of the wave, where inundation (as defined above) is, in principle, measured.

Topographic measurements were made by using surveying rods and eye levels; inundation was measured by differential GPS. A record was kept of the precise dates and times of the individual surveys, to allow for future tidal corrections. In this respect, we note that tidal ranges on Réunion and Mauritius are minimal (0.5 m), while they may be more substantial (1 – 1.5 m) on Rodrigues.

In addition, we were fortunate to gain access, courtesy of the manager of the Rodnet Cybercafé in Port Mathurin, to a collection of 73 digital photos taken (using at least three different cameras) on 26 December 2004 during the attack of the tsunami on the town. Some of these photos include time stamps, although we must question their accuracy. We similarly obtained one photo of the harbor in Saint Gilles, Réunion (Site 27) from the Direction de l'Environnement in Saint Denis.

## RESULTS

Table 1 presents the full data set gathered during the survey. Thirty-five measurements were retained, split about equally between runup values and flow depths estimated from watermarks. The data set is summarized in Figure 2, which for each locality shows the maximum vertical penetration (flow depth or runup, in meters) among sites in its immediate vicinity.

### PRINCIPAL CHARACTERISTICS

The maximum heights compiled in Table 1 and plotted in Figure 2 are typically 0.5–2.9 m, with a single value of 3.8 m at Petit Gravier, Rodrigues (Site 15), measured on a steep hill behind a narrow beach; we interpret this value as involving a splash of the wave on that relief. As documented in previous surveys, notably after the 2001 Peru tsunami (Okal et al. 2002), such data points are not representative of the general penetration of the wave.

In general terms, our runup values are comparable to those surveyed on the eastern coast of Madagascar, 700 km to the west of Réunion (Okal et al. 2006a, this issue), but significantly smaller than the 5–9 m values obtained by Fritz and Borrero (2006, this issue) along the coast of Somalia, 3,000 km to the northwest, where the tsunami was responsible for significant structural damage and about 300 casualties. To our knowledge, no deaths were reported in the Mascarenes, although several eyewitnesses in Rodrigues mentioned the loss of bovine livestock and poultry. This difference is a classic illustration of the directivity patterns for radiation of progressive waves from a rupturing source (Ben-Menahem and Rosenman 1972), known to feature particularly narrow lobes in the case of tsunamis (Okal and Talandier 1991).

The effects of the tsunami on the coastal communities were different in Rodrigues and Réunion, reflecting at least in part the different morphology and development of the coasts of the two islands. In Rodrigues, the low-lying downtown area of the main city, Port Mathurin, was abundantly flooded, with inundation distances reaching 400 m in nearby Grand Baie (Figure 3). In Réunion, deprived of natural beaches except along its western shore, the tsunami went largely unnoticed except inside the many harbors developed along the coast, where it led to substantial damage to the moored flotillas of fishing and leisure boats.

Most eyewitnesses described the arrival of a first wave of relatively small, positive amplitude, followed by a series of greater ones, the largest amplitude being carried by the third wave. This was quantified at Site 7 (Grand Baie, Rodrigues), where flow depth on a wall was measured at 1.7, 2.2, and 2.4 m, respectively, for the first three waves, on the basis of the recollection of an eyewitness (Table 1). These observations are generally similar to those reported at other sites, notably in Sri Lanka (e.g., Chapman 2005), and they are also in line with the results of preliminary global simulations (e.g., Titov 2005). By contrast, in Madagascar and Oman, many eyewitnesses were first alerted to the tsunami by a strong regression of the sea, because the positive first wave was not of sufficient amplitude to be recognized (Okal et al. 2006a, 2006b, both in this issue).

At epicentral distances of 4,300, 4,800, and 5,100 km, respectively, ray-tracing

**Table 1.** Data set gathered by the ITST in Rodrigues, Mauritius, and Réunion, March 2005

| Number | Site | Latitude (°N) | Longitude (°N) | Vertical survey (m) | Vertical survey Nature[a] | Inundation (m) | Date and time surveyed Date | Date and time surveyed (UTC) | Notes |
|---|---|---|---|---|---|---|---|---|---|
| Rodrigues | | | | | | | | | |
| 1 | Anse-aux-Anglais | −19.6751 | 63.4328 | 1.72 | F[b] | | 4 Mar 2005 | 14:30 | Flow depth at road bridge |
| 2 | Port Mathurin | −19.6840 | 63.4186 | 1.52 | F | | 5 Mar 2005 | 07:30 | Watermark at gas station office |
| 3 | Port Mathurin | −19.6809 | 63.4197 | 1.59 | R[b] | 334 | 5 Mar 2005 | 08:15 | Runup near mosque |
| 4 | Port Mathurin | −19.6795 | 63.4239 | 1.64 | R[b] | 85 | 5 Mar 2005 | 11:05 | Runup beyond east bridge |
| 5 | Port Mathurin | −19.6800 | 63.4214 | 1.76 | F | | 5 Mar 2005 | 11:30 | Traffic island near passenger dock |
| 6 | Grand Baie | −19.6748 | 63.4491 | 1.99 | R | 451 | 5 Mar 2005 | 12:20 | Runup at village store |
| 7.1 | Grand Baie | −19.6738 | 63.4492 | 1.73 | F | | 5 Mar 2005 | 12:40 | Cabin on soccer field; 1st wave |
| 7.2 | Grand Baie | −19.6738 | 63.4492 | 2.15 | F | | 5 Mar 2005 | 12:40 | Cabin on soccer field; 2nd wave |
| 7.3 | Grand Baie | −19.6738 | 63.4492 | 2.43 | F | | 5 Mar 2005 | 12:40 | Cabin on soccer field; 3rd wave |
| 8 | Cotton Bay | −19.6852 | 63.4963 | 1.90 | R | | 6 Mar 2005 | 05:40 | Beach in front of hotel |
| 9 | Cotton Bay | −19.6850 | 63.4963 | 1.07 | R[b] | 147 | 6 Mar 2005 | 06:10 | Bridge behind hotel |
| 10 | Saint-François | −19.7026 | 63.4959 | 2.70 | F | | 6 Mar 2005 | 07:15 | Berm on beach |
| 11 | Saint-François | −19.7026 | 63.4959 | 1.16 | R[b] | | 6 Mar 2005 | 07:30 | Riverbed behind beach (I=230 m along river) |
| 12 | Petit Gravier | −19.7286 | 63.4847 | 2.60 | R | | 6 Mar 2005 | 08:00 | Chapel on beach |
| 13 | Petit Gravier | −19.7279 | 63.4842 | 2.88 | R | | 6 Mar 2005 | 08:05 | Concrete dumpster on beach |
| 14 | Petit Gravier | −19.7281 | 63.4833 | 1.54 | F[b] | | 6 Mar 2005 | 08:20 | Branches in riverbed |
| 15 | Petit Gravier | −19.7289 | 63.4825 | 3.80 | S | 24 | 6 Mar 2005 | 08:35 | Hill behind beach |
| 16 | Rivière Cocos | −19.7443 | 63.4090 | <1.0 | | | 6 Mar 2005 | 09:30 | A few cm above highest tides |
| 17 | Anse Goélands | −19.7072 | 63.3793 | <1.0 | | | 6 Mar 2005 | 12:00 | A few cm above highest tides |
| 18 | Baie-aux-Huîtres | −19.6912 | 63.4074 | 2.15 | R[b] | 191 | 6 Mar 2005 | 12:55 | Restaurant "Yasmine" |
| Mauritius | | | | | | | | | |
| 19 | Grande Baie | −20.0005 | 57.5815 | <1.0 | | | 7 Mar 2005 | 08:50 | Not above highest tides |
| 20 | Belle Mare | −20.1604 | 57.7589 | 1.34 | | | 7 Mar 2005 | 10:57 | Beach in front of Hotel St. Geran |

**Table 1. (cont.)**

| Number | Site | Latitude (°N) | Longitude (°N) | Vertical survey (m) | Vertical survey Nature[a] | Inundation (m) | Date and time surveyed: Date | Date and time surveyed: (UTC) | Notes |
|---|---|---|---|---|---|---|---|---|---|
| Réunion | | | | | | | | | |
| 21 | Sainte-Marie | −20.8930 | 55.5359 | 2.03 | R | | 8 Mar 2005 | 14:30 | Parking lot on south side of harbor |
| 22 | Saint-Gilles | −21.0522 | 55.2231 | 2.00 | R | | 9 Mar 2005 | 06:40 | RHS stairs at Roches Noires beach |
| 23 | Saint-Gilles | −21.0526 | 55.2235 | 2.44 | R | | 9 Mar 2005 | 06:45 | Center stairs at Roches Noires beach |
| 24 | Saint-Gilles | −21.0531 | 55.2238 | >1.0 | F | | 9 Mar 2005 | 06:50 | Overflowed rocks at Roches Noires beach |
| 25 | Saint-Gilles | −21.0546 | 55.2247 | 1.30 | F | | 9 Mar 2005 | 07:35 | Harbor; Maeva Visiobull |
| 26 | Saint-Gilles | −21.0555 | 55.2244 | 1.30 | F | | 9 Mar 2005 | 07:45 | Harbor; restaurant "Chez Joseph" |
| 27 | Saint-Gilles | −21.0555 | 55.2239 | 0.85 | F | | 9 Mar 2005 | 07:50 | Harbor; fishing stand |
| 28 | Saint-Gilles | −21.0557 | 55.2235 | 1.30 | R | | 9 Mar 2005 | 07:55 | Harbor; beach beyond (27) |
| 29 | Le Port | −20.9333 | 55.3242 | 2.74 | R | | 10 Mar 2005 | 05:00 | Beach berm, East Basin |
| 30 | Saint-Leu | −21.1683 | 55.2861 | 1.10 | F | | 10 Mar 2005 | 06:45 | Pontoon in harbor |
| 31 | Saint-Pierre | −21.3450 | 55.4771 | 1.40 | F | | 10 Mar 2005 | 08:20 | Launching dock near entrance to harbor |
| 32 | Saint-Pierre | −21.3443 | 55.4765 | 0.80 | F | | 10 Mar 2005 | 08:27 | Yellow pontoon at entrance to harbor |
| 33 | Saint-Pierre | −21.3441 | 55.4754 | 0.50 | F | | 10 Mar 2005 | 08:04 | Pontoon with gauge next to parking lot |
| 34 | Sainte-Rose | −21.1256 | 55.7869 | 1.95 | F | | 10 Mar 2005 | 14:10 | Pontoon at south entrance to harbor |
| 35 | Sainte-Rose | −21.1253 | 55.7878 | 2.00 | F | | 10 Mar 2005 | 14:20 | Stairs on northern side of harbor |

[a] F=flow depth or watermark, R=runup, S=splash
[b] Data point in riverbed

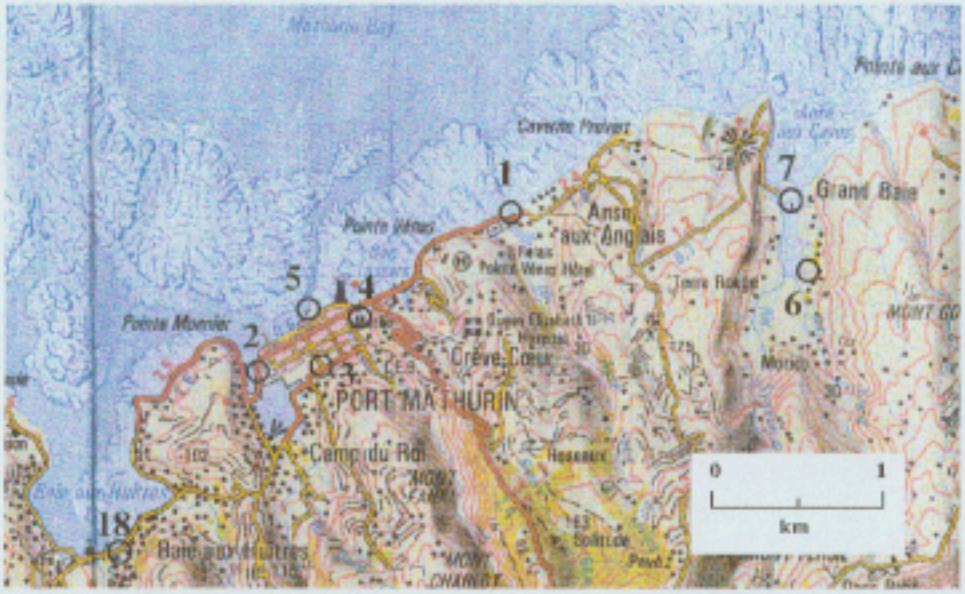



**Figure 3.** Topographic map of the Port Mathurin area, Rodrigues (adapted from Institut Géographique National, Paris 1982). Surveyed sites are identified by open circles and are keyed to the numbers in Table 1. Note that the road network has evolved (notably around Sites 2, 4, and 18) in the 23 years since the map was compiled.

models such as Titov's (2005) predict arrival times (UTC+4) of 10:45 at Rodrigues, 11:20 at Mauritius, and 11:45 at Réunion. Our eyewitnesses reported arrival times ranging from 09:30 to 11:30 on Rodrigues and 10:30 to 12:30 on Réunion, which must be considered in good agreement, given the general uncertainty of temporal estimates reported by eyewitnesses. Time stamps on photos obtained by the team are similarly difficult to interpret in an absolute sense, because the errors of the clocks in the various cameras are unknown. However, we can use them to infer *relative* times between photos taken by the same camera. In addition, the street clock at right in Figure 4a shows a time of 11:56 (UTC+4), to which we attribute a probable margin of error not exceeding 5 minutes (we checked that this clock was showing the correct time on 5 March 2005). This observation then allows an estimate of an absolute time for that photo, as well as all others taken by the same camera.

The duration of the phenomenon was generally given as "extending into the afternoon and evening." As for the description of the periods of the waves, it is similarly variable, with estimates ranging from 20 minutes to 1 hour; these estimates are significantly longer than reported in other parts of the basin (Madagascar and Oman).

In the following sections, we highlight the sites where the most significant observations were made.

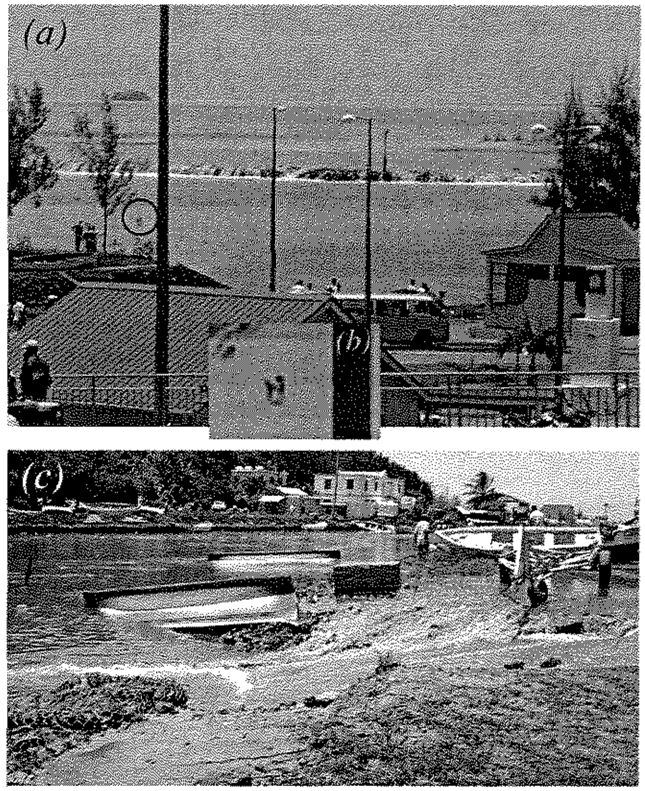



**Figure 4.** Dynamic effects of the tsunami, photographed in Port Mathurin, Rodrigues, on 26 December 2004 (courtesy Rodnet Cybercafé). (a) Tsunami wave at the entrance to a river estuary at Site 4 (the bridges shown in Figure 6a are 30 m and 50 m, respectively, upstream and to the left of this photo). The clock at right reads 11:56 (UTC+4), tentatively associating the phenomenon with an ebbing phase after the third (largest) wave. (b) Enlarged image of a dog standing on the exposed beach; this dog also appears in the circle in (a). (c) Tsunami ebbing back to the sea and scouring an estuary bank at the western end of town (Site 2; the service station is to the right of the photo). Note the capsized canoes and boats, many of which are deposited on the river berm.

## RODRIGUES

### Port Mathurin and Anse-aux-Anglais, Sites 1–5

Extensive flooding covered essentially the entire downtown area, identified in Figure 3 by its regular, rectangular street blocks, but the flow depth remained miraculously manageable, as evidenced by the individuals in Figure 5, who are seen wading through the streets. This certainly contributed to the absence of casualties. Dynamic effects of the tsunami are presented in Figures 4, 6, and 7. Figure 4 illustrates complex wave activity at Site 4 during what is probably an ebbing phase after the third wave (as discussed be-

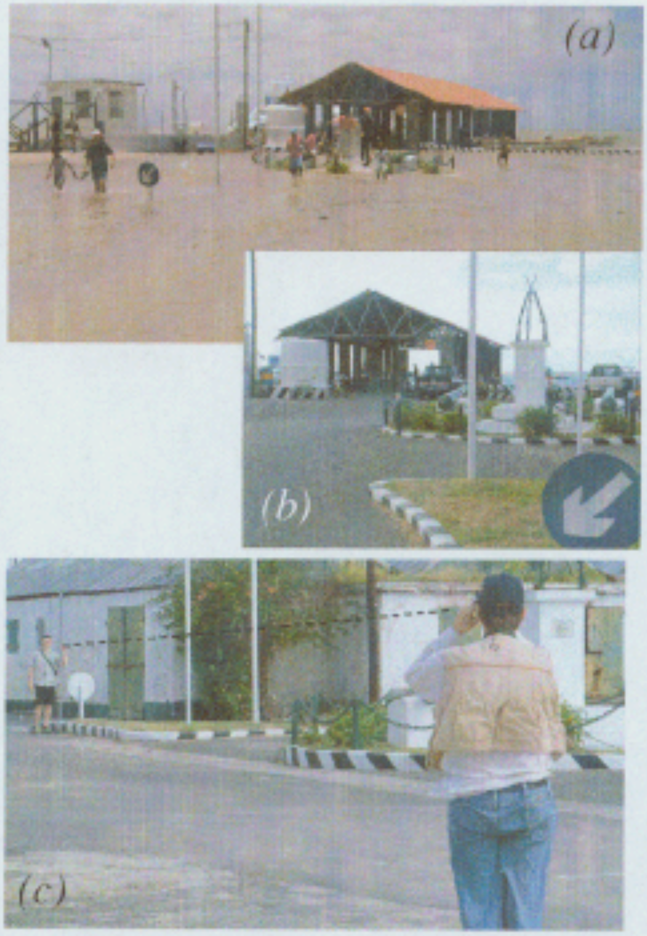



**Figure 5.** Site 5, traffic island and veterans memorial at the passenger ship terminal in Port Mathurin, Rodrigues. (a) Tsunami inundation, photographed at 11:50 (UTC+4) on 26 December 2004 (courtesy Rodnet Cybercafé). According to eyewitnesses, the flow depth was approximately 10 cm higher at its maximum. (b) The same location, photographed and surveyed on 5 March 2005. (c) The surveying technique for this location.

low) and powerful scouring during an ebbing phase near Site 2. Figure 6c shows the dramatic impact of the maximum wave on the road bridge at the east end of town, after it passes below the pedestrian gangway (Figure 6b). The corrected absolute times (UTC+4) stamped by the present authors on Figures 6b and 6c are derived from the reading on the street clock in Figure 4a; the photo of that clock was taken by the same camera 17 minutes later. Although the absolute times have a probable accuracy of only a few minutes, we can use the relative timing between Figure 6b and Figure 6c (30 seconds) to estimate the rate of rise of the water surface at $5 \pm 1$ cm/sec.

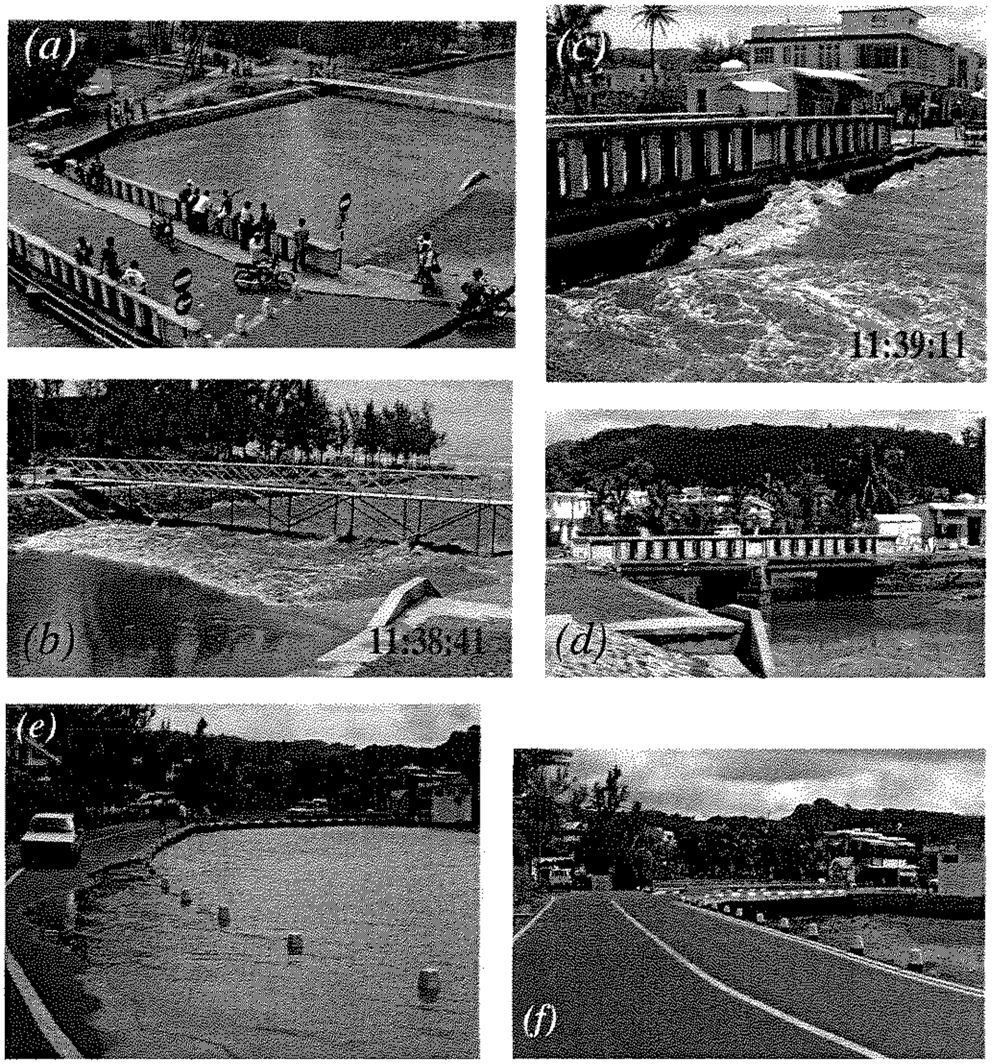
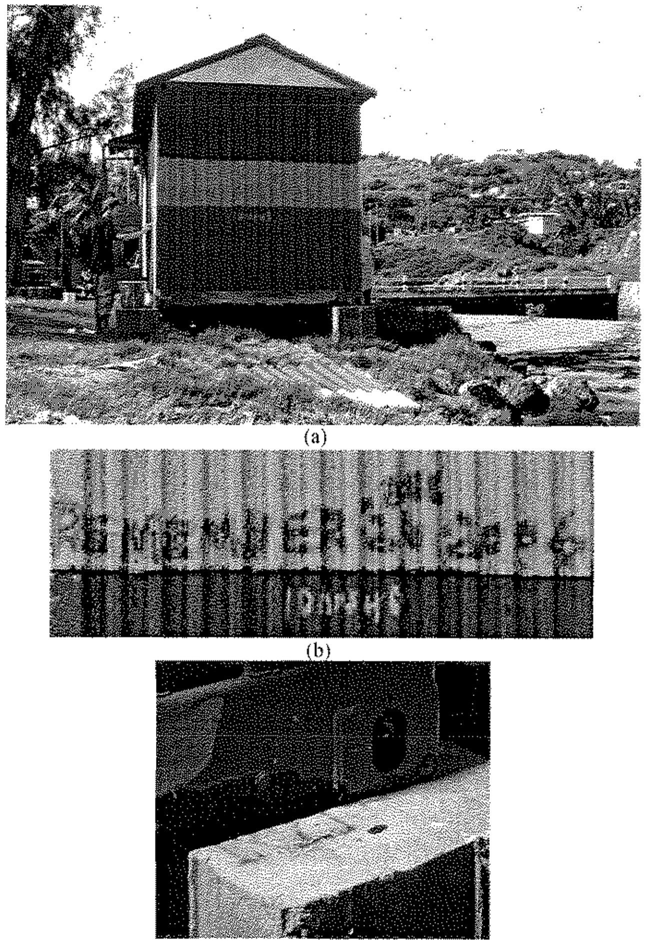



**Figure 6.** Site 4, bridges at the east end of town in Port Mathurin, Rodrigues. (a) Looking west during a period of intermediate flooding on 26 December; the pedestrian gangway is downstream, and the road bridge is about 20 m upstream. (b), (c) These two photos, taken 30 seconds apart, show flooding by the main wave (which may be the third wave) penetrating under the gangway and then reaching the road bridge, which it almost overflows (photos a, b, and c: Rodnet Cybercafé). (d) The same road bridge on 5 March 2005. (e) Flooding, described by eyewitnesses as being of maximum extent, on a section of the road curving along the left bank of the river beyond the bridges to the position where the minibus is in (d); this photo looks inland, away from the sea (photo: Rodnet Cybercafé). (f) The same location on 5 March 2005, which was used to measure runup at Site 4 (1.64 m); this photo looks inland, away from the sea.



(a)

(b)

(c)

**Figure 7.** Site 1, Anse-aux-Anglais, Rodrigues, looking inland (south) from the seashore. (a) This shipping container, which houses a convenience store on the beach berm next to the river estuary, was displaced westward by the tsunami. The road bridge behind the container was barely overflowed by the wave, corresponding to a flow depth of 1.72 m. (b) An inscription on the container (detailed and digitally sharpened) gives the date and time of the tsunami. (c) 15-cm displacement of the shipping container.

Even though we have a reasonable estimate of the absolute timing of the surge in Figure 6b, (11:39 ± a few minutes), it remains impossible to resolve beyond doubt its association with either the second or third wave. Reports at the nearby Site 7 (Grand Baie) suggest that the third wave was the highest (Table 1), and thus we tentatively associate it with Figure 6. Given the predicted arrival time of the tsunami (10:45 UTC +4) in Rodrigues, and allowing for a few extra minutes for the tsunami to cross the reef, this would suggest a period of about 24 minutes, which agrees well with many descrip-


**Figure 8.** Site 2, service station in Port Mathurin, Rodrigues. (a) Looking west during the inundation on 26 December 2004; the seashore is at right (photo: Rodnet Cybercafé). (b) watermark, shown by arrows, was identified and surveyed on 5 March 2005 on the walls of the service station office; this office appears at left behind the flagpole in (a). Note that the water level in (a) does not correspond to the maximum flow depth, suggesting that this untimed photo was taken during an ebbing cycle of the wave.

tions by eyewitnesses. Association with the second wave would require twice the period. In turn, the phenomenon in Figure 4a, 17 minutes later, could be close to the next drawdown. Note in particular the dog (Figures 4a and 4b) standing on what has to be an essentially dry beach.

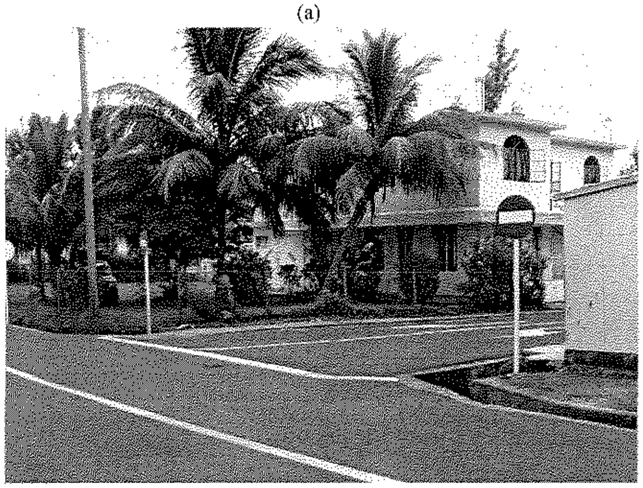
At Site 1 (Anse-aux-Anglais, 1.2 km northeast of Port Mathurin, in Figure 3), a shipping container that housed a beach convenience store was moved 15 cm by the tsunami (Figure 7). Note the inscription of the date and time "10 hrs 40" of the tsunami on its side (the inscription, incidentally, was gone by the next day, the container being repainted as the photo was taken on 5 March 2005). As confirmed by eyewitnesses, this time corresponds to the arrival of the initial wave, which agrees perfectly with the travel time simulations of Titov (2005). It is not clear, however, at which point in the sequence the container was moved.

Flow depths and runup values obtained at the various locations in Port Mathurin are remarkably consistent (1.52–1.76 m), which illustrates the flat nature of the topography of the town. Note in Figure 8 the remarkable watermarks persisting two months after the tsunami at the only service station on the island, and in Figure 9 the complex systems of currents converging on the intersection near the city mosque, illustrating tsunami "traffic" through the gridded street map of the town, at a distance of more than 300 m from the shore.

### Sites 6 and 7, Grand Baie

The northeastern end of the island features strongly eroded, deep estuarine valleys, the largest being Grand Baie, which extends 1 km inland (Figure 3). The runup at Site 6

(a)



(b)

**Figure 9.** Site 3, mosque in Port Mathurin, Rodrigues; its location appears in Figure 3. (a) During the tsunami inundation on 26 December 2004 (photo: Rodnet Cybercafé). (b) The same location on 5 March 2005. The one-way street is oriented east-northeast; the other street leads north-northwest (at left in the photo) to the shoreline. The runup at the site is 1.99 m, for a total inundation of 334 m. The culvert visible next to the "no-entry" signpost actually connects to an outflow channel running west-southwest toward the estuary at Camp du Roi, qualifying this site as a riverbed (which is marked by a superscript in Table 1).

is 2.0 m, for an inundation distance of 451 m. The eyewitness at Site 7, near the mouth of the river, precisely documented the sequence of flow depths on a cabin at the edge of a soccer field and mentioned losing several head of livestock during the inundation. He also reported that several tourists were saved from drowning by local teenagers.

### Site 16, Rivière Cocos, and Site 17, Anse Goélands

At these two sites, eyewitnesses described the tsunami activity as minor fluctuations reaching at most the maximum high tide line. We list these values as being less than 1 m in our data set (Table 1 and Figure 2c), and we interpret them as reflecting the presence of the wide coral reef extending several kilometers in front of the western shores of the island.

## MAURITIUS

Initial reports indicated only minor effects of the tsunami on Mauritius, concentrated on the northeastern shores of the island. For this reason, the team elected not to emphasize Mauritius during the limited time available for the survey. A systematic survey around Grand Baie revealed no distinctive evidence of the tsunami beyond the level of high tides, which we report as <1.0 m in Table 1 and Figure 2b. By contrast, the tsunami was recorded in Belle Mare, on the beach of the Hotel Saint Geran (Site 20) with a runup of 1.3 m, but several eyewitnesses on nearby beaches had not observed it. We wish to emphasize that we conducted no systematic survey on the southern and western shores of the island.

## RÉUNION

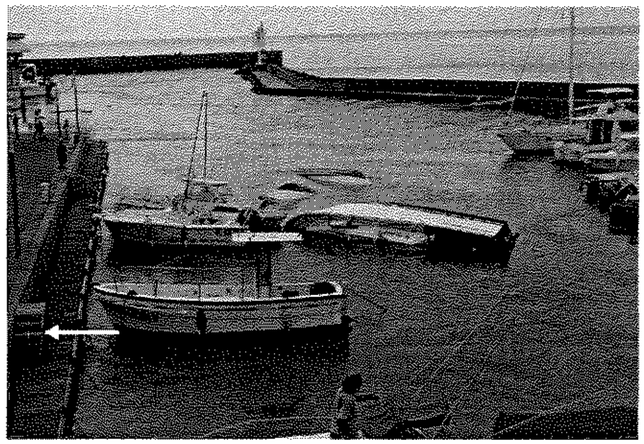
### Site 27, Saint-Gilles, Réunion

Figure 10 shows boats capsized by the tsunami, photographed in the afternoon of 26 December 2004, approximately 3.5 hours after the arrival of the first wave. This picture is representative of the action of the waves in most ports of the island. Most of the damage took place in the northern port of Sainte Marie (Site 21), where we measured runup of 2.0 m. One fishing boat and 10 leisure vessels were sunk, and an additional 44 vessels suffered some level of damage. Three mooring pontoons were damaged beyond repair, with a total loss to port infrastructure alone (not counting vessels) estimated at a preliminary figure of 400 k€ (US $500,000). Similarly, in the port of Saint Gilles, seven boats were sunk and one 10-m pontoon was destroyed, at an additional cost to infrastructures of 120 k€ (US $150,000).

### Site 29, Le Port: the Case of the MSC *Uruguay*

The city of Le Port holds the main harbor in Réunion Island, comprised of two basins, the west and east harbors. According to reports obtained from harbor master Jean-Pierre Croguennec, the 196-m container ship MSC *Uruguay*, docked at Berth 10 (Figure 11), broke all 12 of its mooring hawsers between 15:30 and 15:45 (UTC+4) and became essentially uncontrollable for several hours. Even though the ship remained in the harbor, it began drifting around its berth, striking and damaging the gantry cranes on the nearby dock (Figures 11c and 11d). At 18:20 (UTC+4), the ship once again broke the moorings that the port pilots had managed to secure.

It is noteworthy that two similar incidents took place on the same day, one incident in the port of Toamasina, Madagascar, involving a much smaller, 50-m-long freighter, and the other incident in Salalah, Oman, involving a 285-m container ship (Okal et al. 2006a,



(a)

(b)

**Figure 10.** Site 27, Port of Saint Gilles, Réunion. (a) An area of the port at 15:14 (UTC+4) on 26 December 2004, during the ebbing phase of tsunami (photo: J.-M. Lafond). Note the three capsized boats. The arrow indicates the maximum flow depth, as described by an eyewitness. (b) The team surveying the site on 9 March 2005.

this issue; Okal et al. 2006b, this issue). A most remarkable aspect of these incidents is that, in Réunion and Madagascar, the ships broke their moorings significantly later than the passage of the main tsunami waves, which in Réunion took place between 11:30 and 14:00 local time, while currents were still strong enough at 18:20 to cause a second rupture of the MSC *Uruguay's* hawsers. In Salalah, the ship drifted away soon after the initial arrival of the tsunami, but strong currents persisted in the harbor for several hours, to the extent that a second ship of similar size was prevented from entering the harbor until 11 hours after the arrival of the first tsunami waves.

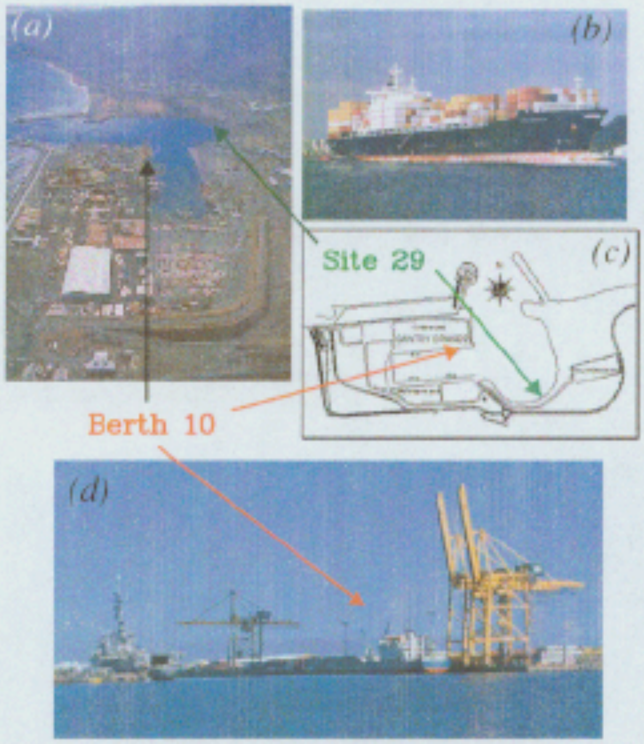



**Figure 11.** (a) Aerial view of the east harbor of Le Port, Réunion. The rectangular basin on this eastward-looking file photo (www.reunion.port.fr) is approximately 600 m long. Arrows identify Berth 10 and Site 29 nearby. (b) File photo of the 196-m-long MSC *Uruguay* (www.shipspictures.hpg.ig.com.br). (c) East harbor, identifying berths and gantry cranes. (d) Berthing location of the MSC *Uruguay* on 10 March 2005, looking northwest from Site 29.

Both the nature of this delay in the occurrence of these incidents and the variable character of the delay can probably be explained, at least qualitatively, by the triggering of oscillations of the port. Such oscillations would be at frequencies that obviously depend strongly on the size and shape of the individual harbor, but which are generally expected to be higher that those typically described as accompanying the main tsunami waves observed on standard shorelines. At sufficiently high frequencies falling outside the shallow-water approximation, dispersion over long oceanic paths could create significant group delays. At any rate, the three incidents in the western Indian Ocean harbors of Réunion, Toamasina, and Salalah underscore the need for a careful reassessment of civil defense policies in port environments.

## CONCLUSION

Through interviews of close to 100 eyewitnesses and officials in the three islands, the team has built a homogeneous data set of 35 inundation sites. Runup values remain moderate, with a maximum of 2.9 m on the southeastern coast of Rodrigues, and in particular, much lower than documented at a greater epicentral distance in Somalia. This illustrates the narrow azimuthal range of constructive interference at the source for the far-field tsunamis of earthquakes with gigantic rupture zones (Ben-Menahem and Rosenman 1972, Okal and Talandier 1991). In this respect, while the Mascarene Islands were spared the maximum onslaught of the tsunami by that favorable geometry, they could suffer greater damage during a repeat of the 1833 south Sumatra earthquake, whose recurrence could be accelerated by stress transfer from the 26 December 2004 and 28 March 2005 earthquakes to the north.

Damage in Rodrigues consisted mainly of widespread, but relatively benign, flooding in the capital city of Port Mathurin and in the bays facing the eastern shore of the island, where the coral reef is least developed; by contrast, the tsunami was barely noticeable in the western part of the island, whose shores are well protected by reef structures extending offshore for several kilometers. Similarly, the effect of the tsunami in Mauritius was minor, as the island appears to have been protected by its well-developed, essentially continuous, fringing reef. In Réunion, damage was concentrated in harbor structures developed along the coast, where runup reached 1–2 m, causing significant destruction of infrastructure in two harbors and sinking many small fishing and leisure boats.

A very significant aspect of the tsunami is the case of the MSC *Uruguay* in the east harbor at Le Port, Réunion, which broke its moorings in a way strikingly similar to incidents in Toamasina, Madagascar, and in Salalah, Oman; at Le Port, the result was moderate structural damage to harbor installations. In particular, the timing of the incident at Le Port is late by 4 hours with respect to the arrival of the initial waves, and late by at least 1.5 hours with respect to the largest ones, as documented at other locations on the island and modeled through simulations (Titov 2005). This warrants a serious review of civil defense policies and in particular of the need for orderly evacuation, over longer time windows than might seem appropriate, of major harbors by large vessels, in the context of future tsunami warnings. Incidentally, the harbor master at Le Port was, to our knowledge, the only one of the three port authorities involved who had the professional vision to order, a mere 45 minutes after the MSC *Uruguay* incident, the orderly evacuation of the harbor by all commercial vessels.

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