179.

Madagascar Field Survey after the December 2004 Indian Ocean Tsunami

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The effects of the 26 December 2004 Indian Ocean tsunami on the island of Madagascar were surveyed in July and August of 2005. Runup and inundation were obtained at 52 sites, covering most of the eastern coast of the country, ranging from a maximum runup of 5.4 m in the south to locations where the tsunami was not observed by eyewitnesses present on the day of the event. The data set is characterized by significant heterogeneity, suggesting the importance of local factors in controlling runup. The report of a 50-m vessel breaking its moorings in the port of Toamasina several hours after the maximum visible activity of the wave underscores the complexity of harbor responses and the need to re-evaluate civil defense policies in port environments. Important factors are how the Malagasy population responded to the warning issued during the Nias earthquake, on 28 March 2005, and the hazard posed to Madagascar by possible future mega-earthquakes in south Sumatra. [DOI: 10.1193/1.2202646]

INTRODUCTION AND BACKGROUND

This paper reports the findings of an International Tsunami Survey Team (ITST) that visited Madagascar in July and August of 2005, in order to map the effect of the 26 December 2004 Indian Ocean tsunami on the island. This disastrous event resulted in approximately 250,000 deaths and was the first tsunami involving casualties and catastrophic destruction in the far field since the 1964 Alaska earthquake (Synolakis et al. 2005). Its source, the Great Sumatra earthquake, featured 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 perhaps by the 1964 Alaska earthquake (Stein and Okal 2005, Nettles et al. 2005).

Although most of the devastation from the tsunami took place in the eastern part of the Indian Ocean (Indonesia, Thailand, Sri Lanka, and India), its western shore was not spared, and substantial damage was wrought in Somalia, where about 300 deaths were reported (Fritz and Borrero 2006, this issue). Even though the island country of Madagascar (Figure 1) was little affected by the tsunami (only one casualty was reported, and damage amounted to marginally flooded houses and an unspecified but low number of

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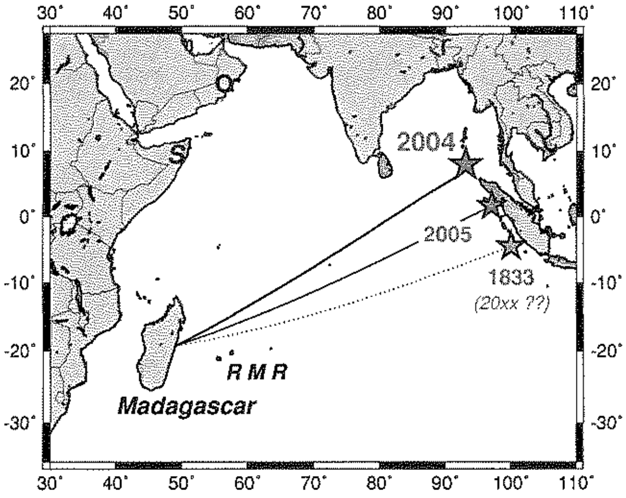

Figure 1. Madagascar and the surrounding region. The stars show, from north to south, the centroid of the 26 December 2004 earthquake, the centroid of the 28 March 2005 earthquake, and the epicenter of the 1833 mega-earthquake along the southern coast of Sumatra (Zachariasen et al. 1999), which could be a model for a future tsunamigenic earthquake threatening Madagascar. The letters S, O, and RMR identify the areas of companion field surveys in Somalia (Fritz and Borrero 2006, this issue), Oman (Okal et al. 2006b, this issue), and the Mascarene Islands of Réunion, Mauritius, and Rodrigues (Okal et al. 2006a, this issue).

damaged or lost fishing boats), it was deemed important to fully document and quantify its effects in order to provide a full coverage by surveys around the entire Indian Ocean Basin.

In particular, and because of the prima facie evidence of a strong variability between the effects of the tsunami on such relatively close shores as Somalia and Madagascar, it is important to build a complete, homogeneous database of runup and inundation parameters, which can serve as a benchmark for simulation models aimed at understanding the distal or local parameters controlling the development and amplification of waves at the beach.

In addition, we regard as particularly important the examination of the response of the Madagascar shoreline to an incident tsunami, and the assessment of the population's awareness of tsunami risk, in view of the possibility of future mega-earthquakes in the Indian Ocean Basin. Specifically, it has been shown that stress release during large earthquakes can modify the Coulomb stresses in neighboring regions, to the extent that it can bring adjoining fault segments to rupture. This concept, known as "stress transfer" (e.g., Harris 1998), has been most spectacularly illustrated along the North Anatolian fault in Turkey, where a group of damaging earthquakes has followed a stepwise westward progression from Erzincan in 1939 to Izmit in 1999 (Stein et al. 1997, Harris et al. 2002), with a devastating event widely expected under the Sea of Marmara in the next years or decades (Yalçıner et al. 2002). Within weeks of the 26 December earthquake, McCloskey et al. (2005) argued that stress transfer could trigger a large earthquake immediately to the southeast of the 26 December rupture zone. Indeed, such an event occurred on 28 March 2005 (Figure 1), and its size ($M_0 = 1.15 \times 10^{29}$ dyne-cm) would have made it the largest earthquake since 1965, if not for the 26 December shock. Its rupture area has generally been described as equivalent to that of the large 1861 event in the same area. Although the 28 March earthquake did not generate an observable tsunami in the far field, its rupture has presumably modified the regional Coulomb stresses, to the extent that a large earthquake could now be expected along the next segment of the subduction zone further to the southeast (Nalbant et al. 2005). This was the site of a mega-event in 1833 (Figure 1), recently quantified by Zachariasen et al. (1999) through the study of uplifted coral reefs on the islands fringing the central Sumatran coast. They estimated its moment at $M_0 \approx 8 \times 10^{29}$ dyne-cm or $M_w = 9.2$, i.e., essentially in the same league as the 26 December event. If we assume that the future earthquake in southern Sumatra would reach a comparable size, then it would have the potential to create a lethal transoceanic tsunami. In their classic study of the interference patterns of far-field tsunamis due to the finiteness of earthquake sources, Ben-Menahem and Rosenman (1972) justified a maximum lobe of directivity in the direction perpendicular to fault rupture, which in this particular case would put the southwestern Indian Ocean Basin—including Madagascar (lying only 14° from that direction), Rodrigues, and Réunion—in a zone of increased risk. This further warrants a close examination of the effect of the 26 December event on the relevant coasts.

In this context, surveys were carried out in March 2005 on the Mascarene Islands of Rodrigues, Mauritius, and Réunion and in July and August 2005 on Madagascar and in Oman. The present paper reports on the Madagascar survey, and companion papers cover the Mascarenes and Oman (Okal et al. 2006a, this issue; Okal et al. 2006b, this issue).

LOGISTICS AND METHODOLOGY

After the team assembled on 25 July 2005 at the University Observatory in Antananarivo, it was decided to split the team into two groups working independently, in order to cover the maximum distance along the shoreline. The northern group, consisting of Okal, Raveloson, and Pančošková, worked between Vohemar and Manahoro, while the southern group, consisting of Fritz and Joelson, worked between Mananjary and Betanty (Figure 2). The team traveled along the shoreline by 4WD vehicles and thus was limited to coastal sections that were readily accessible by road. This limitation explains the gaps in coverage evident in Figure 2, reflecting either the absence of roads (around Masoala Peninsula [M] in the north), or their unimproved character, which prevented travel within the time constraints of the survey (e.g., along the Manahoro-Mananjary gap, between the northern and southern segments).

The team used the traditional ITST procedures to map the penetration of tsunamis in the far field, as described by Synolakis and Okal (2005). In the present situation, we relied primarily on the identification and interviewing of eyewitnesses, and on the recording of their testimony, followed by topographic measurements based on their de-

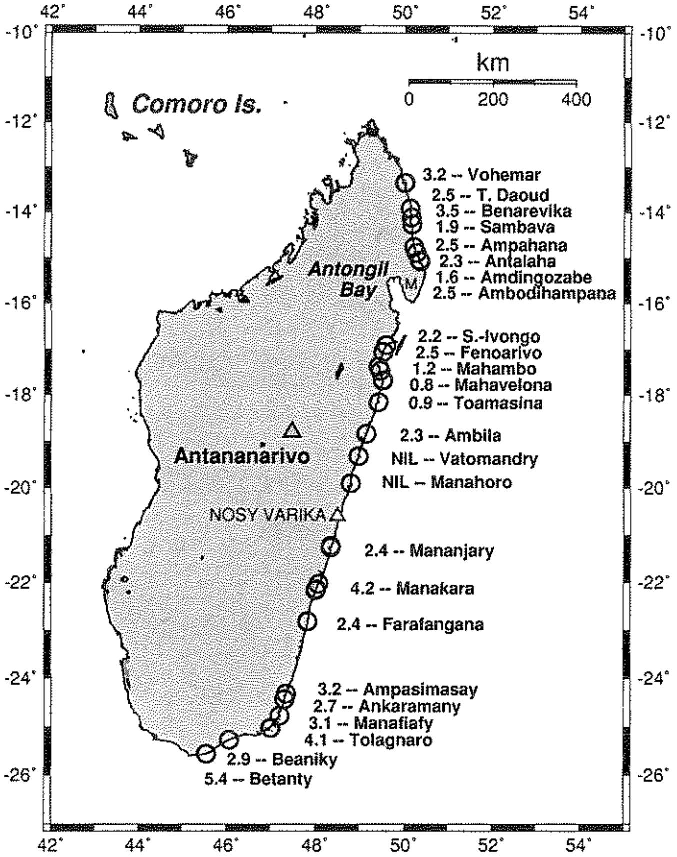

Figure 2. Maximum runup or flow depth values (in meters) surveyed at various localities in Madagascar. The light-colored triangle denotes the city of Nosy Varika, which we recommend for a complementary survey to close the gap between the two groups of data; it also separates the regions covered by the northern and southern ITST groups. The letter M identifies the Masoala Peninsula, bounded by the Bay of Antongil.

scriptions. On a few occasions, we also identified permanent marks of the tsunami action, such as watermarks on buildings (Site 46), scouring and erosion of a road (Site 6), or algae deposits (Sites 32 and 33). 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.

Flow depth and runup were measured by using surveying rods and a combination of laser and eye levels; inundation was measured by differential GPS. The exact dates and times of individual surveys were recorded for subsequent tidal corrections, to allow flow depth and runup measurements to be related to sea level at the time of the tsunami arrival. Preliminary computations using the web site of the French Service Hydrographique et Océanographique de la Marine (www.shom.fr) indicate a tidal range of only 10 cm in the south (Tolagnaro), 50 cm in Toamasina, and 1.1 m in the north (Vohemar). Thus tidal corrections would be expected to be minimal. To our knowledge, there exists no maregraph record of the Indian Ocean tsunami in Madagascar.

RESULTS

Table 1 gives the full data set gathered during the survey. Fifty-two measurements were retained, principally runup values obtained from eyewitness reports. The map in Figure 2 summarizes the data set. In order to streamline the presentation, it features for each locality 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 on the order of 2–4 m, reaching a maximum of 5.4 m at Betanty. Thus they are comparable to those reported further east on Réunion and Rodrigues islands (Okal et al. 2006a, this issue) but remain significantly smaller than the 5–9 m surveyed along the coast of Somalia (Fritz and Borrero 2006, this issue), where systematic structural damage was inflicted on ports and buildings, a level of destruction that was not reported in Madagascar. Similarly, only one drowning was reported in Madagascar, as opposed to about 300 tsunami casualties in Somalia.

Surveyed values feature a large lateral variability along the coast. In practice, one can outline a general trend, with large runup values regrouped at the extremities of the surveyed area, i.e., in the vicinity of Tolagnaro (about 4 m) and north of Sambava (about 3.5 m), with significantly lower values in the central region. Because the nature of the beaches in the various regions varies widely and cannot be directly correlated with the above trends, it is probable that this variability expresses a combination of generation and propagation effects, as suggested by an early simulation of the tsunami (Titov 2005), which does show enhanced amplitudes at the northern and southern extremities of Madagascar.

The physical properties of the waves described to the ITST by eyewitnesses, and the arrival times of the waves, feature fluctuations that are typical of ITST campaigns. A consensus among eyewitnesses indicates that they were alerted to the tsunami by an initial recess of the sea, over distances difficult to quantify, but generally interpreted as reaching or exceeding 100 m. It is suggested that this depression may have been preceded by a small positive wave, too weak to have been universally observed, which

Table 1. Data set gathered by the ITST in Madagascar, July–August 2005

Number	Site	Latitude (°N)	Longitude (°E)	Vertical survey		Inundation	Date and time surveyed		Notes
				(m)	Nature[a]	(m)	Date	GMT	
Northern Team									
1a	Amdingozabe	−15.06193	50.35913	1.65	F	102	28 Jul 2005	07:11	Crate inside shop
1b	Amdingozabe	−15.06193	50.35913	1.14	R	136	28 Jul 2005	07:11	Runup to front of church
2	Ambodihampana	−15.08158	50.37212	2.52	R	80	28 Jul 2005	07:50	Top of stilt at house
3	Antalaha	−14.90050	50.28227	2.10	F		28 Jul 2005	10:55	Flow depth at pier on port
4	Antalaha	−14.90037	50.28148	2.30	R	28	28 Jul 2005	11:09	Palm tree on beach opposite hotel
5	Ampahana	−14.76483	50.22443	2.53	R	50	28 Jul 2005	12:25	Runup on beach next to infirmary
6	Sambava	−14.26990	50.18163	1.77	R	71	29 Jul 2005	08:50	Eroded road, Ampandrozonana Beach
7	Sambava	−14.27062	50.18073	1.91	R	30	29 Jul 2005	09:00	Sunk car location, Ampandrozonana Beach
8	Vohemar	−13.35335	50.00787	1.60	R	10	29 Jul 2005	13:07	Beach at port captain's office
9	Vohemar	−13.35765	50.00357	1.48	R	9	29 Jul 2005	13:32	West end of beach—fisherman
10	Vohemar	−13.35360	50.01563	3.19	R	24	29 Jul 2005	14:10	Local resident at Hiaramabazana Beach
11*	Tanambao-Daoud	−13.92	50.135	2.50	R		30 Jul 2005		*Extrapolated estimate at Monorokely Beach
12	Benarevika	−14.11560	50.15953	3.51	R	29	30 Jul 2005	13:56	Betavda Plantation Beach
13	Manahoro	−19.90248	48.81275		Nil		1 Aug 2005		Four witnesses
14	Vatomandry	−19.319	48.986		Nil		1 Aug 2005		Several witnesses on beach
15	Ambila	−18.84417	49.15388	2.35	R	30	2 Aug 2005	09:18	Beach in front of hotel
16	Toamasina	−18.15672	49.42477	0.90	F		3 Aug 2005	06:30	Mark on tire along wharf in port
17	Toamasina	−18.15768	49.42277	0.78	R	55	3 Aug 2005	07:40	Runup on beach across from port
18	Mahavelona (Foul Pointe)	−17.69017	49.51995	0.77	R	13	3 Aug 2005	10:15	South beach, across from reef
19	Mahavelona (Foul Pointe)	−17.68528	49.51823	0.72	R	13	3 Aug 2005	10:35	Central beach, across from reef

Table 1. (cont.)

Number	Site	Latitude (°N)	Longitude (°E)	Vertical survey		Inundation	Date and time surveyed		Notes
				(m)	Nature[a]	(m)	Date	GMT	
20	Mahavelona (Foul Pointe)	−17.67457	49.51608	0.79	R	4	3 Aug 2005	11:01	North beach, beyond reef end
21	Mahambo	−17.47523	49.46362	1.17	R	7	3 Aug 2005	12:02	Bungalow at Hotel Le Réif
22a	Soanierana-Ivongo	−16.91903	49.58707	2.23	F	20	4 Aug 2005	05:47	Flow depth at house on beach
22b	Soanierana-Ivongo	−16.91903	49.58707	2.00	R	46	4 Aug 2005	05:47	Runup behind house
23	Soanierana-Ivongo	−16.92005	49.58700	1.30	R	12	4 Aug 2005	06:00	Runup at stump on beach
24	Manakatafana	−17.06165	49.52432	1.92	R	22	4 Aug 2005	06:40	Runup at beach near roadside shop
25	Fenoarivo (Fénérive)	−17.38093	49.41523	2.50	R	6	4 Aug 2005	07:44	Beach across from town square
Southern Team									
26	Tolagnaro	−25.02695	46.99611	2.90	R	75	26 Jul 2005	13:17	Trimline on cliff inside port—eyewitness confirmed
27	Tolagnaro	−25.03627	46.99260	2.00	R	7	26 Jul 2005	13:55	Trimline in grass—eyewitness confirmed
28	Manafiafy (Sainte Luce)	−24.77650	47.19987	3.10	R	34	27 Jul 2005	05:09	Eyewitness—site of 12-year-old fatality
29	Ankaramany	−24.43317	47.30677	2.70	R	35	27 Jul 2005	09:06	Eyewitness
30	Ampasimasay	−24.32108	47.34549	3.20	R	29	27 Jul 2005	11:04	Eyewitness
31	Betanty	−25.56941	45.53209	4.40	R	34	28 Jul 2005	13:38	Eyewitness
32	Betanty	−25.56817	45.53433	2.30	R	30	28 Jul 2005	14:15	Algae—eyewitness confirmed
33	Betanty	−25.56508	45.53881	4.80	R	37	28 Jul 2005	14:27	Algae—eyewitness confirmed
34	Betanty	−25.56952	45.53097	5.40	R	28	29 Jul 2005	04:30	Eyewitness
35	Beaniky	−25.27869	46.06108	2.90	R	19	29 Jul 2005	08:48	Eyewitness
36	Tolagnaro	−25.03878	46.99558	4.10	R	26	30 Jul 2005	05:40	Eyewitness
37	Tolagnaro	−25.03487	46.98299	2.20	R	44	30 Jul 2005	06:08	Eyewitness

Table 1. (cont.)

Number	Site	Latitude (°N)	Longitude (°E)	Vertical survey		Inundation	Date and time surveyed		Notes
				(m)	Nature[a]	(m)	Date	GMT	
38a	Mananjary	−21.24501	48.34824	2.20	F	28	1 Aug 2005	05:22	Dune overtopped
38b	Mananjary	−21.24501	48.34824	1.00	R	68	1 Aug 2005	05:22	Runup at inundation limit
39a	Mananjary	−21.26137	48.34547	2.20	R	43	1 Aug 2005	06:14	Eyewitness—1st wave
39b	Mananjary	−21.26137	48.34547	2.40	R	43	1 Aug 2005	06:14	Eyewitness—2nd wave
40	Mananjary	−21.22907	48.35131	2.40	R	21	1 Aug 2005	07:17	Eyewitness
41	Manakara North	−22.13989	48.02431	2.30	R	43	1 Aug 2005	13:21	North of river; eyewitness
42	Manakara Be	−22.14942	48.02202	4.20	R	61	1 Aug 2005	14:16	Eyewitness
43	Manakara Be	−22.16200	48.01556	3.50	R	59	1 Aug 2005	14:44	Eyewitness
44	Farafangana	−22.81895	47.83588	1.60	R	32	2 Aug 2005	08:52	In lagoon—eyewitness
45	Farafangana	−22.80939	47.83716	2.40	F	25	2 Aug 2005	09:36	Dune overtopped
46	Manakara Be	−22.14362	48.02430	1.50	F	38	2 Aug 2005	14:25	Wall of bungalow—eyewitness and video confirmed
47	Manakara Be	−22.14515	48.02395	4.00	R	30	3 Aug 2005	06:03	Pool wall—eyewitness and video confirmed
48	Manakara Be	−22.14718	48.02309	3.50	R	34	3 Aug 2005	06:12	Palm tree—video confirmed
49a	Manakara Be	−22.14344	48.02286	2.00	F	10	3 Aug 2005	06:51	Waterline on house—video confirmed
49b	Manakara Be	−22.14344	48.02286	1.50	F	21	3 Aug 2005	06:51	Runup at extent of inundation
50	Manakara Port	−22.14126	48.02057	1.60	F		3 Aug 2005	07:16	Quay wall—boat cut loose
51	Manakara Be	−22.14631	48.02324	3.80	R	58	3 Aug 2005	11:05	Road hole due to erosion
52	Manakara North	−22.03352	48.07116	2.10	R	25	3 Aug 2005	12:07	12 km north of Manakara—eyewitness

[a] F=flow depth, R=runup

would be in agreement with results obtained from global simulations (e.g., Titov 2005). This was followed by a series of positive waves (typically three or more), of which the second was generally described as the largest.

Temporal estimates (the time of arrival and the period of the waves) are traditionally among the least precise kinds of information obtained from eyewitnesses; however, most descriptions indicate a phenomenon starting around noon, local time (09:00 UTC), and lasting the whole day (with dusk falling at about 19:30 at that time of the year). Given epicentral distances varying from 5,300 km in Vohemar to 6,200 km in Betanty, and taking into account the variable depth of the Indian Ocean Basin, travel times are expected to be 8–8.5 hours (Titov 2005). With a seismic origin time of 00:58:50 UTC, this predicts first arrivals around 12:00 noon in the north of the island and 12:30 P.M. in the south, in good agreement with the eyewitness reports.

The periods of the waves were generally estimated to be in the range of 15–20 minutes.

SPECIFIC SITES

In the following sections, we highlight the sites where the most significant observations were made, arranged geographically from north to south.

Site 6, Sambava

The tsunami was well observed along the Ampandrozonana beach, located on the southeastern side of this city of 28,000 and particularly well patronized on the Sunday after Christmas. The most remarkable effect of the tsunami was the permanent destruction, by scouring, of a section of unimproved road along the beach, over a length of about 40 m. As documented by the individuals providing a scale in Figure 3, the depth of scouring is approximately 30 cm at a distance of 71 m from the unperturbed seashore. This amounts to a runup of 1.8 m. Eyewitnesses estimated an arrival time of 12:30 P.M. local time (09:30 UTC) and described two large waves, the second one being larger, with a period of 15–20 minutes. At the nearby Site 7, which is 125 m away along the beach, eyewitnesses described how a Nissan Patrol 4WD vehicle, which was being used to tow a jet boat out of the ocean and onto a trailer, was caught by the tsunami wave and buried axle-deep in the sand by the retreating flow.

Site 1, Amdingozabe, and Site 2, Ambodihampana

These two villages are about 35 km South of Antalaha; Site 2 represents the southernmost extension of the survey north of the Masoala Peninsula. Both locations were the site of the destruction of unimproved bridges, even though runup was moderate at Site 1 (1.1 m). At Site 2, shown in Figure 4, it reached 2.5 m in the nearby village, suggesting that the bridge may have been overflowed by more than 1 m.

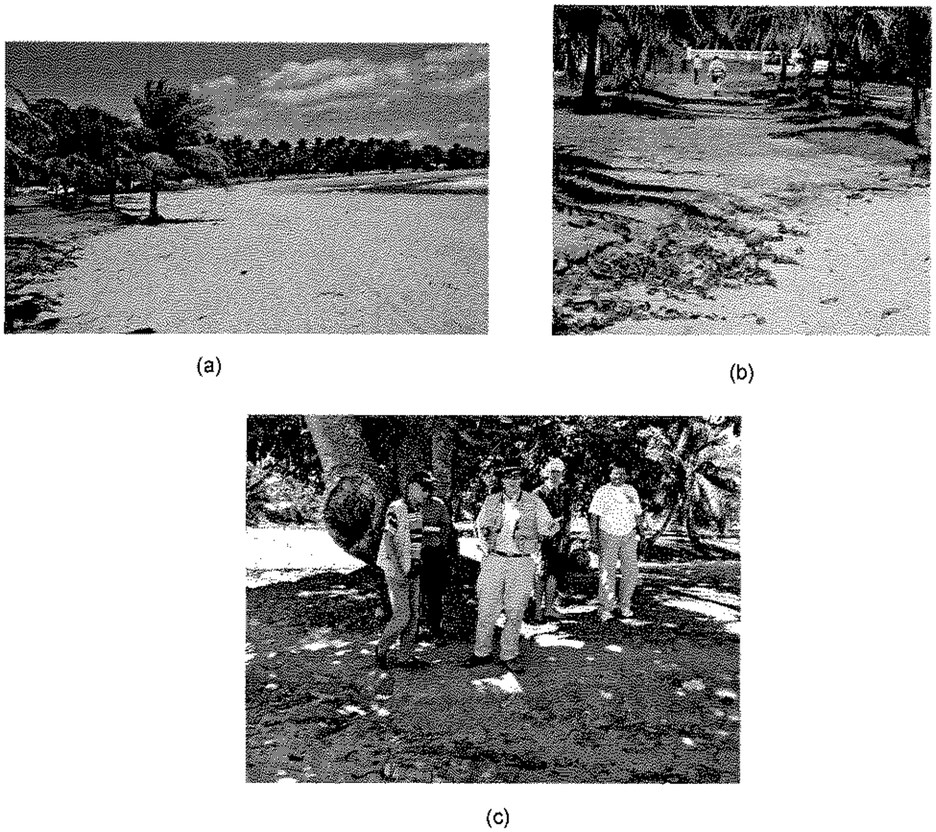

Figure 3. Scouring of a road along Ampandrozonana Beach in Sambava (Site 6). (a) General view of the beach, with the eroded road segment to the left, 71 *m* from the water line. (b) and (c) Close-up of the scouring. Note the advance of the beach, identified by sand deposits, over the previous location of the road.

Site 16, Eddies in the Port of Toamasina

With a population of 180,000, Toamasina (formerly Tamatave) is the largest port in the country. Its harbor was the site of an intriguing phenomenon, related to us by Captain Jami Injona, a port pilot, and (in part) by Captain Talainy, the skipper of the freighter *Ludovic*. The latter explained to us that, as early as 12:30 P.M. local time (09:30 UTC), his ship had been subject to wave activity in the harbor as it lay moored to the wharf. On the basis of Captain Injona's testimony, we measured a flow depth of 0.90 m at Site 16 inside the harbor, which, after tidal correction, would suggest an amplitude of oscillation of 0.6 m. However, by 17:00 (14:00 UTC), this activity had ceased, as well as any visible fluctuations of sea surface elevation in the harbor, to the extent that Captain Talainy left the ship in the command of his second officer and intended to spend the evening in town. Captain Injona then reported a considerable amplification in the

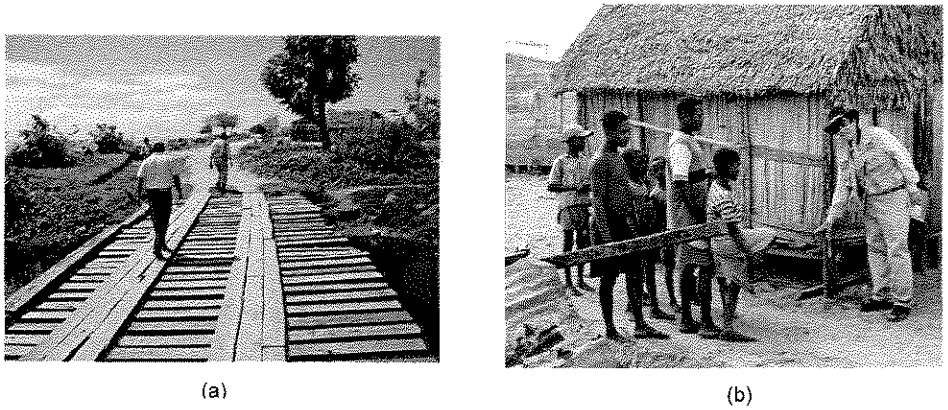
(a) (b)

Figure 4. (a) The road bridge at Ambodihampana (Site 2), looking south toward a village. The former bridge at this location (described by witnesses as "equivalent" to this new one, rebuilt since the tsunami) was carried away by the waves during the tsunami. (b) The water reached a height of 50 cm inside the houses of the village, corresponding to a total runup of 2.5 m, for an inundation of 80 m.

strength of the currents in the harbor (but not in the height of the waves), starting at 19:00 (16:00 UTC) and culminating in the 50-m freighter *Soavina III* breaking its moorings at a nearby wharf and wandering through the harbor for the next 3 hours, with the harbor pilots unable to control the freighter from their tugboats. *Soavina III* eventually grounded on a sand bar, adjacent to a nearby water sports center (Site 17, Figure 5). Miraculously this "ghost" ship did not collide with other ships or with harbor structures.

We note that similar instances of vessels breaking their moorings took place in the wake of the Indian Ocean tsunami in the harbors of Le Port, Réunion (Okal et al. 2006a) and Salalah, Oman (Okal et al. 2006b, this issue), in both cases involving much larger container ships—192 m long and 285 m long, respectively. One of the most fascinating aspects of the *Soavina III* incident remains its timing, because it occurred at least 4 hours after the arrival of the waves that were described as having maximum amplitude. No such discrepancy was observed in Salalah; in Réunion, the ship broke its moorings 1.5 hours after the period of major vertical fluctuations of the water, and a second time about 2.5 hours later, after it had been controlled by tugboats and moored again to its berth.

This episode clearly indicates that significant currents may, in certain harbors, persist for several hours after the most perceptible effect of the tsunami, i.e., the vertical fluctuation of the sea level, has ceased or quieted down. It is probable that such activity is generated from the response of the harbor to high-frequency components of the tsunami wave, as indicated by the period of the phenomenon, described as "a few minutes" by Captain Injona; this response is expected to involve resonance and be highly nonlinear. High-frequency wave trains may not satisfy the shallow-water approximation over vast sections of their transoceanic path and thus be significantly dispersed, arriving much

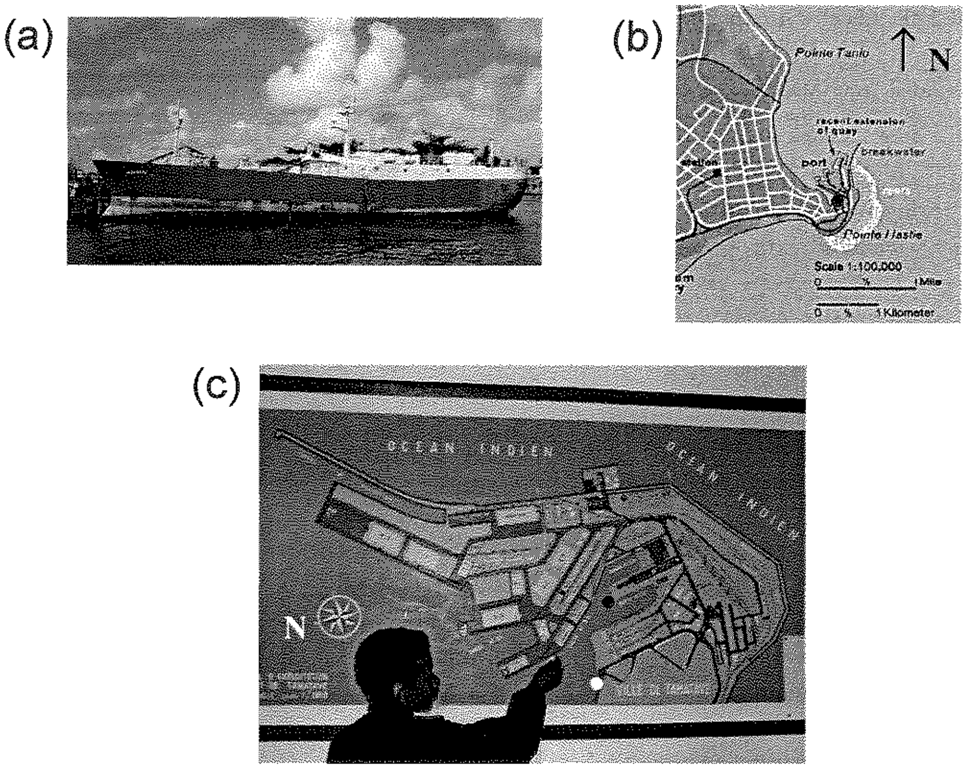

Figure 5. (a) The 50-m freighter *Soavina III*, on 2 August 2005 in the port of Toamasina. (b) The port of Toamasina, showing its complex geometry; the dark circle shows where the freighter *Soavina III* became grounded. (c) Captain Injona points to Channel 3B, where the *Soavina III* broke its moorings at about 7:00 P.M., wandering in the channels up to the location of the darker circle before eventually grounding in front of the Water-Sports Club Beach (the white circle, Site 17).

later than the main tsunami waves. While this remark remains qualitative, it could explain differences in timing relative to the main tsunami waves between the incidents, as the shapes of the harbors in Réunion, Madagascar, and Oman vary widely. Note in particular (Figure 5) the complex geometry of the inner harbor in Toamasina, which should increase its eigenfrequencies and hence delay its response. At any rate, the incidents in the three west Indian Ocean harbors, and especially in Toamasina, indicate that the hazard posed by the arrival of a distal tsunami may last much longer than suggested by the visual observation of anomalous vertical oscillations of the sea surface. This warrants a reassessment of civil defense policies in this respect.

Site 13, Manahoro, and Site 14, Vatomandry

An intriguing result is that the tsunami was not observed in the two towns of Manahoro and Vatomandry, where we failed to obtain a single eyewitness report of an anomalous wave, despite interviewing over a dozen residents who had been present at the beaches on 26 December 2004. This was confirmed by the local gendarmerie unit in Manahoro (population 33,000). The flow depth and runup in these two localities are labeled "Nil" in Table 1 and Figure 2. Our experience in the Toamasina area indicates that runup as small as 0.70 m was recognized, and thus we propose that the amplitude of the tsunami in the two localities must not have exceeded 0.50 m. Unfortunately, there exists a 150-km gap in our data set between the northernmost datum of the southern group (with runup reaching 2.4 m at Mananjary) and Manahoro, which is the southernmost datum of the northern group, where the tsunami was not observed; this gap could not be closed in the framework of the present survey, because of logistical constraints. We recommend complementing the survey in the future at the town of Nosy Varika, which may be reachable from Mananjary along a difficult 100-km track, which is reported to be marginally passable by a 4WD vehicle.

Sites 46–48, Manakara Be

The city of Manakara (population 31,500) lies at the mouth of the Manakara River, whose winding estuary creates a lagoon separated from the sea by a narrow, 9-km-long sand spit at the end of which is the seaside district of Manakara Be (Figure 6). The team was fortunate to recover videotapes and photos documenting the penetration of the tsunami. At the Hotel Parthenay, located at the northern extremity of the sand spit separating the ocean and the lagoon, the owner described the crashing of the first wave against the 1.5-m swimming pool wall and the subsequent flooding of the pool, 4 m above sea level (Site 47, Figure 6c). Seven hotel bungalows were then flooded from the back through a slit vertical breakwater at the river mouth, which extends the sand spit into the estuary by over 300 m (Site 46, Figure 7). Figure 8 shows palm trees felled at the nearby beach during the main wave activity and the resulting permanent beach erosion (Site 48).

Sites 26 and 36, Tolagnaro (Formerly Fort-Dauphin)

The city of Tolagnaro (population 39,000) is the capital of the southernmost province of the country. It is built on a headland surrounded on three sides by the ocean, so most of the city is naturally protected from inundation by its elevation (Figure 9); the port was flooded up to the 2-m-high quay, and it drained completely between the first and second wave. Beach erosion and damaged vegetation were used to document tsunami penetration at Site 36, 1.3 km away. One casualty was reported at Manafiafy (Site 28, 35 km to the northeast), where a 12-year-old boy was pulled offshore while swimming and drowned.

Site 34, Betanty

Betanty, which is the southernmost site visited, approaches the southern tip of the island (which it was long thought to be by early explorers, hence its former name "Faux

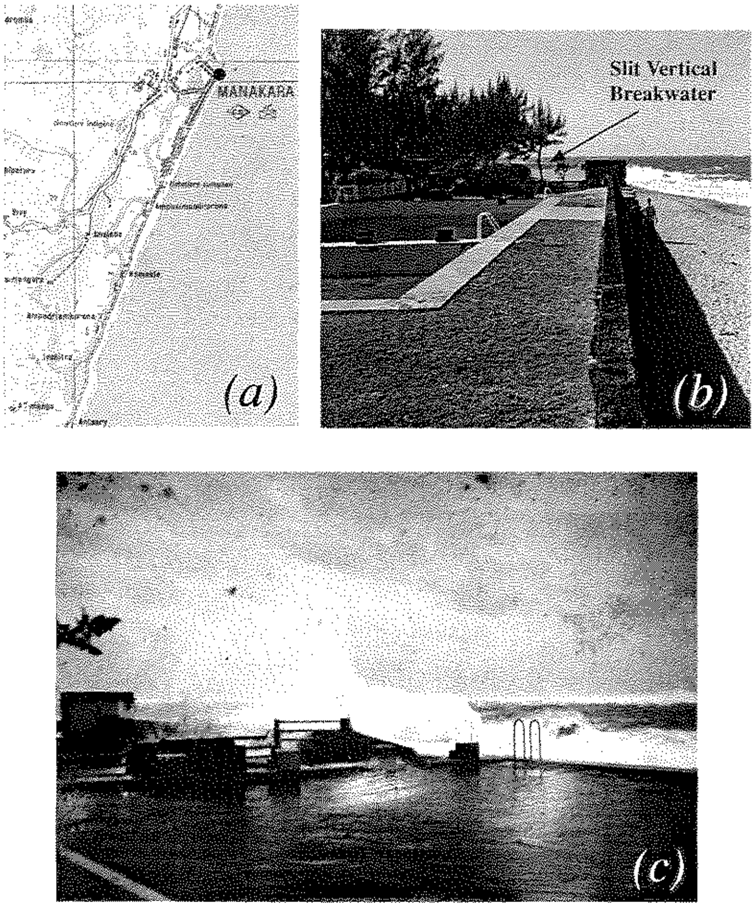

Figure 6. (a) Topography of Manakara, showing the winding estuary of the river and the resulting sand spit that extends for 9 km between the river and the ocean; the solid circle is the location of the Hotel Parthenay. (b) Swimming pool of the Hotel Parthenay (Site 47), photographed by the team in July 2005; and (c) the same swimming pool during the onslaught of the tsunami (eyewitness photo, courtesy of the hotel manager).

Cap" or "False Cap"). Its shoreline is only sparsely populated and features large sand dunes offering natural protection. Algae deposits were used as watermarks to document a runup of 5.4 m (Figure 10), which is the largest value measured in the whole survey. It would be important to determine the origin of this high amplitude—namely, whether it involves a refraction of the tsunami wave field around the corner of the island—by complementing the survey farther to the west; because of logistical constraints, this was not possible within the framework of the present survey.

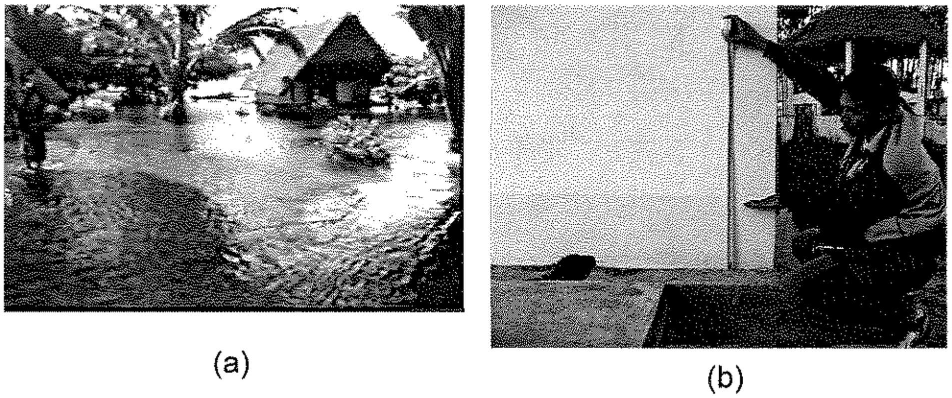

Figure 7. (a) Bungalows at the Hotel Parthenay flooded by a tsunami wave coming from the estuary of the Manakara River, after breaking through a perforated seawall (photo: M. Jolce). (b) Watermark preserved on the wall of a bungalow at Site 46. The runup is 1.50 m, for an inundation of 38 m.

SOCIAL ASPECTS: TSUNAMI ALERT AND EVACUATION ON 28 MARCH 2005

As mentioned in the introduction to this paper, we recall that the Great Sumatra earthquake of 26 December 2004 was followed on 28 March 2005 by a very strong earthquake, occurring to the southeast of the 26 December faulting area and most probably triggered by stress transfer. This second event resulted in a tsunami alert in some far-field locations, and in particular along the coast of Madagascar, even though in the

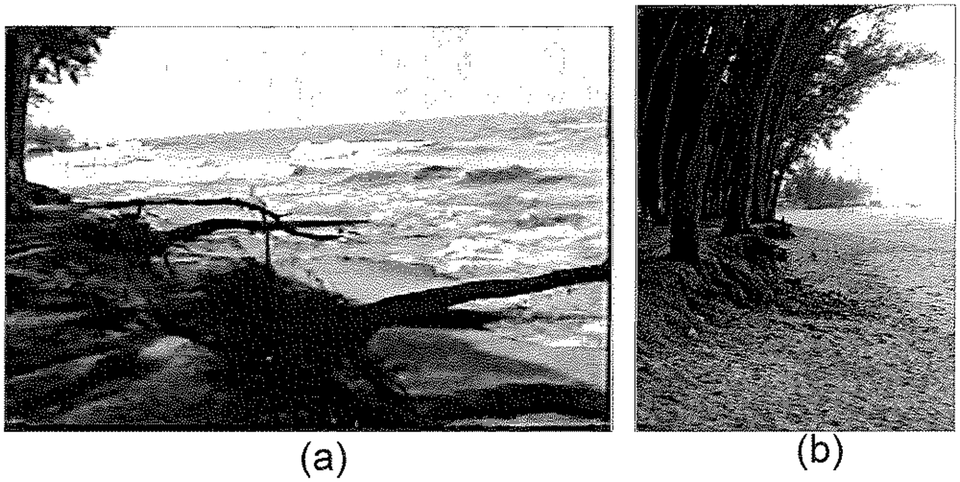

Figure 8. (a) Palm trees felled by tsunami activity at Manakara Beach (Site 48) (photo: M. Jolce). (b) The same location on 2 August 2005, showing permanent beach erosion.

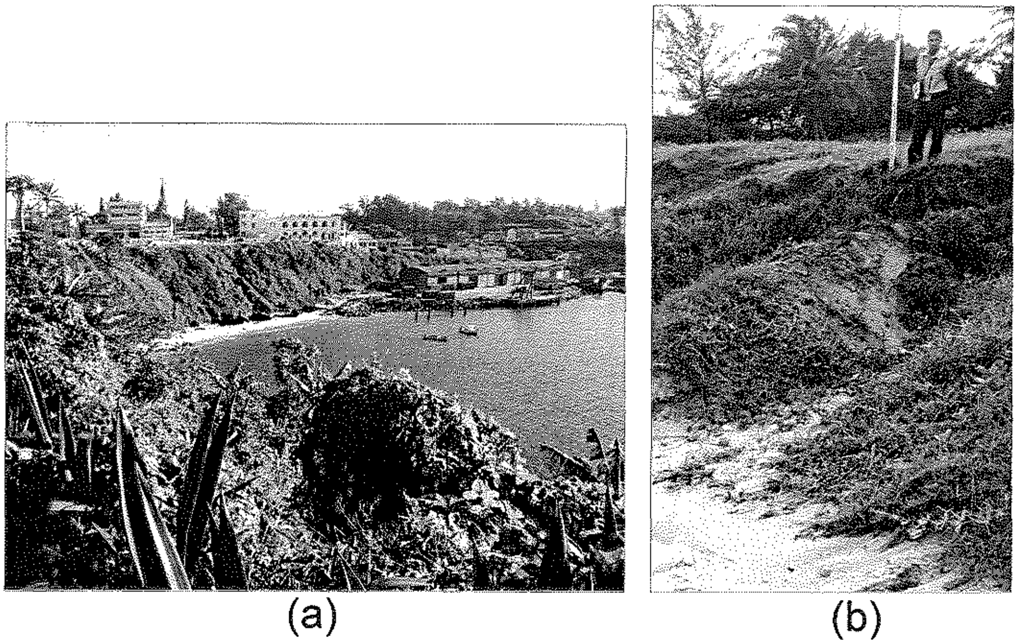

Figure 9. (a) The port and city of Tolagnaro: note the natural protection of the main settlement on an elevated headland. (b) Beach erosion and damaged vegetation at the local maximum runup of 4.1 m (Site 36).

end it did not generate a noticeable far-field tsunami. This most probably resulted from its occurrence in much shallower seas than the 26 December shock, with the rupture area even involving a number of large islands (Kerr 2005).

The Malagasy population was therefore exposed to an unannounced event on 26 December, resulting in an observable, if weak, tsunami, and to an alert on 28 March (Easter Monday), which eventually did not materialize into a detectable wave. As a result, there was a certain level of confusion between the two events in the minds of numerous eyewitnesses. Fortunately, we were able to resolve this confusion, given the very different time of day for the two events: the tsunami of 26 December reached Madagascar in broad daylight, at about 12:30 P.M. local time, whereas the alert for the second event (origin time 16:09 UTC) was issued at about 21:00 local time, i.e., at night, for an expected arrival of the waves in the middle of the night, at about 03:00 the next day. This allowed us to clarify and validate the reports from many eyewitnesses.

Several important lessons can be learned from the 28 March earthquake and the resulting warning in Madagascar, even though the warning ended up being a false alarm. First, we want to stress the exceptional size of the 28 March event, whose moment was larger than those of many earthquakes that generated damaging tsunamis in the far field, such as the 1946 Aleutian event (López and Okal 2006). In this context, we do not re-

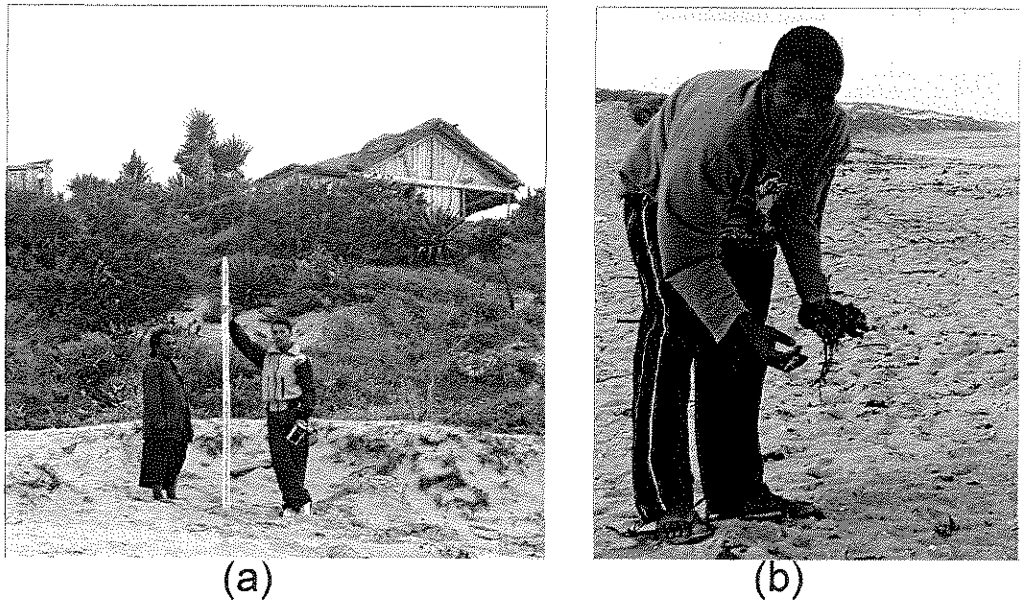

Figure 10. (a) Surveying at Betanty; note the large dunes providing natural protection to the village. (b) At Site 34, an eyewitness displays algae that indicate the extent of penetration of the wave. This is the point of maximum runup in the survey (5.4 m).

gard the eventual false alarm as a failure, but rather as a necessary exercise in precautionary civil defense, within the level of what has to be deemed acceptable. The triggering of the tsunami alert indicates an adequate awareness of tsunami risk on the part of the local authorities and of the population, most of whom responded by evacuating. In particular, we can only applaud the fact that the large majority of the coastal population whom we met had indeed been alerted, which proves the existence and functionality of a means of warning (essentially, commercial radio).

On the other hand, the response of the population to the tsunami alert was generally erratic and often disastrous. Most coastal residents sought to evacuate over excessive distances, in motor vehicles, and often along the main available road, i.e., in a direction parallel to the coastline, which is obviously inefficient in terms of evacuation. As a result, there was chaos in densely populated areas such as Toamasina, where the gendarmerie reported numerous traffic accidents, with six fatalities.

The ITST members strove to remind the population in all villages visited that an efficient evacuation is carried out on foot over distances on the order of hundreds of meters, and to stress the value of vertical evacuation, personally pointing out, where possible, the sturdy multistory buildings located at elevations a few meters above sea level as adequate shelters in this respect (Figure 11). We regard as an important and necessary effort the education of the population about sound evacuation procedures, especially given the strong possibility of a new mega-earthquake striking the southern part of

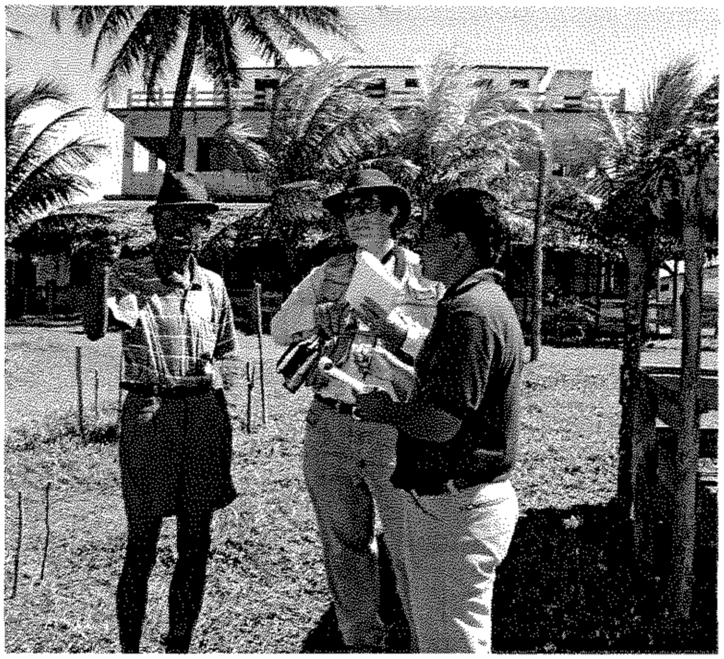

Figure 11. Interview at Ambila (Site 15). The eyewitness at left is the manager of the tourist hotel in the background, which is about 5 m above sea level and 60 m from the seashore. At a height of 10 m, its rooftop terrace could serve as a platform for vertical evacuation in this locality, which is along a narrow spit between the Indian Ocean and the Pangalanes intracoastal waterway.

Sumatra in the future. This could take the form of a repeat of the 1833 earthquake, whose geometry would generate a lobe of maximum tsunami energy in an azimuth close to that of Madagascar and the nearby islands (Réunion, Mauritius, and Rodrigues).

Similarly, in many instances, eyewitnesses described how local residents had taken the uneducated and very dangerous step of venturing onto downdrawn beaches and exposed reef platforms during the initial recess of the sea on 26 December 2004 (Figure 12). The team members repeatedly warned all interviewed residents against such hazardous reactions to any anomalous recess of the ocean: the only safe response to any irregularity in sea level must be to seek immediate refuge at higher elevations. Examples of successful self-evacuations during the 26 December tsunami, widely publicized both in the general media (Anonymous 2005) and across the scientific community (Chapman 2005), illustrate that lives can indeed be saved even in areas subjected to catastrophic levels of destruction. By publishing Figure 12 and its highlighted messages, we wish to emphasize once again the need for continued education of the population of all seashore communities worldwide in this respect.

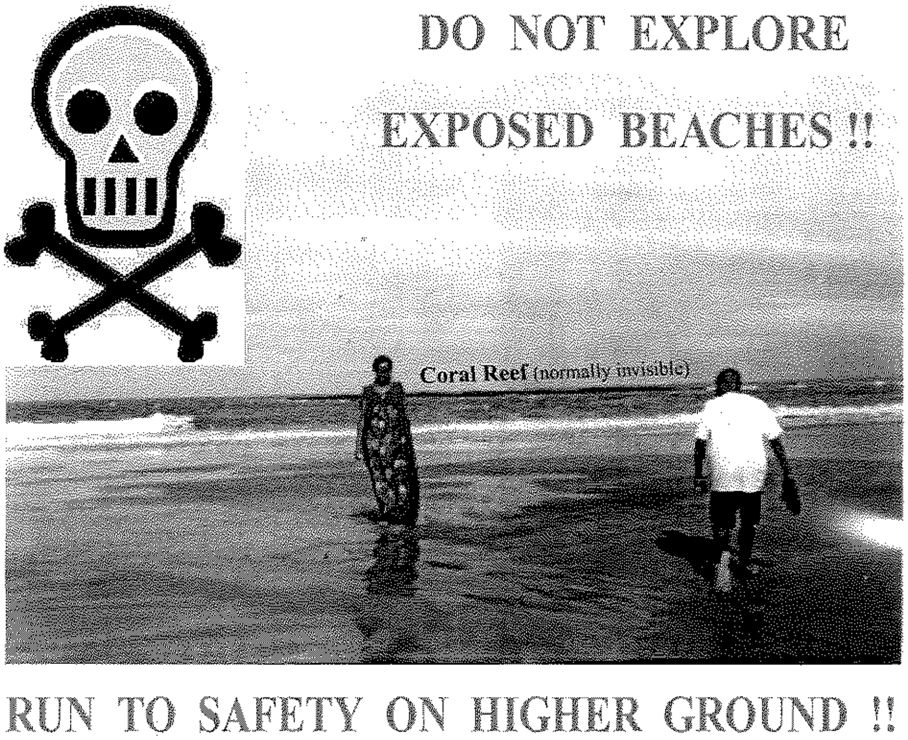

Figure 12. Initial downdraw upon the arrival of the tsunami at Manakara Be, photographed by an eyewitness, showing two residents stepping onto the exposed beach, with the normally invisible coral reef in the background. As emphasized by the labels superimposed on the picture, this is a classic example of what not to do when facing an unexpected recess of the sea. Rather, these residents should be wasting no time self-evacuating to higher ground.

CONCLUSION

The interviewing of over 100 eyewitnesses of the December 2004 Indian Ocean tsunami in Madagascar has resulted in the compilation of a homogeneous data set of inundation and runup values at 52 sites along a stretch of 950 km of the island's eastern coast. While runup values are expectedly lower than in the eastern half of the Indian Ocean, they do reach a maximum of 5.4 m at the southern tip of the island, and they show a strong pattern of variability along the shoreline, to the extent that the tsunami was not observed along a segment of coast measuring at least 80 km. It will be important to determine the origin of such variations, in order to gain insight into the possible effects of future distant tsunamis along the shores of Madagascar. The delayed breaking of the moorings of the freighter *Soavina III* in the harbor of Toamasina, where the tsunami had otherwise been benign, indicates the potential for considerable hazard in port facilities over time windows extending significantly beyond those for conventional wave activity.

The warning issued after the 28 March earthquake illustrates the awareness of tsunami hazards by the authorities and the population. However, the erratic nature of the response of the coastal community highlights the need for continued education in this respect, as do the numerous reported instances of residents yielding to curiosity and venturing to explore beaches and reefs exposed by downdraw during the initial episodes of the 26 December tsunami.

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