INTERNATIONAL TSUNAMI SURVEY TEAM REPORT ON FIELD SURVEY IN MADAGASCAR OF THE 2004 SUMATRA TSUNAMI

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Report on ITST Field Survey, Madagascar, July−August 2005

An International Tsunami Survey Team (ITST) visited Madagascar from 24 July to 06 August 2005, in order to survey the effect of the 2004 Sumatra tsunami on the island.
Members of the team included:

- **Emile A. Okal,** Professor, Northwestern University, Evanston, USA, *Team Leader*;
- **Hermann M. Fritz,** Assistant Professor, Georgia Institute of Technology, Savannah, USA;
- **Ranto Raveloson,** Graduate Student at the University of Antananarivo;
- **Garo Joelson,** Graduate Student at the University of Antananarivo;
- **Petra Pančošková,** M.S., Northwestern University, Evanston, USA.

The team assembled on 25 July at the University Observatory in Antananarivo, hosted by Professor Gérard Rambolamanana. Given the large distances along the island coast, it was decided to split the team into two groups working independently.

- The first ("Northern") group (E. Okal, R. Raveloson and P. Pančošková) focused on the Northern segment of the central coast and on the Northeastern coast;
- The second ("Southern") group (H. Fritz and G. Joelson) explored the Southern part of the Central Coast and the Southern Cape, around Tolagnaro (Fort-Dauphin).

The Northern group flew to Sambava on 27 July, and explored by rental 4WD vehicle the coastal area from Vohémar in the North to Ambodihampana in the South (about 30 km South of Antalaha), over a distance of 200 km of coastline. The group flew back to Antananarivo on 31 July, and left again by 4WD vehicle on 01 August to cover the segment of coastline from Mahanoro in the South to Soanierana-Ivongo in the North, over a distance of 340 km.

The Southern group flew to Fort-Dauphin on 26 July, and explored the Southern coast by rental 4WD vehicle, from Betanty (Faux Cap) to Ampasimasay, over a distance of 220 km along the coast. The group flew back to Antananarivo on 30 July, and left again on 31 July by 4WD vehicle to cover the 190 km of coastline between Farafangana in the South and Mananjary in the North.

The two groups returned to Antananarivo in the evening of 04 August, having thus covered a total of 950 km along the Eastern coast of the country. Debriefing took place at the Observatory on 05 August.

Methodology

The team used traditional ITST procedures in order to map the penetration of tsunamis in the far field: identification and interviews of eyewitnesses, and recording of their testimonies, followed by topographic measurements based on their descriptions. In a few rare occasions, we identified permanent marks of the tsunami action (scouring of a road at Site 6; algae deposits at various other sites).
In this context, we define:

* *Inundation* as the measure of the maximum extent of horizontal penetration of the wave;
* *Flow depth* as the measure of the altitude, relative to unperturbed sea level, of the crest of the wave at a location close to the beach;

* *Run-up* as the measure of the altitude, relative to unperturbed sea level, of the point of maximum inland penetration of the wave, where inundation (see above) is in principle measured.

Flow depth and run-up measurements were made by optical means, using eye levels and surveying rods (Figure 1); inundation measurements were taken by differential GPS (Figure 2). The exact dates and times of the individual surveys were recorded, in order to later effect tidal corrections, which allow to relate flow depth and run-up measurements to the exact sea level at the time of arrival of the tsunami wave.

Results

Table 1 details the database (or product) gathered during the survey. Fifty-two measurements were retained, principally run-up values obtained from eyewitness reports. The map on Figure 3 summarizes the database. In order to streamline the presentation, it features for each locality the maximum vertical penetration (flow depth or run-up; in meters) among sites in its immediate vicinity. Red symbols denote points surveyed by the Northern group; green ones by the Southern group.

The principal conclusions of the survey are as follows:

1. Maximum heights compiled in Table 1 and plotted on Figure 3 are typically on the order of 2 to 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, but remain significantly smaller than surveyed along the coast of Somalia (7 to 8 m; *Fritz and Borrero* [pers. comm., 2005]), where systematic structural damage had been inflicted to ports and buildings. Similar destruction was not reported in Madagascar. Similarly, only one drowning was lamented, as opposed to more than 700 tsunami casualties in Somalia.

2. Surveyed values feature a large lateral *variability* along the coast. In practice, one can outline two general trends: on the one hand, large run-up values are 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. We note in particular that the tsunami was not observed in the two localities of Manahoro and Vatomandry, where we failed to obtain a single eyewitness report of the observation of an anomalous wave, despite interviewing upwards of a dozen residents, who had been present on 26 December. This situation was confirmed by the local Gendarmerie unit in Manahoro.

The two localities are labeled "NIL" on Figure 3. Our experience in the Toamasina area indicates that run-up 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.

Additionally, inside a given group of points, and over distances on the order of one or two km, run-up values can vary considerably.

3. The physical properties of the waves described to us by eyewitnesses, and their arrival times, feature fluctuations which are typical of ITST surveys. A consensus can be drawn among most witnesses, indicating that they were alerted to the tsunami by an initial recess of the sea, over distances difficult to quantify, but generally interpreted as reaching 100 meters. It is suggested that this depression may have been preceded by a small positive wave, too weak to have been universally observed. 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 (time of arrival and period of the waves) are traditionally among the least precise informations obtained from witnesses; however most descriptions indicating a phenomenon starting around noon, local time (GMT +3), and lasting the whole day (with dusk falling around 19:30 at that time of the year). Given epicentral distances varying between 5300 km in Vohemar and 6200 km in Betanty, and taking into account the variable depth of the Indian Ocean Basin, travel times are expected to be 8 to 8.5 hours, predicting arrivals around 12:00 in the North of the island and 12:30 in the South, in good agreement with the eyewitness reports.

The periods of the waves are generally estimated in the range of 15 to 20 minutes.

4. Except for the tragic drowning of a 12-year old boy in front of his parents at Site 28, the most spectacular effects from the tsunami were the disintegration by scouring of a 40−m segment of graded road along the Ampandrozonana Beach at Sambava (Site 6; Figure 4), and the development of an eddy system in the port of Toamasina (Tamatave; Site 16), described in detail below. Damage to small boats was minimal, especially as compared to the case of the ports on Réunion Island.

5. *The eddies in the port of Toamasina*

An extremely singular phenomenon took place in the port of Toamasina, as related to us by Captain Jami Injona, a port pilot, and confirmed (in part) by Captain Talainy, the skipper of the freighter *Ludovic*. The latter explained to us that as early as 12:30 local time, his boat had been subject to turbulent activity in the harbor, as it lay moored to the wharf. Captain Injona then reported a considerable amplification in the strength of the currents in the harbor (but not in the height of the waves), starting at 19:00 (GMT+3), and culminating in the 50−meter freighter *Soavina III* breaking its mooring, and wandering through the harbor for the next 3 hours, with the harbor pilots unable to control her from their tugboats. The ship eventually grounded on a sand bar, along the beach of a nearby water-sports center (Site 17; Figure 5). Miraculously, this "ghost" vessel did not collide with other ships or with harbor structures.

We note that this incident is strikingly similar (albeit on a reduced scale) to that of the much larger container ships *Maersk Mandraki* and *Maersk Virginia* in the harbor of Salalah, Oman, the same day. However, the most fascinating aspect of the *Soavina III* incident remains its timing, as it occurred at least 4 hours after the arrival of the waves described as having maximum amplitude; no such discrepancy was observed in Salalah. It may correspond to the resonance of harbor channels upon arrival of high-frequency components, traveling slower across the ocean basin, due to dispersion. At any rate, it indicates that the hazard posed by the arrival of a distal tsunami in a harbor may last much longer than suggested by the visual observation of anomalous vertical oscillations of the sea surface.

Discussion: Tsunami alert and evacuation

We documented a certain level of confusion in the minds of numerous witnesses between the events of 26 December 2004 (the day after Christmas) and 28 March 2005 (Easter Monday). We recall that the Sumatra mega−event of 26 December (which reached a moment of 10^{30} dyn-cm, *i.e.*, a magnitude $M_w = 9.3$) was followed on 28 March, by a very strong earthquake ($M_0 = 1.1 \times 10^{29}$ dyn-cm or $M_w = 8.7$), occurring to the South of the 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 end, it did not generate a noticeable far-field tsunami.

The local 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, which eventually did not materialize into a detectable wave. Hence the confusion, which was, however, easily resolved in eyewitness reports, by noting the very different time of day for the two events: The tsunami of 26 December reaches Madagascar around 12:30, while the alert for the second event was issued around 21:00 local time, *i.e.*, at night, for an expected arrival of the waves around 03:00 the next day. This allowed us to clarify and validate the reports from many eyewitnesses.

Two important lessons can be learned from the second Sumatra event, over and beyond its character as a false alarm. On the one hand, 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 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, chaos built up in densely populated areas such as Toamasina, where the Gendarmerie reported many traffic accidents with six fatalities.

The ITST members strove to remind the population in all visited villages 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, when available. We regard as an important and valuable necessity the education of the population about sound evacuation procedures, especially in the context of the strong possibility of a new mega-earthquake striking the Southern part of Sumatra in the future; such an event could be a repeat of the 1833 earthquake, estimated at $M = 9$, and whose geometry would generate a lobe of maximum tsunami energy in the precise azimuth of Madagascar and the nearby islands (Réunion, Mauritius, Rodrigues).

Recommendations

Because of the limited amount of time available, it was not possible to extend the survey outside the coastal segments shown on Figure 3. In this context, we recommend to urgently pursue the surveying effort in the following areas, identified by light triangles on Figure 3, and listed in the order of decreasing scientific priority:

a. *Nosy Varika*

This village is located about midway through the 150−km gap between the Northern and Southern groups of data. It would be crucial to fill this gap, which separates zones with very different tsunami effects; this would hopefully allow us to better resolve the cause of the disappearance of the observable tsunami at Manahoro and Vatomandry.

There exists a 100−km long road between Mananjary, reported to be marginally passable by 4WD vehicle.

b. *Southwest Coast, from Cap Sainte-Marie to Itampolo and Toliara*

We note that the strongest run-up value was obtained at the Southern point of the Island, and thus it would be important to study the possible refraction of the wave around it, in the framework of the observation of strong amplitudes on the Western Coast of Sri Lanka.

c. *Eastern Coast North of Soanierana-Ivongo*.

It would be important to fill the gap existing between S.-Ivongo and Cape Masoala, and in particular to study the response of the large Bay of Antongil. Extending the survey to this area could also allow a visit to Sainte-Marie Island, in order to compare the effects of the tsunami on the island and on the coast in its lee.

There exists a 240−km long unimproved road between S.-Ivongo and Maroantsera, which however requires several days of 4WD travel in each direction.

d. *Northern Bays, from Antsiranana to Nosy Be*.

As in **b.** and **c.** above, it would be interesting to determine the response of the large bay at Diego-Suarez, and to study the possible refraction of the tsunami wave around the Amber Cape at the Northern tip of the island.

e. *Extension to the Comoro Islands*

Following a recent visit of a UNESCO working group to the Comoro Islands, it was reported that substantial damage to harbor infrastructure and fishing boats took place on Grand Comoro Island, where one fatality was also reported.

TABLE 1: Dataset surveyed by the ITST in Madagascar, July−August 2005

Number	Site	Latitude (deg. N)	Longitude (deg. E)	Vertical Survey (m)	Vertical Survey Nature	Inundation (m)	Date & Time Surveyed	(GMT)	Notes
					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	Run-up 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	Run-up 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: Fishermen
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 estimated 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		01-Aug-2005		Four witnesses
14	Vatomandry	-19.319	48.986		NIL		01-Aug-2005		Several witnesses on beach
15	Ambila	-18.84417	49.15388	2.35	R	30	02-Aug-2005	09:18	Beach in front of hotel
16	Toamasina (Tamatave)	-18.15672	49.42477	0.90	F		03-Aug-2005	06:30	Mark on tire along wharf in port
17	Toamasina (Tamatave)	-18.15768	49.42277	0.78	R	55	03-Aug-2005	07:40	Run-up on beach across from port
18	Mahavelona (Foul Pointe)	-17.69017	49.51995	0.77	R	13	03-Aug-2005	10:15	South beach, across from reef
19	Mahavelona (Foul Pointe)	-17.68528	49.51823	0.72	R	13	03-Aug-2005	10:35	Central beach, across from reef
20	Mahavelona (Foul Pointe)	-17.67457	49.51608	0.79	R	4	03-Aug-2005	11:01	North beach, beyond reef end
21	Mahambo	-17.47523	49.46362	1.17	R	7	03-Aug-2005	12:02	Bungalow at Hotel Le Récif
22a	Soanierana-Ivongo	-16.91903	49.58707	2.23	F	20	04-Aug-2005	05:47	Flow depth at house on beach
22b	Soanierana-Ivongo	-16.91903	49.58707	2.00	R	46	04-Aug-2005	05:47	Run-up behind house
23	Soanierana-Ivongo	-16.92005	49.58700	1.30	R	12	04-Aug-2005	06:00	Run-up at stump on beach
24	Manakatafana	-17.06165	49.52432	1.92	R	22	04-Aug-2005	06:40	Run-up at beach near roadside shop
25	Fenoarivo (Fénérive)	-17.38093	49.41523	2.50	R	6	04-Aug-2005	07:44	Beach across from town square

TABLE 1: Dataset surveyed by the ITST in Madagascar, July−August 2005 (ctd.)

Number	Site	Latitude (deg. N)	Longitude (deg. E)	Vertical Survey (m)	Vertical Survey Nature	Inundation (m)	Date & Time Surveyed	(GMT)	Notes
				Southern Team					
26	Tolagnaro (Fort Dauphin)	-25.02695	46.99611	2.90	R	75	26-Jul-2005	13:17	Trimline on cliff inside port -- eyewitness confirmed
27	Tolagnaro (Fort Dauphin)	-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-yr. 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 (Faux Cap)	-25.56941	45.53209	4.40	R	34	28-Jul-2005	13:38	Eyewitness
32	Betanty (Faux Cap)	-25.56817	45.53433	2.30	R	30	28-Jul-2005	14:15	Algae --eyewitness confirmed
33	Betanty (Faux Cap)	-25.56508	45.53881	4.80	R	37	28-Jul-2005	14:27	Algae --eyewitness confirmed
34	Betanty (Faux Cap)	-25.56952	45.53097	5.40	R	28	29-Jul-2005	04:30	Eyewitness
35	Benaiky	-25.27869	46.06108	2.90	R	19	29-Jul-2005	08:48	Eyewitness
36	Tolagnaro (Fort Dauphin)	-25.03878	46.99558	4.10	R	26	30-Jul-2005	05:40	Eyewitness
37	Tolagnaro (Fort Dauphin)	-25.03487	46.98299	2.20	R	44	30-Jul-2005	06:08	Eyewitness
38a	Mananjary	-21.24501	48.34824	2.20	F	28	01-Aug-2005	05:22	Dune overtopped
38b	Mananjary	-21.24501	48.34824	1.00	R	68	01-Aug-2005	05:22	Run-up at inundation limit
39a	Mananjary	-21.26137	48.34547	2.20	R	43	01-Aug-2005	06:14	Eyewitness -- 1st wave
39b	Mananjary	-21.26137	48.34547	2.40	R	43	01-Aug-2005	06:14	Eyewitness -- 2nd wave
40	Mananjary	-21.22907	48.35131	2.40	R	21	01-Aug-2005	07:17	Eyewitness
41	Manakara -- North	-22.13989	48.02431	2.30	R	43	01-Aug-2005	13:21	North of river -- Eyewitness
42	Manakara Be	-22.14942	48.02202	4.20	R	61	01-Aug-2005	14:16	Eyewitness
43	Manakara Be	-22.16200	48.01556	3.50	R	59	01-Aug-2005	14:44	Eyewitness
44	Farafangana	-22.81895	47.83588	1.60	R	32	02-Aug-2005	08:52	In lagoon -- eyewitness
45	Farafangana	-22.80939	47.83716	2.40	F	25	02-Aug-2005	09:36	Dune overtopped
46	Manakara Be	-22.14362	48.02430	1.50	F	38	02-Aug-2005	14:25	Wall of bungalow -- Eyewitness and Video confirmed
47	Manakara Be	-22.14515	48.02395	4.00	R	30	03-Aug-2005	06:03	Pool wall -- Eyewitness and Video confirmed
48	Manakara Be	-22.14718	48.02309	3.50	R	34	03-Aug-2005	06:12	Palm tree -- Video confirmed
49a	Manakara Be	-22.14344	48.02286	2.00	F	10	03-Aug-2005	06:51	Waterline on house -- Video confirmed
49b	Manakara Be	-22.14344	48.02286	1.50	F	21	03-Aug-2005	06:51	run-up at extent of inundation
50	Manakara Port	-22.14126	48.02057	1.60	F		03-Aug-2005	07:16	Quai Wall -- Boat cut loose
51	Manakara Be	-22.14631	48.02324	3.80	R	58	03-Aug-2005	11:05	Road Hole due to erosion
52	Manakara North	-22.03352	48.07116	2.10	R	25	03-Aug-2005	12:07	12 km North of Manakara -- Eyewitness

Codes to nature of vertical mesurements: **F**: Flow depth; **R**: Run-up.

Figure 1. Measurement of flow depth and run-up by standard topographic methods using a leveling rod *(Left;* Site 22*a* at Soanierana-Ivongo) and an eye level *(Right;* Site 1 at Amdingozabe).

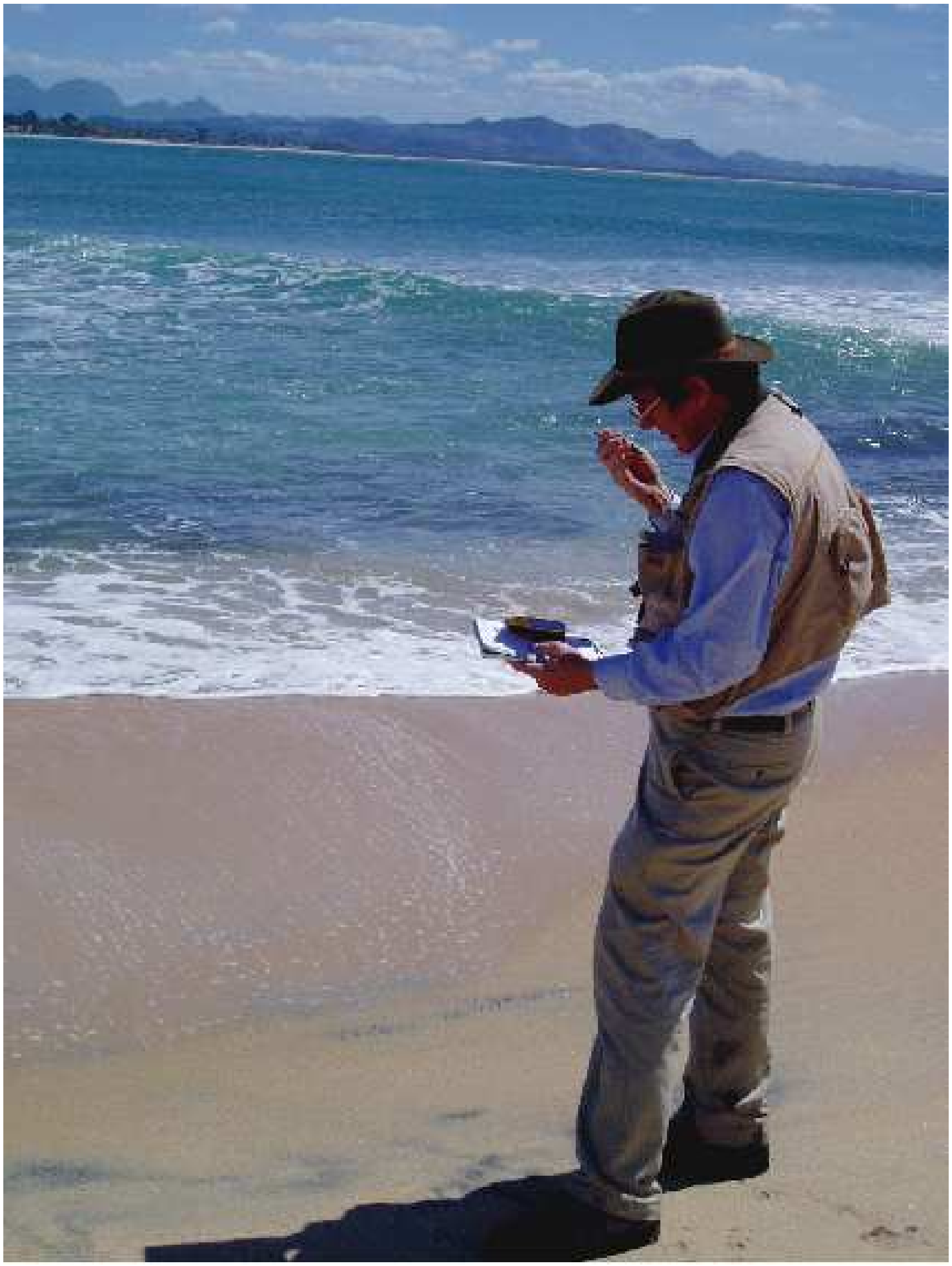

Figure 2. Example of GPS measurement, allowing precise surveying of the site (in this case Site 6, on Ampandrozonana Beach in Sambava), and in addition, a computation of the inundation parameter, by differential GPS surveying.

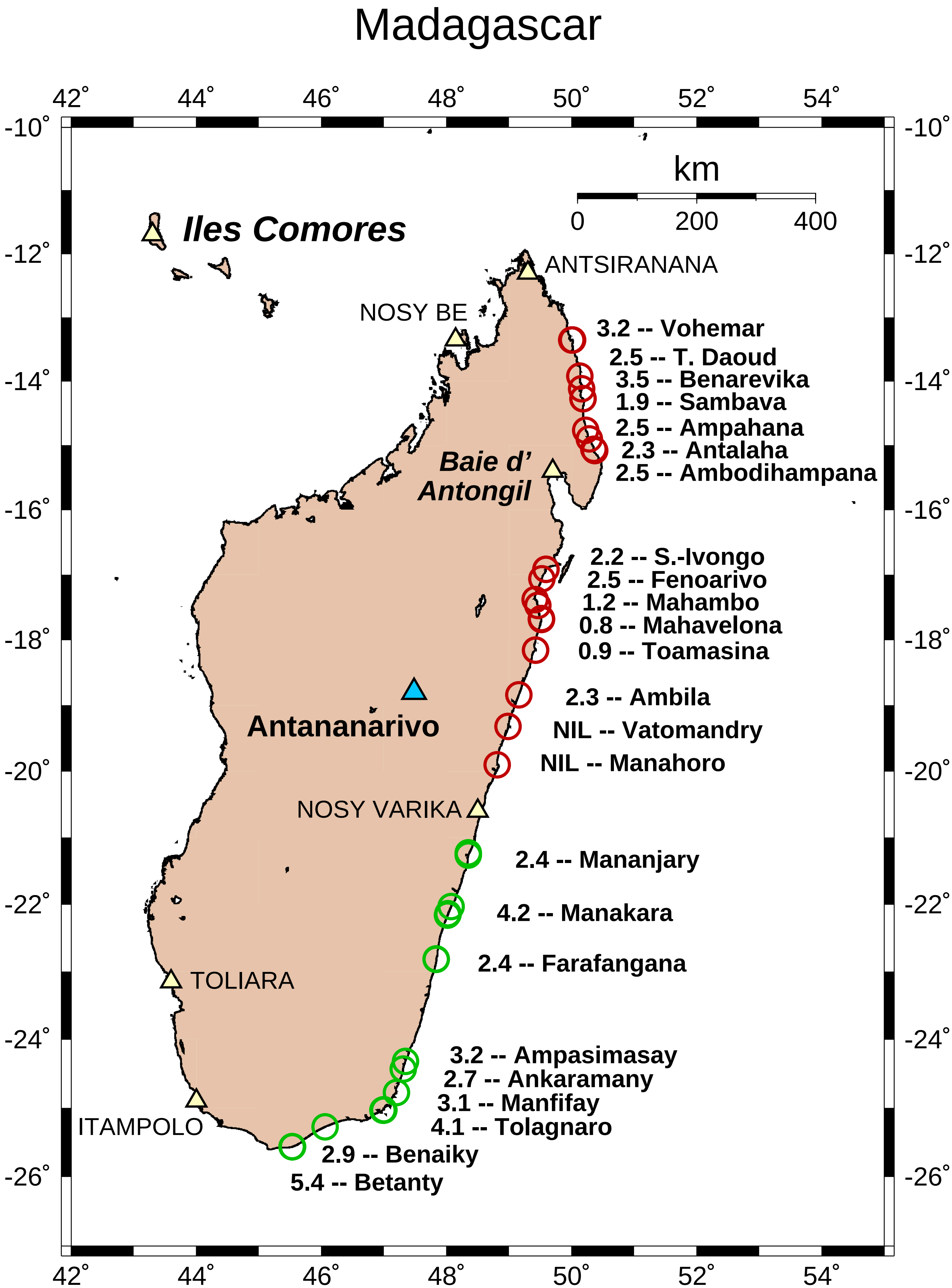

Figure 3. Map of Madagascar showing maximum run-up values (in meters) surveyed at the various sites visited by the Northern group (in red) and the Southern group (in green). Light-colored triangles denote sites recommended for complementary surveying (see text).

Figure 4. Scouring of a road along Ampandrozonana Beach in Sambava (Site 6). *Top Left:* General view of the beach, with the eroded road segment to the left, 71 m away from the water line. *Top Right* and *Bottom:* Close-up of the scouring. Note the advance of the beach, identified by sand deposits, over the previous location of the road.

Figure 5. *Top:* The 50−m freighter *Soavina III* photograped on 02 August 2005 in the port of Toamasina. *Bottom:* Captain Injona uses a wall map of the port to describe the path of *Soavina III* from her berth in Channel 3B (pointed to on map), where she broke her moorings around 7 p.m., wandering in the channels up to the location of the red dot, before eventually grounding in front of the Water-Sports Club Beach (white dot; Site 17).